Experimental analysis and modelling of the rainfed rice cropping systems in West Africa

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Bonn, den, 12 Juli, 2012

Omonlola Nadine Worou

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Abstract

There is a need to improve rice productivity to meet the increasing demand for rice in West Africa since it is acknowledged that existing rainfed rice cultivation practices deal with irregularities of climate like drought or submergence with iron toxicity risk on the one hand and on the other hand land management associated with soil fertility and the topography. This study addressed the above issues by investigating experimental results in both rainfed lowland and upland system.

In a rainfed lowland system, the study examined first the constraints to rice production in inland valleys in West Africa which depend on the rainfall distribution and the heterogeneity of the topography that leads frequently to mobilization of Fe^{2+} and runoff causing erosion and loss of N. During 4 years (2007 to 2010), a three factorial trial showed that the grain yield across the seasons had quite diverse response with respect to slope position (up and down) and management practices (bunds and fertilizer). The impact of fertilizer has been significant in the year 2009 leading to the increase of grain yield by 0.45 $Mgha^{-1}$ with fertilizer compared to the control. Negative correlation with Fe concentration in rice was only found at the upper slope position. Our findings showed that, at the upslope, Fe concentration in rice is higher with bunding. At downslope position, rice yield was significantly correlated with ponding water level in the first month, cation exchange capacity and organic C of the soil and N concentration in the rice tissue.

As the exploitation of lowland inland valleys for rice production requires improved understanding of the effect of management practices on soil water, nutrient dynamics and rice yield, the crop model EPIC (Environmental Policy Integrated Climate) was further applied to the upper slope position in order to capture processes involved in crop development and yield in temporarily inundated rice fields and to assess the suitability of the model for this specific agroecosystem. The model was parameterized using observed soil water characteristics and crop parameters and run against observation data. The simulated LAI development, aboveground biomass and grain yield compared well with field observations. MRE (mean relative error) of simulated yield was 6 to 18 % except for with bund plots in 2009 and 2010, where grain yield was overestimated by the model when no fertilizer was applied (MRE=45%). This was due to the negative effect of elevated iron concentration in the rice plant, which the model was not able to consider in the simulations.

In upland rice experiments, our study was motivated by the challenge for increasing productivity to grow rice on low-input farmland. Therefore, we assessed improved upland varieties in 6 sites of Benin Republic. Although uniform fertilizer input was applied across the experiments, the effect of site and interaction between site and years appeared as factors that strongly influence rice production. Environments with higher organic carbon coupled with sufficient rainfall water during the cropping period led to higher grain yield. These conclusions therefore confirmed that the test of the performance of field scale crop models under different agro-ecological conditions is a prerequisite for the evaluation of the impact of management strategies for larger scales. Therefore, the EPIC model was again tested for upland land rice production by taking into account seasonal variability in Guinean and Guinean-Sudanian zones in Benin and Nigeria (West Africa). The results showed the accuracy of the model to simulate LAI, total above ground biomass and grain yield. The model exhibited more variability in yield for increasing N fertilizer application than P. In addition, general precision in model output is reduced when considering farmer's field condition. Large root mean square RMSE in calibration (<35) and the validation (>100) suggested that robustness of the model became restrictive under severe drought condition while the rice response to N fertilizer became reduced.

The general use of the model for rainfed rice production at a large scale requires identification of areas with iron toxicity, drought and flooding risk and improvement of the model with respect to the impacts of iron toxicity and drought on rainfed rice.

Zusammenfassung

Es besteht ein Bedarf die Produktivität des Anbaus von Reis zu verbessern, um der steigenden Nachfrage nach Reis in Westafrika Sorge zu tragen. Bestehende Regenfeldbau-Praktiken beschäftigen sich mit durch den Klimawandel hervorgerufenen Unregelmäßigkeiten wie Dürren oder Überflutungen mit den Risiken Eisentoxizität auf der einen Seite und auf der anderen Seite mit der von der Topographie abhängigen Bodenfruchtbarkeit.

Diese Studie behandelt die genannten Probleme durch die Untersuchung experimenteller Ergebnisse sowohl im Regenfeldbau der Standorte im Tief- und Hochland.

In einem Regen bewässerten Tiefland-System wurden für die Studie zunächst die Limitierung der Reisproduktion in Tälern im Landesinneren in Westafrika, verursacht durch Fe2 + Mobilisierung und Verlust von Verfügbarem Stickstoff durch Erosion untersucht. Diese Faktoren variieren in Abhängigkeit von der Niederschlagsverteilung und der Heterogenität der Topographie. Während eines Zeitraums von 4 Jahren (2007 bis 2010), zeigte eine diese drei Faktoren betreffende Studie, dass der Kornertrag durch die Jahreszeiten ganz unterschiedliche Reaktion in Bezug auf Steilheit Position (nach oben und unten) und Management-Praktiken (Dämme und Dünger) hatte. Die Auswirkung von Düngemitteln zeigte im Jahr 2009, eine Erhöhung der Ausbeute von 0,45 Korn Mgha-1 mit Dünger. Diese war im Vergleich zur Kontrollgruppe signifikant.

Negative Korrelation mit der Fe-Konzentration wurde nur in den Höhenlagen gefunden. Unsere Ergebnisse zeigen, dass mit steigender Meereshöhe, die Unverträglichkeit von Reispflanzen gegenüber der Fe-Konzentration mit ansteigt. In den Tallagen korreliert die Reis-Ausbeute deutlich mit dem Wasserniveau im ersten Monat, der Kationenaustauschkapazität und der Konzentration organischen Kohlenstoffs des Bodens und N-Konzentration im Gewebe der Reispflanzen.

Die Nutzung von Tiefland Tälern im Hinterland für die Reisproduktion erfordert verbessertes Verständnis der Wirkung von Bodenmanagement-Praktiken auf die Wasser-, Nährstoffdynamik und die verbundenen Auswirkungen auf den Ertrag.

Zudem wurde das EPIC Erntemodell (Environmental Policy Integrated Climate) auf die Höhenlagen angewendet, um die Entwicklung der Kulturen und den Ertrag in zeitweise überschwemmten Reisfeldern zu beobachten und die Eignung des Modells für dieses spezifische Agrarökosystem zu beurteilen.

Das Modell, wurde auf die beobachtetes Bodenwassercharakteristika und Anbaubedingungen von Reis angewendet.

Der simulierte LAI Entwicklung, die oberirdische Biomasse und Kornertrag stimmen gut mit den Feldbeobachtungen überein. Der MRE (mittlere relative Fehler) der simulierten Ausbeute betrug 6 bis 18% mit Ausnahme von eingedämmten Parzellen in 2009 und 2010, wo der Kornertrag durch das Modell überschätzt wurde, wenn kein Dünger aufgebracht wurde (MRE = 45%). Dieser entstand aufgrund der negativen Auswirkungen der erhöhten Eisenkonzentrationen, die durch das Modell nicht simuliert werden konnten.

Bei den Versuchen in den Höhenlagen bestand die Motivation die Produktion unter Anwendung extensiver Bewirtschaftungsweise zu erhöhen.

Daher beurteilen wir verbesserte Hochland-Sorten an 6 Standorten der Republik Benin.

Trotz einheitlichem Dünger-Eintrag auf allen Flächen, übten die Lage, bzw. die Lage in Abhängigkeit zum Anbaujahr einen starken Einfluss auf die Reisproduktion aus. Böden mit höherem Gehalt an organischem Kohlenstoff bei ausreichenden Niederschlägen während der Erntezeit hatten höheren Kornertrag.

Diese Schlussfolgerungen bestätigten, dass die Betestung der Leistungsfähigkeit der Erntemodelle im Feld-Maßstab unter verschiedenen agro-ökologischen Bedingungen eine Voraussetzung für die Evaluierung der Auswirkungen von Strategien für größere Maßstäbe ist.

Daher wurde das EPIC-Modell ein weiteres Mal für die Hochland Reisproduktion unter Berücksichtigung jahreszeitlich bedingter Unterschiede in der Guinea- und Guinea-Sudan-Zone in Benin und Nigeria (Westafrika) getestet.

Die Ergebnisse zeigten die Genauigkeit des Modells zur Simulation von LAI, gesamter oberirdischer Biomasse und Kornertrag. Das Modell zeigte mehr Variabilität im Ertrag bei der Erhöhung der Düngung mit N als mit P.

Darüber hinaus reduziert der unterschiedliche Zustand der einzelnen Flächen die Gesamtpräzision der Modellierung.

Die Messung der Wurzeldurchmesser (RMSE in Kalibrierung (<35) und Validierung (> 100)) zeigt, eine Schwäche des Modells unter starker Dürre, und gleichzeitig eine reduzierte Antwort der Reispflanzen auf N-Düngung.

Die allgemeine Verwendung des Modells für Regenfeldbau in der Reisproduktion in großem Maßstab erfordert die Identifizierung von Gebieten mit erhöhter Eisen Toxizität, Dürre- und Überschwemmungsrisiko und die Verbesserung des Modells in Bezug auf die Auswirkungen der Eisen-Toxizität und Dürre auf Regen bewässerten Reis.

CHAPTER

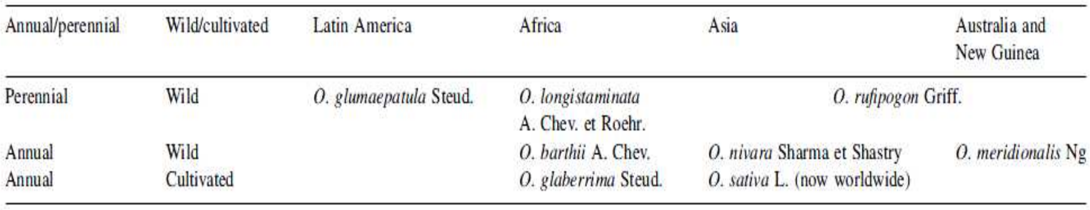
1. General introduction

1.1. Rice

Rice is a cereal crop, a member of the grass family, Graminae. It belongs to the genus *Oryza* L.. Vaughan et al. (2008) described that the taxonomy of the A-genome of Oryza species has long been ‘a matter of opinion’, and the distinction of species has mainly been based on three criteria: geography, annual/perennial habit and cultivated or wild habitat (Table 1.1).

In West Africa, rice cultivation is probably not more than 3500 years old. The cultivated species (*O. glaberrima*) was domesticated from the wild annual *O. barthii*. The Asian species *O. sativa* introduced into West Africa in the 17th century is rapidly spreading into rainfed lowland areas formerly dedicated to *O. glaberrima* (Chang, 1976). Rice is a self-pollinated crop. Because of this, genetically segregated lines remain relatively unchanged from generation to generation. Genetic changes occur mostly through deliberate "crossing" or hybridizing of parental cultivars (Evenson and Gollin, 1997). Rice is an essential food for more than two billion people.

Table 1.1: Geographic distribution, life cycle and cultivation status of A-genome Oryza species (Vaughan et al., 2008).



Annual/perennial	Wild/cultivated	Latin America	Africa	Asia	Australia and New Guinea
Perennial	Wild	*O. glumaepatula* Steud.	*O. longistaminata* A. Chev. et Roehr.	*O. rufipogon* Griff.	
Annual	Wild		*O. barthii* A. Chev.	*O. nivara* Sharma et Shastry	*O. meridionalis* Ng
Annual	Cultivated		*O. glaberrima* Steud.	*O. sativa* L. (now worldwide)	

1.2. Importance of rice in West Africa

Rice has long been the food staple in many traditional communities and in major cities in West Africa. Since the early 1970s, it is a major source of calories intake in West Africa and comes third after maize and cassava for the continent as whole (Diagne et al., 2010). Indeed, the annual rice consumption increased at the rate of 6.5% (Olaleye et al., 2002, WARDA, 2007) which made the demand increase faster than anywhere in the World. This is due to both population growth (2.6% per year) and the increasing proportion of rice in the African diet (1.1% per year) (Cuero, 2006, Defoer et al., 2002). In fact, the per capita rice consumption in West Africa increased from 14 kg in the 1970s to 22 kg per person per year in the 1980s, and in 2005 it is almost 32 kg per person per year (Fig. 1.1). The demand for rice in West Africa has also far outpaced the production. It is reported that rice imports in West Africa have grown at an annual average rate of 8% since 1997 (WARDA, 2002).

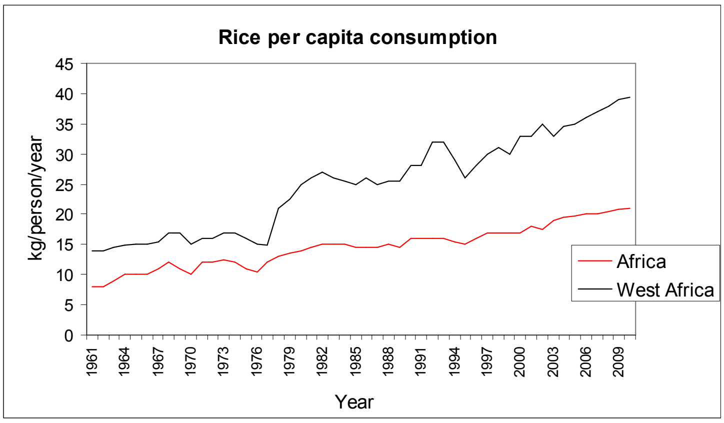


Figure 1.1: Evolution of rice consumption in Africa and West-Africa from FAO, 2009 (Diagne et al., 2010).

In general, the rice cropping systems in West Africa refer to determinant factors including field position, labour, capital inputs and management. Andriesse and Fresco (1991) made a distinction in rainfed system between permanent, wet rice cropping systems (lowland type) and shifting rainfed rice cropping systems (upland type).

1.2.1. The lowland type

The West Africa sub-region has many lowland types, notably river flood plains, inland valley swamps, interior plains, coastal plains and delta uplands, inland swamps, irrigated humid, irrigated Sahelian and mangrove environments (Africa Rice, ex-WARDA, 1988). In the inland valley, annual crops are traditionally grown on uplands and upper slopes, but increasing pressure on land leads to a shift of cropping down-slope to the lowlands (van de Giessen, 2005).

Paddy rice systems have been observed to be economically sustainable and ecologically sound due their high efficiency in nutrient replenishing mechanisms and their intrinsic resistance to soil erosion (Issaka et al., 1997). Buri et al. (1999) have reported the potential and nutrient supplying capacity of the inland valley swamps and river flood plains for the essential macronutrients, which has also been reported for the microelements (Buri, 2000).

Furthermore, Baghat et al. (1999) found that saturated soil conditions save more than 40 % water compared to continuous shallow ponding and produced the same rice yield when weeds were controlled by herbicides. In the inland valley system, water is the major driving force for interaction between adjacent sections of the toposequence. The water balance of the hydromorphic part of lowland systems derives from rain falling on the upland portion which may partially leave this agro-ecosystem as runoff water, moving down-slope as surface flow. The rest infiltrates and may either be lost as evapotranspiration or may percolate into deeper layers down to the groundwater table (van de Giesen et al., 2005).

1.2.2. The upland type

The upland system refers to rice grown on both flat and sloping fields that were prepared and seeded under dry conditions, and generally exclusively depend on rainfall for moisture (IRRI, 1975). Upland rice varieties are grown much like maize. Whereas they account for major share of often extreme poverty; they are a rich source of diversity in cropping type (monoculture, rotation with legume crops, intercropping).

In sub-Saharan Africa, upland rice yields are less than 1 Mgha^{-1} on average despite a potential near 4 Mgha^{-1} (Dingkuhn et al., 1998, Dingkuhn, 2000).

1.3. The study area

The study covers Benin and South-West Nigeria; both are located in Western Africa at the Guinea Coast (see Fig. 1.2).

The two countries truly represent the climatic profile from the very wet to the semi-arid ends of the subcontinent. The average annual temperatures are approximately 27°C, with temperature amplitudes of 5–6 °C. The Benin Republic covers about 112,622 km², whereby the distance between North and South extends 650 km (6°-12°30N) and about maximal 120 km from East to West (0°30´-4°E), respectively.

The North and the Centre areas are essentially dominated by tropical ferruginous soils (Dubroeucq, 1977), originally from Precambrian crystalline rocks (granite and gneiss). In the Centre region particularly this type of soil is rather deep, without laterite, and often has a somewhat higher inherent fertility (Saidou et al., 2004). A major landscape feature of Southern Benin and Southwest Nigeria is a series of low-lying plateaus with red soils called "*terre de barre*" that occupy approximately 5320 km² (INRAB, 1997, Carsky, 2003). In general, small-scale variability of the soils is very high (Giertz and Hiepe, 2009).

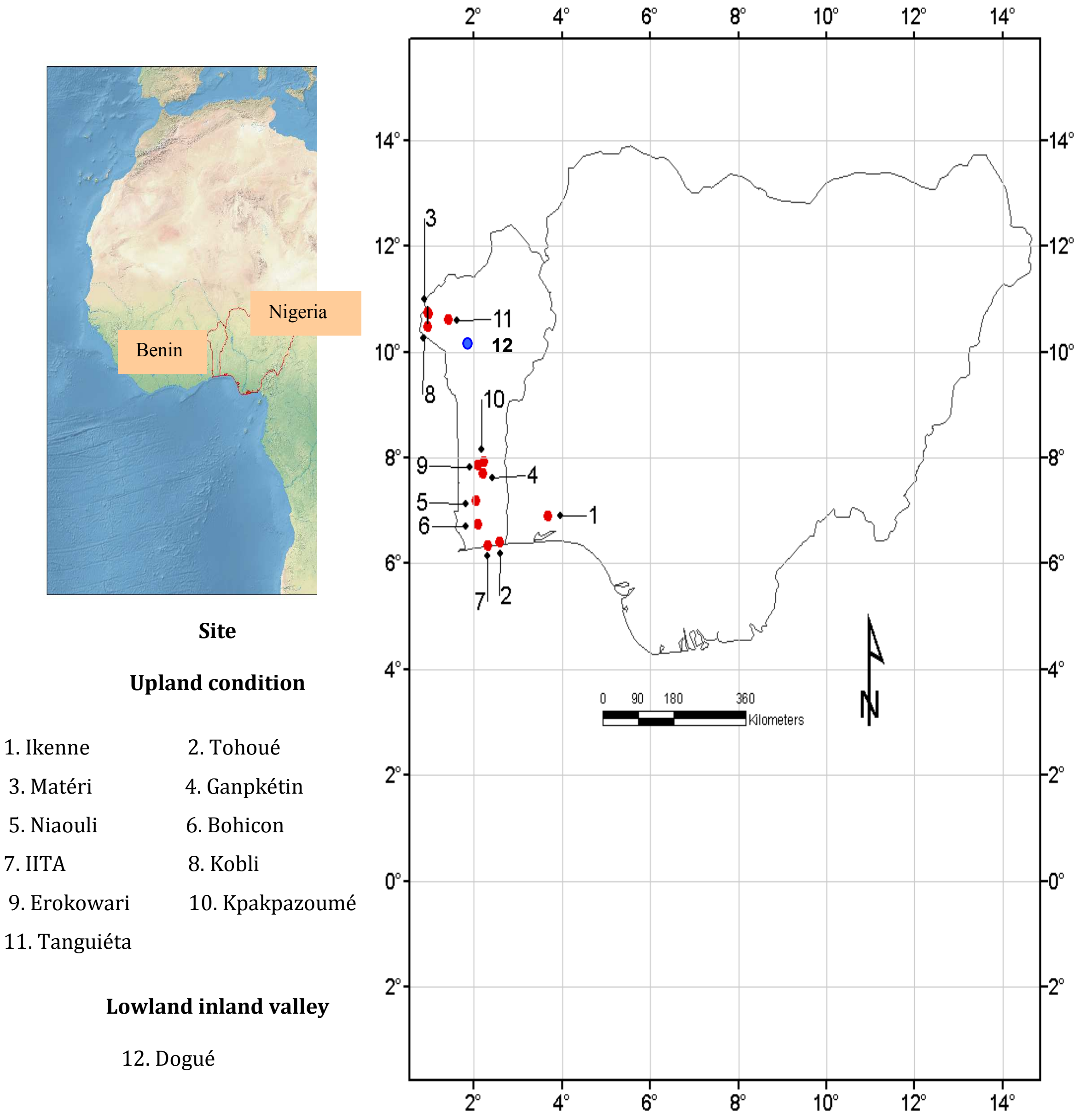
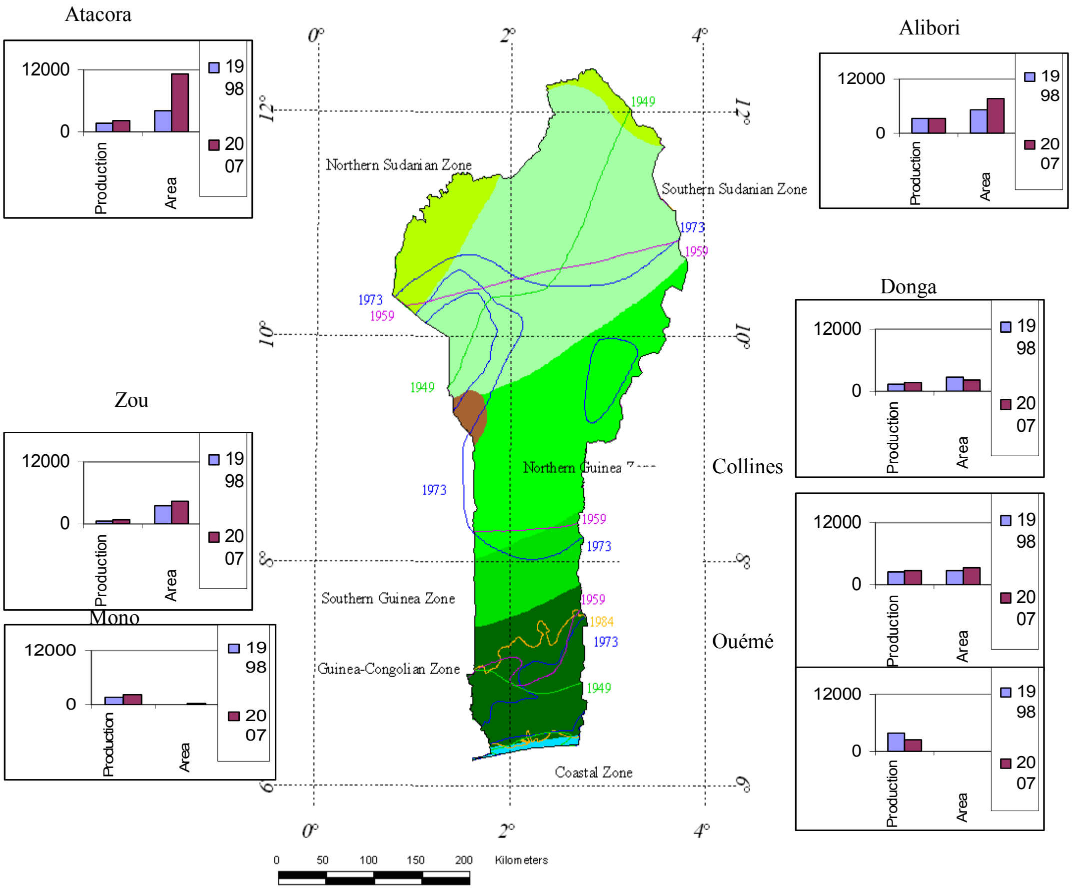


Figure 1.2: Geographical location of the study area.

Rice has become an important staple diet in Benin. Rice consumption in the country drastically increased at an annual rate of 47% between 2001 and 2005 (Africa Rice Centre, 2007). However, the country is far from being self-sufficient in rice. Indeed the country had to import 50 000 Mg per year to respond to the deficit in 2002 (Adégbola and Sodjinou, 2003). In parallel, urban areas, rapid changes in eating patterns have lead to the shift toward consuming more energy-dense processed foods such as refined imported rice (Sodjinou, 2006). This has been attributed to several factors including variations in physical characteristics, absence of foreign matter (impurities), nutritional quality and cooking behaviours (Fofana et al., 2011). In order to cope with these trends, strategies to boost agricultural production have been implemented at the national level. These strategies include management of lowlands, the extension of high yielding varieties, the design and delivery of an improved framework for postharvest processing (Adegbola et al., 2008).

From a farmer survey in 2008, it appeared that rice in Benin was grown in lowlands with a share of 10% of production area of which 88% were irrigated and upland (2%) (Table 1.2). All the systems presented a real potential for expansion (Fig. 1.3). Indeed, since 1990, production is steadily increasing in all the districts. According to the national statistics, DPP (2008), paddy rice production increased from 10,940 Mg in 1998 to 64,937 Mg in 2007.



Map Layout: Alex Wezel; Department of Landscape and Plant Ecology
University of Hohenheim, Germany, 1999

Figure 1.3: Map of the Republic of Benin with agroecological zones, rice progression in production (kgha $^{-1}$) and in area (ha) related to the districts average (DPP statistics, 1998, 2007).

Table 1.2: Estimated share (%) of rice production for different production systems and two countries, adapted from Africa Rice (1997) and Adégbola et al. (2008).

Country	Mangrove swamp	Deep-water floating	Irrigated		Rainfed lowland	Rainfed upland
			Sahel	Savannah /humid		
Benin %	0	0	0	88	10	2
Nigeria %	1	3	0	27	53	17

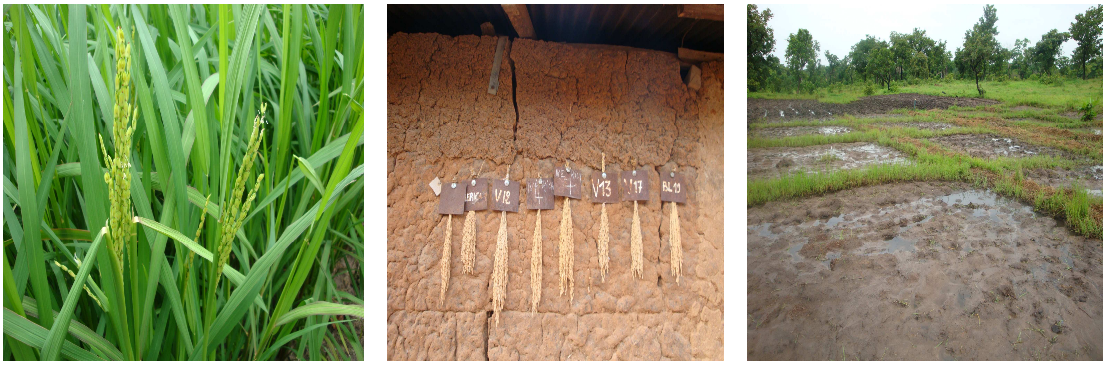
1.4. The NERICA rice

NERICA (New Rice for Africa) represents fertile interspecific progenies between *Oryza sativa* L. and *O. gaberrima* Steud. (Fig. 1.4). It is obtained after a backcrossing and doubled haploid breeding developed by the Africa Rice Centre. NERICA is, therefore, not genetically modified. It combined the high yield potential of *O. sativa*, resulting from high spikelet number caused by secondary branches on the panicle, with useful traits of *O. glaberrima* such as rapid leaf canopy establishment and high N responsiveness. The progenies partly inherited the *O. glaberrima* parents' high specific leaf area (SLA) during early growth, theoretically improving competitiveness with weeds, and from the *O. sativa* parents the rapid decrease in SLA towards the reproductive stage, theoretically allowing for high leaf photosynthetic rates and high grain yield (Jones et al., 1997).

The NERICA varieties were developed from out of the thousands of crosses which allow to distinguish two families of elite material: at first, 18 varieties suited for upland systems (NERICA1 to NERICA18) most of them developed from *O.sativa* and parent CG4 (*O.glaberrima*); Indeed, the average yield of NERICA per hectare is found to be 2.5 Mg on farms in Uganda (Kijima et al., 2006), which is significantly higher than the average upland rice yield of one ton per hectare in SSA (Balasubramanian et al., 2007).

Furthermore, Africa Rice scientists addressed the demand for production by taking into account stresses related to lowland ecologies (Moukombi et al., 2009). 60 varieties suited for lowland systems, NERICA-L (NERICA-L1 to NERICA-L60) are developed from their most frequently used parents IR64 (*O. sativa*) and TOG5681 (*O. glaberrima*) (Diagne et al., 2010). The most important breeding objectives for the lowland varieties of NERICA were yield potential, grain quality, high environmental adaptation and tolerance against Rice Yellow Mottle Virus and African Gall Midge (Rodenburg et al., 2009). Up to date the superior yielding ability of NERICA-L41 over the parents under drought was demonstrated in Bocco et al. (2012).

In Benin Republic, being one of the selected pilot countries, there is high hope for increased rice production with the introduction of NERICA. Adégbola et al. (2002) estimated the total area under NERICA varieties was 5,000 ha in 2003. There was evidence that the adoption of NERICA increases the income of NERICA adopters significantly in Benin (Adekambi et al., 2008). The National Project for Nerica Dissemination (PDRN) promoted series of on-farm experiments that allowed farmer's capacity to self-produce seeds as commonly done with other rice varieties. This should exclude the need to purchase new seeds for several years, which enables the wide adoption of NERICA in the country where rice seed markets are underdeveloped (Kijima et al., 2011).



(a) (b) (c)

Figure 1.4: NERICA culture in Benin, (a) maturation phase of Nerica 1 crop in the field at Tohoué (2009), (b) promising NERICA lines disseminated during the participatory varietal selection, (c) preparation of with bund field for NERICA-L on farm station in Dogué village (2010).

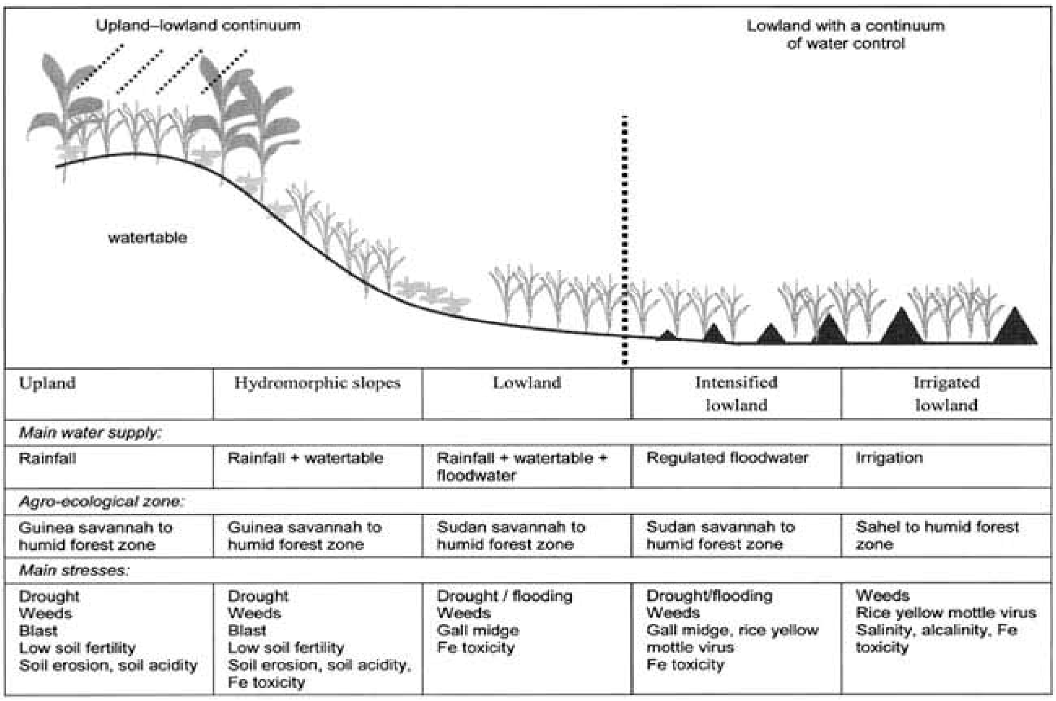
1.5. Problem statement

1.5.1. Challenges for food security in SSA

Increasing attention is given to food crop production technologies in order to enhance productivity, safeguard food security and alleviate poverty. It is recommended that the adoption the new high yielding varieties (that led to the green revolution in Asia) could lead to significant increases in agricultural productivity in Africa and stimulate the transition from low productivity subsistence agriculture to a high productivity agro-industrial economy (World Bank, 2008). This required that important issues for transferring the sustainable productivity techniques in recent years in Asia (i.e., use of bund, high yielding variety) to sub-Saharan's unfavourable production environments had to be addressed. It also directed breeding activities towards the development of drought tolerance in rice at flowering and severe drought stress (CGIAR, 2006). It is reported that improved varieties have recently become available: for irrigated rice, improved varieties occupied 97% of the planted area, whereas they were present only for 39% of the rainfed upland rice area (UNEP, 1998). In controversy there is a risk that adoption of new varieties may tend to be temporary because in the wake of dry years, farmers revert to their traditional, low but stably yielding cultivars. This makes a return of investment of national crop breeding programs low and often negative (Dingkuhn, 2006). Consequently, the choice of well adapted cultivars should be coupled with cultural practices and decision criteria for optimal use of fertilizer and water resources in West Africa.

1.5.2. Constraints of rice cultivation in West Africa

Fig. 1.5 shows the constraints associated to rice culture types in West Africa.



Upland	Hydromorphic slopes	Lowland	Intensified lowland	Irrigated lowland
Main water supply:				
Rainfall	Rainfall + watertable	Rainfall + watertable + floodwater	Regulated floodwater	Irrigation
Agro-ecological zone:				
Guinea savannah to humid forest zone	Guinea savannah to humid forest zone	Sudan savannah to humid forest zone	Sudan savannah to humid forest zone	Sahel to humid forest zone
Main stresses:				
Drought Weeds Blast Low soil fertility Soil erosion, soil acidity	Drought Weeds Blast Low soil fertility Soil erosion, soil acidity, Fe toxicity	Drought / flooding Weeds Gall midge Fe toxicity	Drought/flooding Weeds Gall midge, rice yellow mottle virus Fe toxicity	Weeds Rice yellow mottle virus Salinity, alcalinity, Fe toxicity

Figure 1.5: Major production constraints of rice production systems in different agro-ecological zones (Defoer, 2004)

Lowland constraints

Iron toxicity is one of the major constraints to rice production in the lowlands of West Africa (Becker and Asch, 2005). Ferrous iron (Fe^{2+}) is abundantly taken up by the plant and becomes concentrated in the leaves, causing limb discoloration, reduced tillering, stunted growth and substantially reducing yields (Chérif et al., 2009*).* Iron toxicity is associated with poor water control, resulting in reducing soil conditions that promote the accumulation of soluble ferrous iron in the soil solution. Under these specific water conditions, soluble iron in the soil solution (Fe^{2+}) is absorbed by roots and accumulates in leaves (Audebert and Fofana, 2009). The critical iron content in leaves above which yield loss occurs is about 500 mg Fe kg in dry leaf weight (Marschner, 1995).

In addition, as lowlands are composed of adjacent land units comprising uplands, hydromorphic valley fringes and seasonally flooded valley bottoms, it makes soil N fertility likely to be eroded along the slopes of inland valleys, primarily in the nitrate form, to the contiguous lowlands (Bognonkpe and Becker, 2009).

Upland constraints

Originally, upland production is characterized by slash-and-burn systems where farmers used extended fallow to restore soil fertility (Saito et al. 2010b). The increasing demand of land due to population growth causes intensification in rice culture leading to problems of weeds, crop disease, low soil fertility and high soil acidity (Becker et al., 1995, Becker and Johnson, 2001). The supply of inorganic fertilizer to overcome the low soil fertility is in most of the case justified. Many studies discussed and propagated the use of leguminous crops in rotation for the fixation of nitrogen (Becker and Johnson, 1998, Oikeh et al., 2008).

Rice plants in upland systems also respond to drought by enhanced leave senescence due to the decrease of leaf conductance and leaf water potential. As a consequence, the intercepted photosynthetically active radiation is reduced which decreases dry matter production and grain yield. It is known that the response of rice yield to drought depends on the timing of the drought in relation to plant development, partly because the reproductive stage is very sensitive.

1.5.3. Agricultural and rice issues in Benin

Rice demand in Benin is by far higher than the domestic production resulting in a chronic annual importation of rice. The country has a comparative advantage to produce rice locally while national production only contributes 0.31% to the entire

West African production (Ahoyo, 1996). For the rice production at smallholder farms, irrigation is only rarely an option. Large scale irrigation systems exist and were installed as a part of a program of technical cooperation between the Republic of China and Benin during the 1960s in Malanville, Dévé and Koussin-Lélé in order to produce paddy rice. However, due to management failure there was the degeneration of all installed irrigation systems in the 1970s. The inland valleys, mainly spread over the Centre and North of Benin, are not traditionally used for agricultural production. Currently, only 1300 ha, which represents about 0.7% of the potential area for agricultural production in inland valley is used for rice production despite financial support and technical aid by the FAO and the Beninese government (Grüber et al., 2009).

Physical, chemical, and biological soil deteriorations have already become critical problems in Benin as in other countries in Africa. The use of fertilizers and other off-farm input remains low due to the poor development of functioning subsidies, agricultural credit and extension services. Assessments about fertilizer use often refer to cotton production. Farmers who produce cotton have taken advantage of fertilizer market arrangements because the related programs aim to increase fertilizer use (Adégbidi et al., 2000). However, the decline in world market prices for cotton has led to stagnating cotton areas which in turn resulted in declining fertilizer use to 62,000 tons in 2007. Other information about fertilizer use refers to the commune level and suggests that the application of fertilizer per hectare has remained stable at approximately 45 kg NPK fertilizer during the last decade, with large differences between communes. Applications of 50 kg per hectare and more are frequently recorded in the Northern and Central regions, whereas for most regions in the south, no use of the input is reported (Kuhn et al., 2010). Moreover, farmers in the country tend to use fertilizers more on cotton and less on staple crop such as maize (Kormowa et al., 2003).

Finally, at the field scale, Adégbola et al. (2008) recorded among 215 farmers in 4 major rice growing areas in Benin abiotic stresses that limit production in different types of production systems. The constraints that are applicable to all production systems were soil fertility and post-harvest losses. In addition, farmers indicated for the upland system the effect of drought as an important constraint. For lowland rice, constraints indicated by farmers refer to the weak capacity of water management, the drought, the flooding and the plant lodging.

1.5.4. Which soil-crop simulation models for rainfed rice culture in West Africa?

Early works on rice modelling and simulation in 1990s attempted to determine critical traits for high yield potential in rice (Dingkuhn et al., 1991; Kropff et al., 1992). As such, the maximum rice yield of 10 Mgha^{-1} has been achieved in tropical environments (Kropff, 1994). However, optimum crop production estimation became more complex because of the involvement of several factors like fertilizer, pest control, genotype, environment and cultural practices (Kumar, 2005). The simulation models in rice have been developed according to specific research objectives which determined the underlying model assumptions.

Table 1.3: Example of models used for rice development.

Type of model	Characteristics	Application reference
CERES-rice (Ritchie and Otter, 1985)	variety-specific, water-balance, nitrogen balance	Rainfed rice (Mahmood et al., 2004)
Cropsyt (Stöckle and Nelson, 1994)	multiyear, multicrop, daily time step, soil erosion, soil-plant nitrogen budget, residue decomposition, soil erosion, pest	Flooding rice (Confalonieri and Bocch, 2005)
ORYZA-2000 (Bouman et al., 2001)	variety specific, simulation in seedbed with transplanting shock, phenological development, photosynthesis parameters from leaf N calculation of spikelet numbers and grain numbers for sink limitation	Irrigated lowland (Feng et al., 2007) Lowland and upland (Bouman et al., 2001, Bouman et al., 2006)
EPIC (Williams, 1995)	N,P,K balance, biomass accumulation, photosynthesis from Leaf area index, rotation , soil erosion	Upland rice (Adejuwon, 2004)

Some of the most popular rice models are ORYZA2000 (Bouman et al., 2001) and CERES-Rice (Ritchie and Otter, 1985). They consider the influence of soil, water and climatic variables on rice productivity (Table 1.3). These models may be suitable to address some of the issues relevant for rice production in West Africa particularly if sufficient data for model application are available. For instance in Benin, as in many other developing countries, data on soil and landscape have been collected over several decades, but so far they have been used only to a very limited extent in identifying and targeting technologies (Igué et al., 2004). However, Adam et al. (2011) stressed the risk associated with the reuse of a model without any adaptation which might lead to inaccuracies in model outputs, caused by the misrepresentation of processes in the model, the incorrect input data including parameter values, or a misinterpretation of the system. Appropriate data are of great importance to improve a model and the parameter estimation. Niu et al. (2009) highlighted that in irrigated systems, crop parameters related to photosynthesis and leaf area had a large uncertainty, while in rainfed environments soil and weather inputs were more important than crop parameters in introducing uncertainty. Therefore, the application of the model for rainfed conditions should mainly help to understand the relationship between the soil water availability during monsoon and potential productivity (Mahmood, 2004). Moreover special nutrition problems in West Africa relate not only to low levels of food availability but also to seasonality and to the high year-to-year variability of food production. There is vulnerability in agricultural land to high variability in climate at different time and space scales. This is worsened by the low capacity to adapt the developing world to the effects of climate change (Thomas and Twyman, 2005). Furthermore, resource use efficiencies particularly for N at plot and farm scales are highly affected by spatial heterogeneity as well. In fact, this spatial heterogeneity within the farm is firstly reflected by crop growth and crop management intensity e.g. plant density, also the variability at farm scales including topography and soil types, history of use, degradation intensities and the soil physical discontinuities (Titonell et al., 2006).

In addition, it has been reported that models should be used with the genetic parameters of the varieties grown, the use of default parameters may lead to unsatisfactory results (Akponikpè et al., 2010). Satisfactory modelling results were achieved when rice varieties within a region were assumed to be of the same ecotype, which was then considered for the upscaling from the region to the county level as shown for CERES-Rice (Min and Zhi-qing, 2009). In the case of EPIC, it was demonstrated that the model was able to simulate the sensitivity of the crop production systems to seasonal rainfall. Further, for rainfed upland rice, the model simulated yields that varied between 109 and 117 percent of observed yields. A key issue for validating the model was the multiplicity of crop varieties with contrasting performances under similar field conditions (Adejuwon, 2004).

Clearly, in order to explain the general processes of yield formation of rice in West African, a simulation model should sufficiently cover the different varieties grown and the wide range of pedoclimatic conditions (Graf et al., 1991).

1.6. Objectives of the thesis

The main research aim of this thesis is to explore the lowland and upland rice culture in the West African environment by addressing some local management strategies for smallholder farming systems by means of experimentation and modelling.
Four objectives were derived:

- Determining effects of topography, fertilizer and bunds application on NERICA lowland productivity in a representative inland valley in Sudanian zone in Benin Republic;

- Making a multi-variable calibration of the EPIC model for lowland rice productivity using 4 years experimental data;

- Assessing the pedoclimatic effects on the productivity of improved upland rice varieties in the Benin Republic;

- Making multi site calibration and validation of the EPIC model for NERICA rice across different agroecological zones of West Africa.

The thesis follows an interdisciplinary approach by combining issues in agronomy, soil hydrology and ecophysiology. Factors of the physical environment affecting the rice crop such as the rainfall variability and soil characteristics are of particular interest in this study.

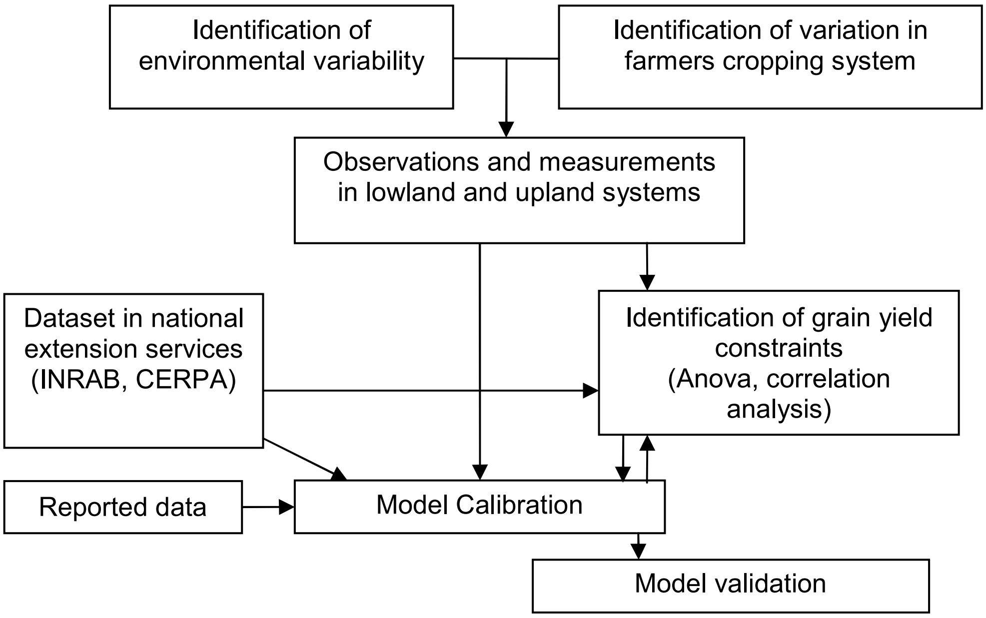


Figure 1.6: Overview of the methodological steps in the thesis.

The adopted method is summarized in Fig. 1.6. I made use of one on-farm lowland experiment (Objective 1, Chapter 2) and 6 upland experiments (Objective 2, Chapter 3) for farm field analysis in order to identify major environmental variability at the spatial and time scale. In addition, self-designed field experiments, on-farm experiments and the capitalization of previous experimental data are used to either calibrate the EPIC model or to perform a model validation (Objectives 3 and 4, Chapter 3 and 5).

2. Spatial and temporal variability of rice yield and growth constraints in rainfed lowland systems

2.1. Introduction

Inland valleys constitute over 38% of the total wetlands in the sub-Saharan region and are cropped extensively with lowland rice in the wet season (WARDA, 2008). The rainfed lowland rice cropping has attributes of non-irrigated with bund fields occasionally flooded during a certain period of time. Low and unstable yields were recorded on about two-thirds of total rainfed lowland rice area due to water shortage during the growing period, flooding and nutrient limitation (Tsubo et al., 2006, Haefele et al., 2006, Samson et al., 2004, Fukai, 1999, Fujisaka, 1990). Yields are strongly influenced by seasonal characteristics as well as by spatial heterogeneity over soil types, topographic sequences and agrohydrologic conditions (Wade et al., 1998). The topography is the main driver of leaching and soil erosion on one hand and on the other hand it influences the duration of submergence period, resulting in heterogeneity in inherent soil fertility. The soils in areas of higher altitude become less fertile as a result of depletion of nutrients due to runoff which generates in contrast a higher organic carbon and clay content in the soils in the lower position (Homma et al., 2003, Tsubo et al., 2005). These records from rainfed lowland from Asia may be different for West Africa where the use of water control means such as simple bund and short canals constructed by cultivators is less common. Raes et al. (2007) by a mean of modelling demonstrated that bund could appreciably increase the production of rain-fed lowland rice in Tanzania more in wet year than the normal year. The bund are reported to have benefit to the production by increasing the ponded water depth, regulating the hydric regime and producing increases in grain yield through enhancing fertilizer use efficiency (Touré et al., 2009, Srivastava et al., 2009).

Iron in the soils is also recognized to be another source of variation in rainfed lowland environment. Chérif et al. (2009) confirmed that the iron toxicity is one of the constraints of the cultivated lowland in West African savanna. It occurs on average in more than 50 % of the lowlands and approximately 60 % of cultivated rice fields are affected by this constraint. Fe toxicity produces nutritional disorders associated with a reduction process of Fe^{3+} into Fe^{2+} in the flooded conditions. Indeed, nutrient and water management are reported in Becker and Asch (2005) as methods to alleviate the risk of iron toxicity.

Therefore, a good understanding of the yield determining factors in lowlands is a prerequisite for the management in terms of fertilization and water retention. Beside, there is absence of long-term trial on rice crop yields inland valley of West Africa that combines effect of bund and fertilizer. This study examined variation in the production of dry matter and grain yield under lowland conditions in four consecutive years at Dogué inland valley, Benin. The objective of this chapter is to quantify the effect of slope position, bund and fertilizer application on rice yield and to point out the some constraints to rice yield in relation to slope position.

2. 2. Materiel and methods

2.2.1. Site description

The experiment was conducted in a researcher managed on-farm trial located in Dogué village (9°05´N, 01°55´E). The area is located in southern Donga district, North West of Benin Republic (West Africa). The rainfall is presented as mono-modal distribution across the 4 years. Daily weather data were collected from the research climate station of the IMPETUS project at about 1 km from the field. The rainfall pattern is shown in Fig. 2.1. During the growing period from July to November, the rainfall recorded in 2007, 2008, 2009 and 2010 was 793, 833, 690 and 1191 mm, respectively. The onset of the dry season was earlier in 2009 than in the other years.

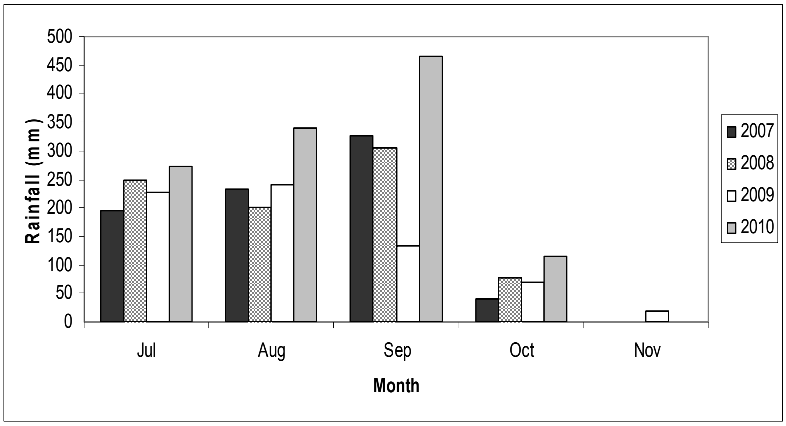


Figure 2.1: Monthly rainfall in 2007, 2008, 2009, 2010 during the growing period in Dogué village.

2.2.2. Experiment

A spilt plot design was laid out with the combination of three factors: (1) slope position: upslope (up) and downslope (down), (2) fertilizer inputs: with and without mineral fertilizer at a rate of 60kgN and 40kgPha^{-1} and (3) runoff control (bund): with and without bund.

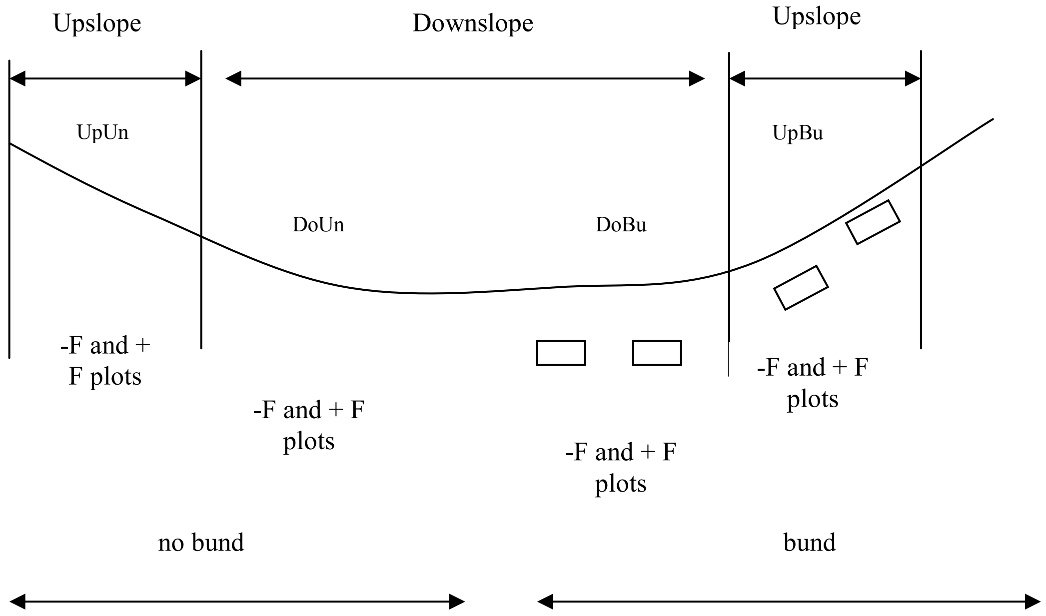


Figure 2.2: Experimental layout and treatments in the Dogué field trial in 2007, 2008, 2009 and 2010. Bund and without bund plots are located in the same slope. UpUn: upslope without bund, UpBu: upslope with bund, DoUn: downslope without bund, DoBu: downslope with bund; +F: with fertilizer, -F: without fertilizer application.

The fertilizer treatment was laid out at random into four replications at combination of bund and slope position each (Fig. 2.2). Subplot size was 5 m x 5 m. Experiments were repeated for four years (2007 to 2010) at the same position for all the plots.

The site is characterized by ferruginous tropical soils in the well drained areas. The slope of 3 % situated between an upland with sandy loams overlying ironstone and the bottom with more hydromorphic and loamy soils. According to FAO soil classification the soils at the upper slope are Lixisols and at the lower slopes Gleysols.

2.2.3. Field management

Chemical and physical soil characteristics were summarized in Table 2.1. Every cropping cycle was separated by a fallow period during the dry season. After clearing and completely removing the fallow vegetation that is grown in dry season, the land was hand ploughed then sown with the lowland rice variety NERICAL-26. The rice was dibble seeded at 20 cm x 20 cm spacing and thinning at to 2 plants per hills. The sowing date varied between years: 18, 1, 7 and 3 July in 2007, 2008, 2009 and 2010. Weeding was carried out when necessary. Harvest was made on 17 Nov., 7 Nov., 6 Nov. and 19 Nov. in 2007, 2008, 2009 and 2010 respectively. All crop residues were removed from the plots after harvest.

Table 2.1: Soil physical and chemical properties of the 0-20 cm layer in Dogué experimental field trial. n is the number of samples. SD is the standard deviation.

Soils properties	Unit	Upslope		Downslope	
		Mean (n=16)	SD (n=16)	Mean (n=16)	SD (n=16)
Physical properties					
Fine earth (elements < 2mm)	%	96.00	4.00	90.00	7.00
Sand	%	39.42	-	25.15	-
Clay	%	4.10	-	18.50	-
Chemical properties					
pH (H_2O)	-	5.36	0.27	5.63	0.34
C_{org}	%	0.65	0.07	0.93	0.27
Total N	%	0.039	0.005	0.064	0.015
Bray P	ppm	1.21	0.64	1.76	0.98
CEC	cmol kg-1	4.17	0.56	5.53	1.36
K^+	cmol kg^{-1}	1.64	0.53	2.36	1.41
Ca^{2+}	cmol kg^{-1}	0.19	0.17	0.23	0.13
Mg^{2+}	cmol kg^{-1}	0.56	0.08	0.69	0.18
Na^+	cmol kg^{-1}	0.00	0.00	0.03	0.04

2.2.4. Field measurements and lab analysis

Total aboveground biomass was collected at 38 DAS from two subplots of 1m x 1m. Leaf samples were extracted for analyses of Fe and N concentration with one repetition per treatment for Fe and two for N in 2007, with two repetitions for both Fe and N in 2008, whereas in 2009 and 2010, it was performed 4 repetitions for Fe and N. Fe concentration was determined by atomic absorption spectrometry and the total N with a CNS auto-analyzer. The plant uptake was calculated as the product of the total aboveground biomass at 38 DAS with the obtained N leaf concentration.

At maturity, rice grain and total aboveground biomass were obtained. For both plant biomass and grain the sampling area was made of two randomly selected 1m x 1m area. The weight of samples was corrected to the number of hills and the moisture content after 72h oven drying.

Soil samples for each plot (total of 32 plots) were collected in 2006 during the fallow period at up- and down-slope positions from 0 to 20 cm depth. Soil texture was determined using pipette method. Organic carbon estimation was made using Walkley and Black method (1934). The total N in the soil was measured with the Kjeldahl method. The exchangeable bases were extracted with the acetate of ammonium and measured by spectro-photometry with atomic absorption. The Cation Exchange Capacity (CEC) is determined by an extraction with chloride of potassium followed by micro distillation and titrimetry. The assimilable phosphorus was determined by modified method Bray.

During the appearance of ponding water, water level was recorded with a ruler periodically (1 to 3 times in the week) during the cropping season.

2.2.5. Statistical Analysis

Data were analyzed using SAS (Version 9.0). PROC mixed procedure using the Restricted Maximum Likehood method was performed for ANOVA. The model was firstly run with slope position, bund, fertilizer and year factors as main effects. Random effect concerned the nested effect of bund in position level. Furthermore, the model was run by classifying year. The Tukey test was used and allowed mean separation when the analysis of variance showed a significant factorial effect. We used Pearson correlation coefficients (R) to examine the relationship among grain yield, ponded water level, Fe concentration and N concentration in rice (SAS Institute, 2003). The significance level was fixed at $p < 0.05$.

2.3. Results

2.3.1. Growth and Grain Yield

Examination of the factors position, bund, fertilizer and year on grain yield, N and Fe in leaves content is made in Table 2.2 for the combined 4 years. The effect of year variation was significant for the three explained variables (grain yield, N leave content and Fe concentration). In addition, bund and fertilizer had significant effect on rice yield. Year to year variation interacted also with the position and fertilizer effects on grain yield. Fig. 2.3 shows in combination of 4 years, that the highest grain yield was observed in the upper slope position and significantly with bund condition and for fertilizer application. N in plant was only significantly responsive to position level and bund. Position had also significant effect on Fe concentration in addition to many other interactions. The interactions concerned mainly the position with bund, fertilizer and year. The three levels interactions were related to year, position and fertilizer.

Table 2.2: Effects of position (P), bund (B), fertilizer (F) and year variation (Y) on grain yield, N leaf content (N plant) and Fe concentration for 4 years combined. d.f.: degree of freedom; DDF: denominator degree of freedom of covariance parameters.

Factors	d.f	DDF	*F ratio*		
			Grain yield	N plant	Fe concentration
Y	3	84	0.03	<0.0001	<0.0001
P	1	12	ns	0.03	<0.0001
B	1	12	0.03	0.002	ns
F	1	84	0.0001	ns	ns
PxB	1	12	ns	ns	0.01
BxF	1	84	ns	ns	ns
FxP	1	84	ns	ns	<0.0001
BxPxF	1	84	ns	ns	ns
YxP	3	84	<0.0001	ns	<0.0001
YxB	3	84	ns	ns	0.04
YxF	3	84	0.03	ns	ns
PxBxY	3	84	ns	ns	ns
FxBxY	3	84	ns	ns	ns
PxFxY	3	84	ns	ns	0.02
FxBxPxY	3	84	ns	ns	ns

ns, not significant at the <0.05 probability level, nd = not determined

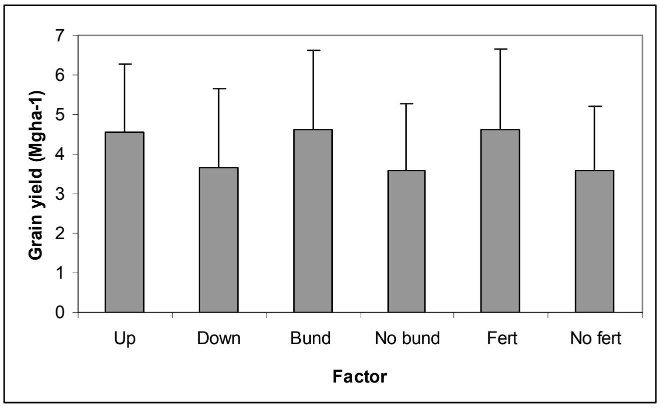


Figure 2.3: Overall trends of factors impact of rice grain yield. Year 2007, 2008, 2009, 2010 are combined. Up and Down refer to upslope and downslope position respectively. Fert and no fert refer to fertilizer and no fertilizer application respectively.

Table 2.3 presents the effect of the three experimental factors on the grain yield, N in plant and Fe concentration at maturity for each year. Grain, N in plant and Fe concentration had diverse responses on bund and slope position during the 4 years of observation. For grain yield, the slope position had a significant effect 2 out of 4 years (2008 and 2010). The bund effect was also significant only in 2007. Fertilizer impact on grain yield started with the two last years. Significance of interaction between factor sources was limited to the position and bund in 2008 and 2010.

In the case of N in plant, there was in addition to position effect in 2008, bund and fertilizer effects in 2008 and 2009, the interaction between position and fertilizer application in 2007. Fe concentration was affected by position in all year except 2009 however in this year, position rather interacted with bund.

Table 2.3: ANOVA table grain yield, N leaf content (N plant) and Fe leaf concentration as function of slope position (P), bund (B) and fertilizer (F) input in 2007, 2008, 2009 and 2010.

Source of variation	Year	Grain yield	N plant	Fe concentration
P	2007	ns	ns	nd
	2008	0.001	0.005	0.01
	2009	ns	ns	ns
	2010	0.008	ns	0.03
B	2007	0.02	ns	nd
	2008	ns	0.004	ns
	2009	ns	0.005	ns
	2010	ns	ns	ns
F	2007	ns	ns	nd
	2008	ns	0.01	ns
	2009	0.0006	0.002	ns
	2010	0.02	ns	ns
F x P	2007	ns	0.001	nd
	2008	ns	ns	ns
	2009	ns	ns	ns
	2010	ns	ns	ns
P x B	2007	ns	ns	nd
	2008	0.03	ns	ns
	2009	ns	ns	0.0009
	2010	0.009	ns	ns
B x F	2007	ns	ns	nd
	2008	ns	ns	ns
	2009	ns	ns	ns
	2010	ns	ns	ns
P x B x F	2007	ns	ns	nd
	2008	ns	ns	ns
	2009	ns	ns	ns
	2010	ns	ns	ns

ns, not significant at the <0.05 probability level, nd = not determined

Table 2.4: Mean grain yield, mean N content and Fe concentration by year in Dogué field trials.

Year	2007	2008	2009	2010
Grain yield (Mgha^{-1})	3.81	4.14	4.37	4.36
N plant (%)	1.65	2.13	2.40	2.11
Fe concentration (ppm)	669	411	206	647
CV (%) grain yield	31	31	33	26

2.3.2. Spatio-temporal evolution of rice production and relationship with N, Fe and water level according to fertilizer bund and position factors

The year 2007 showed the lowest yield during the 4 years of observation (Table 2.4). Bund operation was the significant factor on yield in this year (Table 2.3). No effect of fertilizer application was recorded but bund contributed to the increase of grain yield (Fig. 2.4). The upslope plots with bund showed slightly higher N concentrations than the downslope plots. However, N was lower in the fertilizer plots in upslope and higher in the fertilizer plots in downslope. In controversy, higher iron content above 800 ppm was recorded in the downslope plots at 38 DAS.

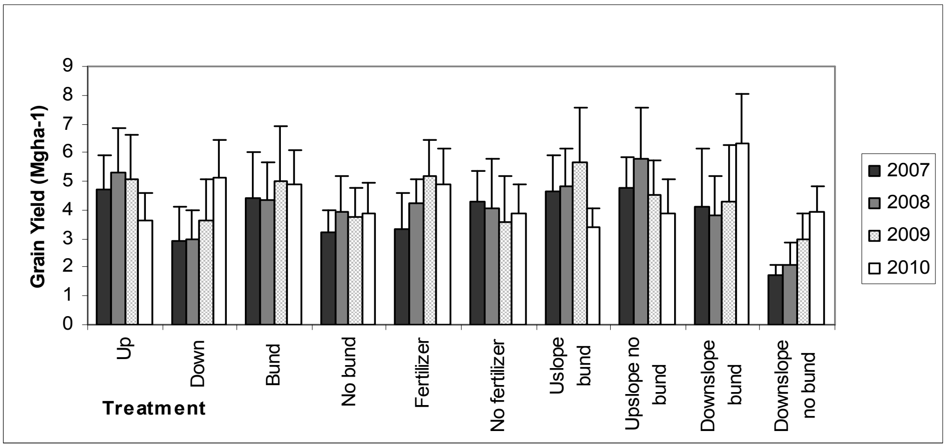
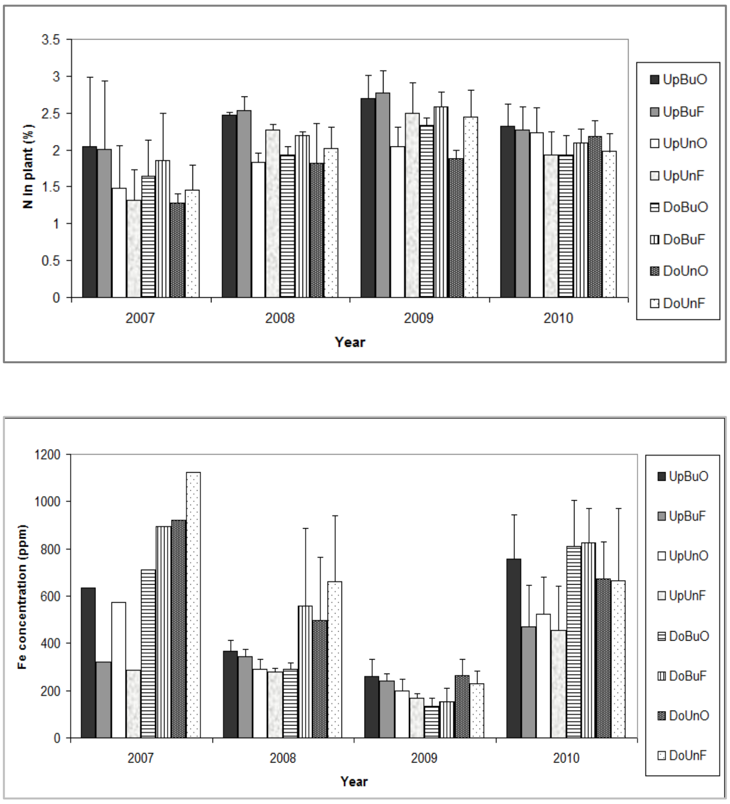


Figure 2.4: Grain yield average under different management practices over 4 seasons.

More grain yield on average was gained in 2008 (Table 2.4). The overall mean N content in plant was increased compared to 2007 (Fig. 2.5). These changes may be responsible for the average grain yield increase in 2008. The factor significance was limited to slope position and its interaction with bund. The plots with bund in downslope had higher grain yield but no bund plots were higher in upslope (Fig. 2.4). At 38 DAS, the N content in the plants was higher in the upslope position, with bund and all fertilizer plots (Fig. 2.5). The highest iron concentration at 38 DAS was observed for downslope plots with fertilizer. The value exceeded the threshold of 500 ppm whereas the upslope plots had lower concentrations. The years 2009 and 2010 showed the highest yield (Table 2.4). Fertilizer represented the highest importance in terms of significance level in 2009 for grain yield, N in plant and N uptake (Table 2.5). The highest N content and N uptake corresponded to the highest yield obtained and correlated as well with the fertilizer application what justifies the level of significance observed with the factor fertilizer in this year. Fe concentration was recorded as the lowest value and is only affected by interaction between position and bund. Position and fertilizer had a significant effect on rice productivity in 2010 and the effect of position was inversed the trends of yielding: the mean grain yield was estimated at 5.2 $Mgha^{-1}$ in the downslope position, whereas at the upper slope it was 3.8 $Mgha^{-1}$ (Fig. 2.4).

The impact of bund was observed through accumulation of ponding water during the cropping period (Table 2.6). In all the situations, downslope plots held more water than plots at the upper slope position. The mean ponded water depth was more enhanced by the bund in downslope than in the upslope plots. The water level in upslope plots with bund was particularly high in the year 2010 while highest amount of rainfall was observed. The effect of bund on ponding water started earlier within the first month after sowing. All treatments were significantly different from each other in downslope.

Fertilizer and position interact yearly highly with reference with F ratio in the total experiment (Table 2.2). The effect of fertilizer on Fe concentration in rice is shown per year in Fig. 2.6. For downslope plots there was a trade-off between the fertilizer application and the Fe concentration in 2007 and 2008. However in the upslope plots the Fe risk was associated to the no fertilizer plots in 2007 and 2010.



(a)

(b)

Figure 2.5 : Seasonal evolution of N (a) and Fe (b) proportion according to the different management options. UpBuO = Upslope with bund, no fertilizer, UpBuF =Upslope with bund and fertilizer, UpUnO= Upslope no bund no fertilizer, UpUnF=Upslope no bund with fertilizer, DoBuO= Downslope bund no fertilizer, DoBuF =Downslope with bund and fertilizer, DoUnO=Downslope no bund no bund no fertilizer. DoUnF = Downslope no bund with fertilizer. Values with the same letter within the same year are not significantly different (p=0.05).

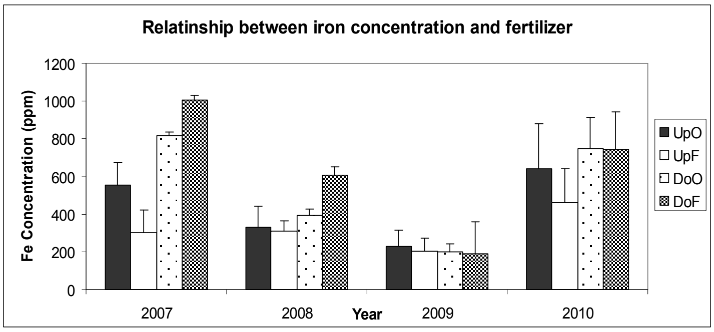


Figure 2.6: Effect of fertilizer on Fe concentration at 38 DAS according to the year and the land position. DoO: Downslope without fertilizer, DOF: Downslope with fertilizer, UpO= Upslope without fertilizer UpF = Upslope with fertilizer.

Table 2.5: Effect of slope, bund and fertilizer on Fe concentration, N in plant content at 38 DAS and N uptake according to the year in Dogué experimental field trial.

Year	Variables	2007		2008		2009		2010	
Position		Up	Do	Up	Do	Up	Do	Up	Do
	Fe concentration (ppm)	428	911	320	501	217	195	551	744
	N content (%)	1.7	1.6	2.3	1.9	2.5	2.3	2.2	2.0
	N-Uptake (kg ha^{-1})	41	28	85	65	138	112.	62	36
Bund		Bu	Un	Bu	Un	Bu	Un	Bu	Un
	Fe concentration (ppm)	614	725	390	432	196	215	716	579
	N plant (%)	1.9	1.4	2.3	1.9	2.6	2.2	2.1	2.1
	N-Uptake (kg ha^{-1})	40	29	80	70	138	112	39	59
Fertilizer		Fert	No fert	Fert	No fert	Fert	No fert	Fert	No fert
	Fe concentration (ppm)	655	684	460	361	197	214	604	691
	N plant (%)	1.7	1.6	2.2	2.0	2.6	2.2	2.1	2.2
	N-Uptake (kg ha^{-1})	40	29	94	56	169	81	64	34

Up= Upslope, Do=Downslope, Bu=bund, Un= No bund, Fert= fertilizer, No Fert = no fertilizer

Table 2.6: Combined effect of slope and with bund on mean ponded watertable level during the growing period and during 30 DAS (first month of growing cycle), Fe and N concentration in leaves and grain yield. Fe con. refers to leaves Fe concentration at 38 DAS, n is the number of samples. The numbers with same letters are not statistically different at $p<0.05$ within the same year.

Year	Position	Bund	Mean Ponded water level (cm) (n=8)	Mean Ponded water level at 30 DAS LWM1(cm) (n=8)	Mean grain yield ($Mgha^{-1}$) (n=8)	Fe con. (ppm)	N in plant (%)
2007	Upslope	Bund	1.74b	0.54b	4.65a	427.50c	2.03a
		No bund	0.55b	0.10b	3.77a	429.50c	1.40a
	Downslope	Bund	3.56a	2.16a	4.09a	801.05b	1.75a
		No bund	0.83b	0.24b	1.71b	1021.00a	1.45a
2008	Upslope	Bund	1.23b	1.11b	4.85a,b	356.00b	2.50a
		No bund	0.68b	0.35b	5.81a	285.00a,b	2.05b
	Downslope	Bund	3.81a	2.71a	3.84b,c	579.25a	2.06b
		No bund	1.06b	0.84b	2.07c	424.50a,b	1.92b
2009	Upslope	Bund	0.70b	0.84b	5.65a	250.04a	2.74a
		No bund	0.48b	0.15b	4.53a	184.54a,b	2.28b
	Downslope	Bund	5.74a	3.90a	4.32a	143.45b	2.45 a,b
		No bund	0.98b	0.89b	3.00a	247.09a	2.17b
2010	Upslope	Bund	2.59b	2.07b	3.32b	613.32a,b	2.30a
		No bund	0.45c	0.43c	3.88b	489.77b	2.08a
	Downslope	Bund	4.90a	3.53a	6.35a	819.84a	2.01a
		No bund	1.57b	1.41b	3.90b	668.35a,b	2.08a

2.4. Discussion

The rainfall conditions during the experimental seasons were on average uniform during the first three years but in 2010, total rainfall was above the average. Mean grain yield of the 4 years ranged from 3.81 $Mgha^{-1}$ to 4.36 $Mgha^{-1}$.

2.4.1. Effect of land position

Soil characteristics of the experimental field were representative for topography induced soils. The gap in grain yield between the up and downslope was reduced in 2009 and reinversed in 2010 (Fig. 2.4). The higher ponding water depth in early season and across the season in 2010 supported the hypothesis of intensified N-leaching and hence N-losses in 2010 in upslope plots. The land position is associated with fertility: decline of soil fertility is mainly caused by erosion due to the frequent depletion of N from the upper slope during the rain events. It has been shown differences in soil texture and organic C between upper and lower slope (Table 2.1). This reinforced the hypothesis of erosion occurrence in upper slope because organic C, N and available P are associated with the selective transport of fine aggregates which are chemically richer than the coarser ones (Wan and El-Swaify, 1997). Moreover, the cropping frequency at upslope explains also the loss of organic C and N through an enhanced mineralization and crop export due to historically more frequent cropping activities (Wezel et al., 2002).

2.4.2. Effect of fertilizer application

On average over all treatments, fertilizer application (60kgN and 40kgPha^{-1}) increased yield whereas this increase was not significantly different for the first two years (Table 2.3). The impact of fertilizer has been high in the year 2009 leading to the increase of grain yield by 0.45 Mgha^{-1} with fertilizer. Boling et al. (2010) found N deficiency in no fertilized plots was responsible for 35%-63% of yield gaps on farmer's fields in Java. In year 2009, where the strongest effect was recorded and in 2010, the fertilizer resulted in a higher yield at upper slope than in the lower position.

2.4.3. Effect of bund

Bund appears to have in overall experiment duration a positive impact on grain yield although in yearly variation it was only significant in 2007 and interacted with position in 2008 and 2010. The bund was important in maintaining flooded conditions on the plots by preventing runoff and N loss through runoff. The use of water control technology was described by former works to reduce spatial variability in soil water content and to be effective for weeds management (Hayashi et al., 2009). In downslope position, maximum water accumulation seems not to be related to the total rainfall since maximum of ponded water level was obtained in year 2009, recorded as the driest year. The observed fluctuations came in line with the findings of Touré et al. (2009) where the mean ponded water depth in plots with bund increased from valley fringe (0-9 cm) toward valley bottom (2-20cm). In this study, the upslope soil presented high sand proportion and that facilitated the downward water movement and by this way reduces the impact of bund on water availability. It was also consistent with Touré et al. (2009) who observed that fields without bund had increased water supply towards the downslope position. In addition, the bund contributes to the conservation of nitrogen. N acquisition was increased by bund at upslope condition significantly in 2008 and 2009 and at downslope in 2009 (Table 2.6). The same impact of bund was recorded previously by Touré et al. (2009). They described the enhancement of soil temperature that might be higher in upland condition and thereby have accelerated the dissolution of N from fertilizer used in the experiment. In addition, it is expected that soil humidity and inundation condition during the first month of crop establishment is associated with the distribution and quantity of rainfall. In year 2008 and 2010, bund had positive effect on yield in downslope plots but not in upslope plots (Fig. 2.4). Saito et al. (2010a) determined that the lowland interspecific genotypes performed better under flooded condition which is associated with biomass accumulation. However, 2008 and 2010 had the highest amount of rain and highest ponded water levels in downslope without bund compared to 2009 and 2007. There occurred a continuous flow of water which caused N loss and generated lower N uptake in plots without bund in downslope. In these years, the interaction between position and bund was significant (Table 2.3).

3. Simulation of soil water dynamics and rice crop growth as affected by bund and fertilizer application in inland valley systems of West Africa

3.1. Introduction

Benin has an estimated 322,000 ha of wetland with high potential for agricultural production but only a small proportion of this area is used for food production. The wetland is mainly used for rainfed lowland rice production (Adegbola and Singbo, 2003, Verlinden and Soulé, 2003). Farmers in the country still have limited access to water sources and extraction of groundwater because of poor low organizational structure for water management (Grüber et al., 2009). Therefore, the use of inland valleys for rainfed lowland rice systems presents potential for benefiting from soil moisture for crops. Lowlands in inland valleys represent non-irrigated field for rice that are flooded for at least some part of the cropping season at water depths that do not exceed 50 cm for more than 10 consecutive days (Meertens et al., 1999). These lowlands constitute attractive land for rice production intensification in West Africa. Alternating water was shown to contribute to effective water save in the case of irrigated conditions (de Vries et al. 2010). However, the temporal and spatial variability of water fluxes in inland valleys was illustrated by Bognonkpe and Becker (2009) with a loss of upland N to the lowland at 18 kg N ha^{-1} in a month depending on N supply by the upland and rainfall intensity. Previous studies have shown that water management related to bund or nutrient management is major interventions to be considered when using inland valleys for rice production in West Africa (Becker and Johnson, 1999; Touré et al., 2009).

Simulation models can provide tools for making appropriate management decisions towards sustainable rice culture development at farm and regional scale. The results from models can be integrated with knowledge in crop physiology, environmental conditions and technical operations. Previously, rice was a focus in numerous modelling works: At the process scale, modelling was concerned with determinants of production such as leaf area index (Yoshida et al., 2007) or emphasized on key processes like lateral flow dynamics at field scale (Tsubo et al., 2007). The modelling of a precise water balance has been targeted by recent works with concern on processes such as percolation, groundwater recharge, drainage and seepage (Wopereis et al., 1993, Panigrahi et al., 2001, de Silva and Rushton, 2008, Antonopoulos, 2010, Inthavonga et al., 2011). In fact, Wopereis (1993) concluded that water retention characteristics seem to have a higher impact on rice grain yield simulation rather than soil hydraulic conductivity characteristics. Indeed, the approach used by Wang et al. (2011) for the EPIC (Environmental Policy Integrated Climate) model suggested additional soil texture parameters for improving the precision of simulated soil water balance and for obtaining higher model efficiency. In addition, the EPIC model offers a suitable complexity in process integration for analyzing at the same time the effects of soil fertility and water availability on growth and crop yield. EPIC has been subjected to calibration and validation for wheat (Wang and Li, 2010) after evaluation of soil moisture condition. It was used also for other cereals, mainly maize from temperate to tropical climate conditions (Kiniry et al., 1995, Brown et al., 1997, Ko et al., 2009). However, the multi-site test for the model evaluation in Gaiser et al. (2010a) revealed the importance to consider site specific farm management options e.g. the use of improved varieties, Aluminium (Al) toxicity risk or soil pH. Niu et al. (2009) highlighted that in irrigated systems, crop parameters related to photosynthesis and leaf area had a large uncertainty, while in rainfed environments soil and weather inputs were more important than crop parameters in introducing uncertainty. Therefore, the application of the model for rainfed conditions should mainly help to understand the relationship between the soil water availability during monsoon and potential productivity (Mahmood, 2004).

Moreover special nutrition problems in West Africa relate not only to low levels of food availability but also to seasonality and to the high year-to-year variability of food production. There is vulnerability in inland valleys to high variability in climate at different time and space scales. Furthermore, resource use efficiencies particularly for N and Fe inducing iron toxicity at plot and farm scales are highly affected by spatial heterogeneity as well (Srivastava et al., 2009). This spatial heterogeneity within the farm is reflected by crop growth and crop management (presence of bund), also the variability at farm scales including topography and the soil physical discontinuities which affect soil water distribution. At present, little attempt has been made to simulate soil water dynamics and its interaction with bund and fertilizer application in inland valley systems of West Africa. This study therefore sort to understand soil water dynamics and rice crop growth as affected by bunding and fertilizer application in inland valley systems of West Africa using the EPIC model. use four seasons experiment for calibrating the EPIC model on rice productivity under two management options Lacking simulation models to describe the complex processes affecting rice production in inland valleys, the objective of the present study is to use four seasons experiment for calibrating the EPIC model on rice productivity under two management options (bund and fertilizer application). The simulation of potential yield in more precise soil water and ponding water level dynamics during the rice growing period should contribute to quantify the effect of any kind of stress such as iron toxicity in a sloping terrain of inland valleys.

3.2. Material and methods

3.2.1. Simulation model

EPIC (Williams, 1990, Jones, 1991) originally set up in the year 1980s to quantify the effect of erosion by wind or water on soil productivity is currently adapted to be a decision support system for analyzing the productivity and sustainability of complex cropping systems. Gassman et al. (2004) compiled the complete record of the model validation among which soil management impact, crop growth and yield studies are presented. EPIC is a field scale model and consists of 6 sub-modules: weather, soil, field operation, crop, erosion and economy. The main data inputs are: daily weather data, initial conditions for soils and operation files. The outputs relevant to this study are data on crop production (total biomass, leaf are index, grain yields) and water balance. The aboveground biomass is estimated by a reduction of 40% of the biomass to root weight at emergence and 20% at maturity.

Concerning crop production, the model has been parameterized for rice among other 138 crops. Biomass is produced from the interception of active radiation by the plant canopy which is characterized by the leaf area index (LAI). The LAI grows with the number of accumulated heat units until the maximal value at anthesis is reached in the case of cereals and then decreases. For simulating the phenological development, the model uses the approach of daily accumulation of heat. Total biomass is linearly correlated with the light interception which is converted into biomass through a crop parameter dependent concept of radiation use efficiency. Indeed Confalonieri et al. (2009) using this relatively simple approach, were able to adequately describe rice production. Final grain yield is generated from the product of total final biomass with the harvest index (HI). The model considers different levels of stresses represented as reducing factors for daily LAI and biomass production: mineral nutrients (N, P and K), water, aeration in the root zone and temperature. The fertilizer amount at the specified depth on the scheduled date is used in data input. The application rate is the difference between the average annual N uptake rate and the amount of N present in the root zone.

In the output file the number of days with stress is generated after a daily balance. For instance, with reference to the water balance module, the model works at daily time step by using equation 1. Soil water dynamics in EPIC is linked with water movement influenced by evapotranspiration, runoff, sublateral flow, percolation with

$$R = ET + Q + SSF + PRK + CST \text{ (eq.1)}$$

Where R is the amount of rainfall (mm), ET is evapotranspiration (mm), Q is runoff (mm), SSF is subsurface flow (mm), PRK is percolation (mm) and CST is the change in soil water storage (mm).

The storage routing technique allows in fact vertical or horizontal flow from a soil layer when soil water content exceeds field capacity. EPIC executes the soil water movement from the fluctuation in soil water content. Above field capacity, the water loss by percolation increases groundwater recharge. Water drains from the layer with regard to layer storage and saturated conductivity until the storage returns to field capacity. There is user defined possibility for allocating the maximum ponded water depth by negative value in minimum water table depth.

3.2.2. Experiment

The experimental data used for calibration of the model was obtained in a four years experiment in the northern part of the Ouémé catchment (Benin Republic).

The area is characterized by a mosaic of dense savannah vegetation and cropped area.

The soil was characterized as a Ferric Lixisol with iron oxide concretions.

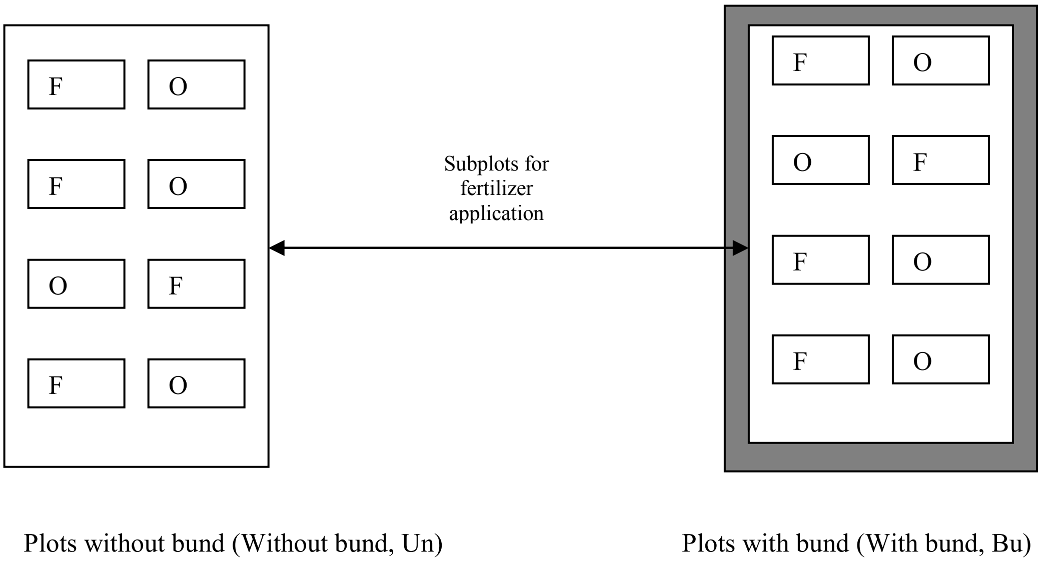


Figure 3.1: Experimental layout as split-plot design (O = without fertilization, F = with fertilization).

The experiment located at an inland valley fringe was carried out using a split-plot design with, bund building as the main plots and fertilizer treatment as randomized subplots (Fig. 3.1). Each subplot presented a size of 25 m².

3.2.3. Weather input

The weather input consisted of daily precipitation, maximum and minimum air temperature, radiation and relative humidity.

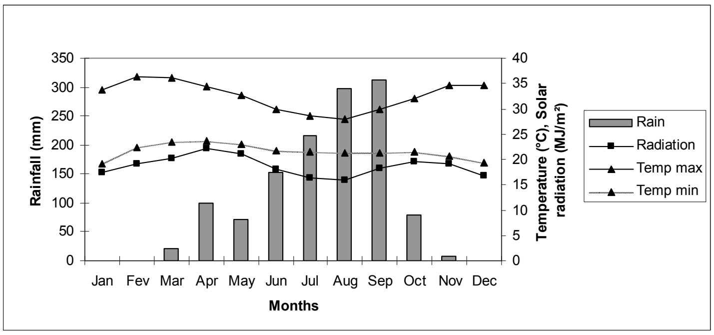


Figure 3.2: Average monthly maximum and minimum temperature (temp) and rainfall distribution for 10 years (2001-2010) at Dogué research station.

The mean monthly distribution of some climatic parameters is shown in Fig. 3.2. Manual tillage was carried out around 2 weeks prior to sowing. Data was collected from a weather station installed close to the field. The rainfall is rather uniformly distributed with the maximum precipitation occurring during September. The mean relative humidity ranges from 20 % in the dry season to 80% during the monsoon. The Penman–Monteith method (1965) was used to estimate the potential evapotranspiration as described in Williams (1995).

3.2.4. Data collection

Table 3.1 records the sequence of field operations during 4 years of observation.

Table 3.1: List of field operations for rice cropping in Dogué.

Year	Clearing	Tillage/Bund construction	Crop treatment		
			Sowing	Fertilizer application	Harvest
2007	18-Jun	2-Jul	18-Jul	18-Jul	17-Nov
2008	19-Jun	21-Jun	1-Jul	1-Jul	7-Nov
2009	7-Jul	13-Jul	7-Jul	7-Jul	6-Nov
2010	18-Jun	26-Jun	3-Jul	3-Jul	19-Nov

Bund was constructed with the height of 30 cm above the soil surface just after the tillage. The cultivar ‘NERICA-L26’ was used. It was sown by direct seeding at 20cm x

20cm with 5 seeds per hill each year. The density was reduced to 50 000 plants per hectare by manual thinning. The sowing dates (18 July 2007, 1 July 2008, 7 July 2009 and 3 July 2010) in the rainy season were representative for farmer's practice in the region. The applied fertilizer rate was 60 Kg N+ 40 Kg P_2O_5 ha^{-1} at sowing.

Weed management was done by hand hoeing. Each year, at 38, 60 DAS and at maturity, the above ground biomass was collected from 2 replicates of 0.36 m² per plot and weighted. Grain yield was also collected from 2 replicate subplots of 1 m² at maturity. The dry weight of grain and shoot biomass was obtained after 72 h in the oven. In parallel, at 21, 60 and 87 DAS, LAI was measured with the LAI-2000 (Li-COR, 1992, 2004) in year 2010 acc. to Sone et al. (2009). 12 replications were done during the reading.

Attention was given to evaluate the iron toxicity risk in the field being one potential external factor leading to a difference between observed and simulated crop productivity. Leaves were oven-dried at 70 °C after being collected, at 38 DAS in all years and 60 DAS in 2010 and 2008.

Initial soil conditions were measured in 2007 (Table 3.2). Soil texture and chemical characteristics were determined on a profile pit prior to the installation of the experiment. The methods used for chemical and physical analyses are presented in Srivastava et al. (2009). The layers consist of overall sandy materials, slightly acid with low nitrogen content. In addition, a low cation exchange capacity (CEC) is noticeable due to the depletion in clay minerals. In addition, at each plot, the depth of ponded water was measured every week using a ruler.

Table 3.2: Soil parameters of the plots used in the model simulations.

Proprieties	Unit	Layers			
	Cm	0-14	14-28	28-50	50-85
Silt	%	13	12	12	12
Sand	%	76	82	82	82
Bulk density	$t\ m^{-3}$	1.47	1.43	1.47	1.55
%C	%	1.84	0.65	0.48	0.48
%N	%	0.06	0.05	0.03	0.03
pH		5.80	6.10	6.30	6.30
Bases	$cmol\ kg^{-1}$	6.82	2.70	1.23	1.64
CEC	$cmol\ kg^{-1}$	11.50	6.00	4.00	5.50

Year 2007 and 2008 were used as reference to examine hydrological conditions in the experiment. Soil moisture content values were measured at 16 points with TDR probes. Data were collected during the wet season in 2007 and the dry-wet seasons in 2008 at 0-20, 20-40 and 40-60 cm depth. A total of 12 tensiometers were used to record the soil water potential at weekly intervals. Tensiometers were installed in the center of the plot close to the TDR probes. The three (3) tensiometers in each plot covered the depths of 30 cm, 50 cm and 70 cm. For pressure heads around -330 mbar (field capacity), soil water content in each depth was estimated from Fig. 3.3. The estimation of the wilting point was done with the minimal value of soil water content during the dry season.

The plots with bund and without bund comprised a set of 4 piezometers installed to monitor the variations of the groundwater table depth during and after rain events at weekly frequency.

In-field variability and inaccuracy of sampling and measurements of aboveground biomass in the experimentation have been taken into account during the calibration process. Therefore, the elimination of outliers was performed on total aboveground biomass and grain yield from the observed data over the 4 years for each treatment using the box plot analysis in SPSS V2 software. This exercise allows narrowing the standard deviation in observation data that will be used to compare with the simulations from 1.90 to 1.56 $Mgha^{-1}$ for grain yield and 6.08 to 4.89 $Mgha^{-1}$. The separation of means was performed after running One-way-Anova in SPSS using the LSD method.

3.2.3. Model calibration and evaluation

The calibration started with a warm up period of 6 years in order to stabilize the soil organic carbon pools in the model. Graphical presentations and statistical measurements were used for evaluation of the model. In graphic representations, the simulated (y) and measured (x) values of soil water content through the soil profile, the depth of ponded water, crop aboveground biomass and crop grain yield were compared. Linear regression was obtained from scatter diagrams and expressed by equation 2.

$$y = \alpha x + \beta \text{ (eq.2)}$$

where α and β are slope and intercept of the linear regression between observed (x) and predicted values(y);

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i) \qquad \text{(eq.3)}$$

$$\mathrm{MRE} = \frac{1}{n}\sum_{i=1}^{n}\frac{(y_i - x_i)}{x_i} \qquad \text{(eq.4)}$$

Mean residual Error ME and mean Relative Error MRE were calculated with equation 3 and 4 respectively, where n is the number of pairs of observed (x_i) and corresponding simulated values (y_i).

Coefficient of determination (R²), mean residual error (ME) (eq.3) and mean relative error (MRE) (eq.4) are presented as the statistical parameters used for evaluating the goodness of fit between the observed and simulated data. A value of the ME and MRE of close to 0, expresses little systematic deviation or bias in the entire data set. A negative ME indicates that the model overall underestimates the predictions.

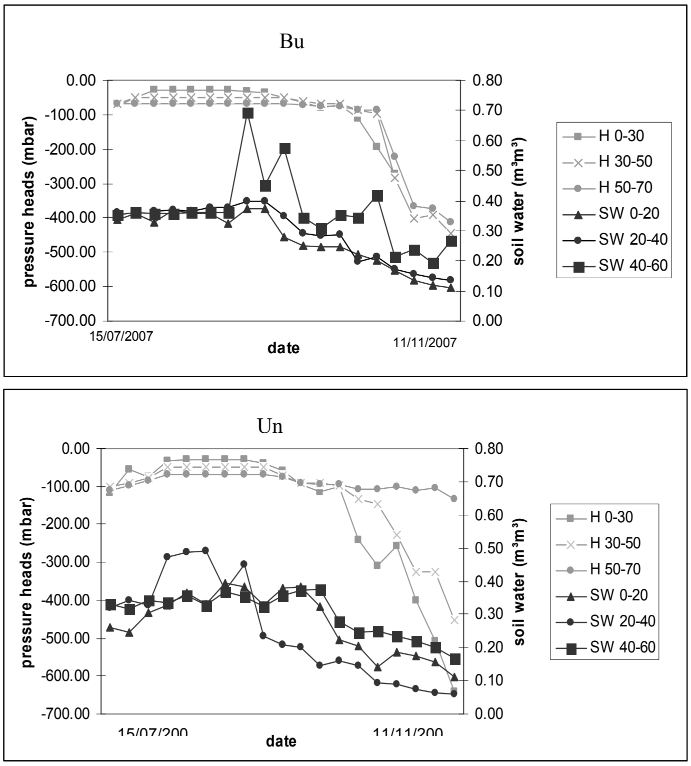


Figure 3.3: Determination of soil water at field capacity using pressure heads and soil water distribution over a record period in 2007 (H: pressure heads measured in three soil depths, SW: soil water measured at the three soil depths) Bu is plots with bund, Un refers to plots without bund.

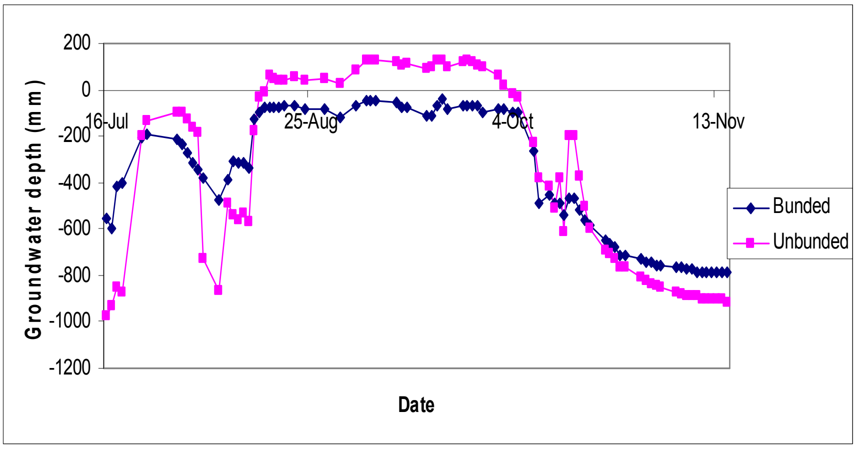


Figure 3.4: Groundwater distribution in the cropping period in 2007 at Dogué field station for with and without bund treatment.

3.3. Results and Discussion

3.3.1. Parameters used for calibration

For terrain characterization, a slope inclination at 3% was used. The soil water routine of the model was calibrated for adequately representing hydraulic condition under the two bund treatments.

Table 3.3: Soil input parameters used for calibration of soil water dynamics.

Treatment				Soil depth (cm)	Water content		Saturated conductivity (mm/h)[1]
	Maximum groundwater storage (mm)	Maximum watertable (m)	Minimum watertable (m)		Field Capacity (m^3/m^3)	Wilting Point (m^3/m^3)	
Bund	150	0.8	-0.04				
				0-14	0.16	0.08	11.69
				14-28	0.15	0.10	12.45
				28-50	0.38	0.10	12.45
				50- 80	0.38	0.10	12.45
No Bund	100	0.8	-0.03				
				0-14	0.10	0.02	11.69
				14-28	0.15	0.05	12.45
				28-50	0.37	0.05	12.18
				50- 80	0.37	0.10	12.18

[1] model estimation

Soil water retention and water table input characteristics for bund and no bund treatment are presented in Table 3.3.

The corresponding field capacity of each layer has been recorded in the field with reference to the pressure heads (Fig. 3.3). Slightly different soil water contents at field capacity (FC) were determined in the bund treatments. The difference may be attributed to the field heterogeneity particularly within the plots with bund where abundant coarse fragments were identified at 60 cm depth in some plots. The no bund treatment had a lower wilting point due to the slightly sandier texture.

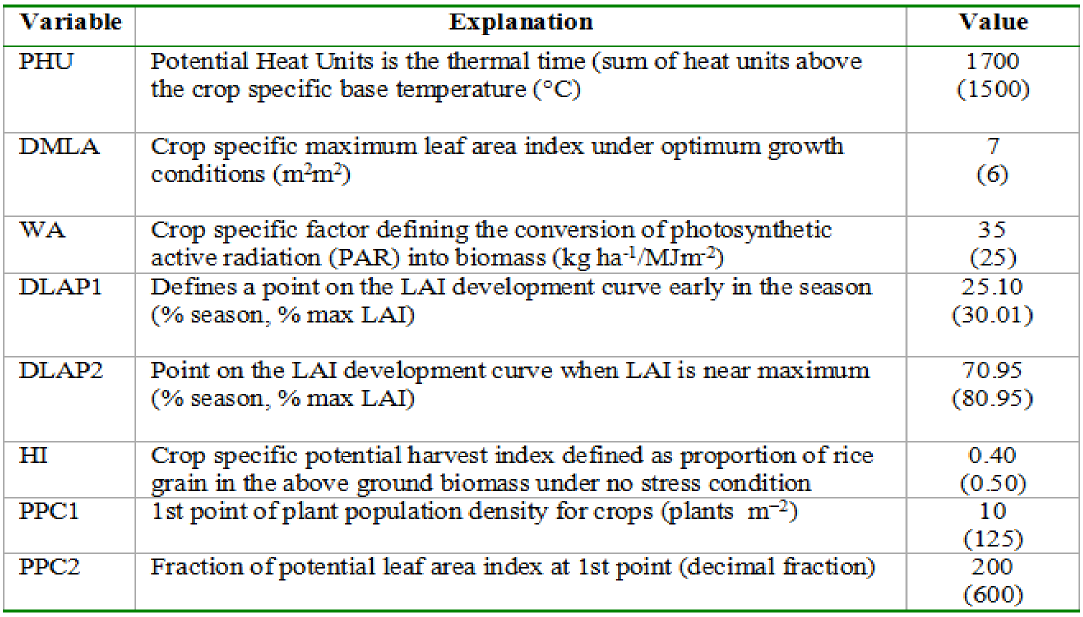
The dynamics of soil water are determined by hydraulic forces. As described by Williams and Izaurralde (2006), the vertical or percolation component flows to the groundwater is lost from the system except when the capillary rise occurs. One constraint to this flow is the volume of groundwater storage capacity. In the experiment, records with piezometer in 2007 (Fig. 3.4) showed differences in groundwater depth distribution according to the treatment. During the growing season, the saturation of the soil with water appeared earlier in no bund than in plots with bund. This may be due to higher percolation rates (i.e. higher groundwater storage capacity) in plots with bund. The value of 100 mm was then adapted as groundwater storage capacity for the no bund condition and 150 mm for bund condition.

The model drives the water table up and down between input values of maximum and minimum depths from the soil surface. The definition of the maximum level of ponded water during the simulation shaped the distribution of water for submergence. A negative value of the maximal water table level expresses the submergence level above the soil surface. According to the average value in observations, a level of -0.03m was set for no bund condition whereas it was increased to -0.04m in the case of bund condition in order to represent the effect of bund in retaining surface water.

Factors of mineralization of nitrogen are reported to have high sensitivity to the crop in tropical areas, as shown with maize data by Gaiser et al. (2010b). The adjustment of denitrification threshold at 0.001 and parameter 30 at 0.99 was carried out according to Gaiser et al. (2010a) and Gaiser et al. (2010b).

The potential heat unit was calculated from the daily temperature as accumulated temperature from sowing to maturity minus the crop base temperature. Then, due to annual air temperature fluctuations and crop duration, the value ranged from 1500-1700°C. LAI dynamics are driving the photosynthetic activity and depend on the crop development. DMLA is the potential leaf area index which corresponds to the LAI at anthesis. It was increased to 7 instead of 6. It can be considered that the NERICA-L26 as an improved variety that has been developed for low potential conditions to have potentially favorable growth traits for weed suppression with broad and droopy leaves, high straw biomass production, tallness and high LAI (Heuer et al., 2003).

Table 3.4: Main changes in crop parameters related to the calibration of the model for the rice cultivar NERICAL-26. Default crop parameters are in bracket.



Variable	Explanation	Value
PHU	Potential Heat Units is the thermal time (sum of heat units above the crop specific base temperature (°C)	1700 (1500)
DMLA	Crop specific maximum leaf area index under optimum growth conditions (m^2m^2)	7 (6)
WA	Crop specific factor defining the conversion of photosynthetic active radiation (PAR) into biomass (kg ha^{-1}/MJm^{-2})	35 (25)
DLAP1	Defines a point on the LAI development curve early in the season (% season, % max LAI)	25.10 (30.01)
DLAP2	Point on the LAI development curve when LAI is near maximum (% season, % max LAI)	70.95 (80.95)
HI	Crop specific potential harvest index defined as proportion of rice grain in the above ground biomass under no stress condition	0.40 (0.50)
PPC1	1st point of plant population density for crops (plants m^{-2})	10 (125)
PPC2	Fraction of potential leaf area index at 1st point (decimal fraction)	200 (600)

A list of the modified parameters for the NERICA-L26 variety used in this experiment is presented in Table 3.4. DLAP1 and DLAP2 describe the shape of the LAI growth curve. They are a function of the accumulated thermal heat which controls the growth of the plant from emergence until maturity. For NERICA-L26 the DLAP1 was changed from the default values 30.01 to 25.10 and the DLAP2 from 70.95 to 80.95. The DLAP2 was identified by Félix and Xanthoulis (2005) to strongly influence biomass accumulation among 16 other controlled variables in legume species. The modified DLAP2 is in line with Bocco et al. (2012) who observed with NERICA-L lines a 50% flowering stage at around 79 days when maturity DAS was 102. The potential increase in biomass growth depends mainly on the product of the energy biomass ratio WA and the intercepted photosynthetically active radiation. Considering that the cultivar is a modern variety the WA was increased by 10$kgha^{-1}/MJm^{-2}$. At a value of 35$kgha^{-1}/MJm^{-2}$, WA fits among other cereals and the rate published in Kiniry et al. (1996) and Kiniry et al. (1988). The value of maximum harvest index HI was adapted to 0.40 instead of 0.50 which is the model default value corresponding to high yielding US varieties (Lang, 1996). The final harvest index calculated by the model is mainly influenced by water stress.

Sheehy and Johnson (1988) reported that at a given temperature and concentration of atmospheric CO_2, canopy photosynthesis is governed by irradiance, canopy architecture, and leaf photosynthesis. The rate of photosynthesis depends not only on the fractional light interception or the maximum quantum yield of an individual leaf but on the rate of canopy photosynthesis. Therefore, the adapted plant population LAI rate was increased from 20 plants for 20 % of the maximum LAI value to 10 plants for 20 % of maximum LAI value (PPC1 and PPC2).

3.3.2. Simulation of soil water regimes

Soil water measured in two consecutive years 2007 and 2008 was compared to the simulated estimation on 2 treatments (presence or not presence of bund). Data was modeled using measured field capacity and wilting point at -0.33 bar and -15 bar. Results of the water content simulation under bund and no bund condition compared with observed soil water content are presented in Fig. 3.5. In both treatments water content simulations reached the saturation point coinciding with the observations during the rainy season in 2007 and 2008. However, in 2007, water storage decreased more gradually in the observations than in the simulation. In this year, the model did not simulate well the delay of the water loss as the soil matrice potential increased. Even though the model estimated the saturated hydraulic conductivity to 12 mm/h using the percentage of clay and the soil strength factor, the estimated hydraulic conductivity seemed to be much lower. The soil strength factor determinants are bulk density and texture.

The EPIC model at field scale resolution may not be able to fully capture the desiccation phase at the end of the rainy season in this particular slope situation. Some investigations aiming at elucidating the terrain controls on soil moisture have shown that topography becomes increasingly important in wet periods, but during dry periods soil moisture patterns depend primarily on soil properties, with topography having a limited effect (Penna, 2008, Grayson et al., 1997, Meyles et al., 2003).

In addition, during inundation periods the soil may form a crust on the surface, which on the one hand reduces water infiltration, but can also cause a delay in soil drying after the rainy season. The SCS approach implemented in EPIC, considers the effect of crusting on infiltration, but not on delayed soil drying. Other models such as ORYZA2000 are considering this effect of puddle formation in computing the soil water dynamics for lowland soils with the module PADDY (Bouman et al., 2001, Feng et al., 2007). The estimation of water content at different depth gives the vertical representation of water content distribution through the soil profile down to 60 cm depth (Fig. 3.6).

In 2007, where data were mainly collected during the rainy season, the largest bias was obtained with a general underestimation of soil water content in both treatments and all layer depths. This is attributed to the rapid drop of soil water content after the rainy season in contrast to the observed delay (Fig. 3.5).

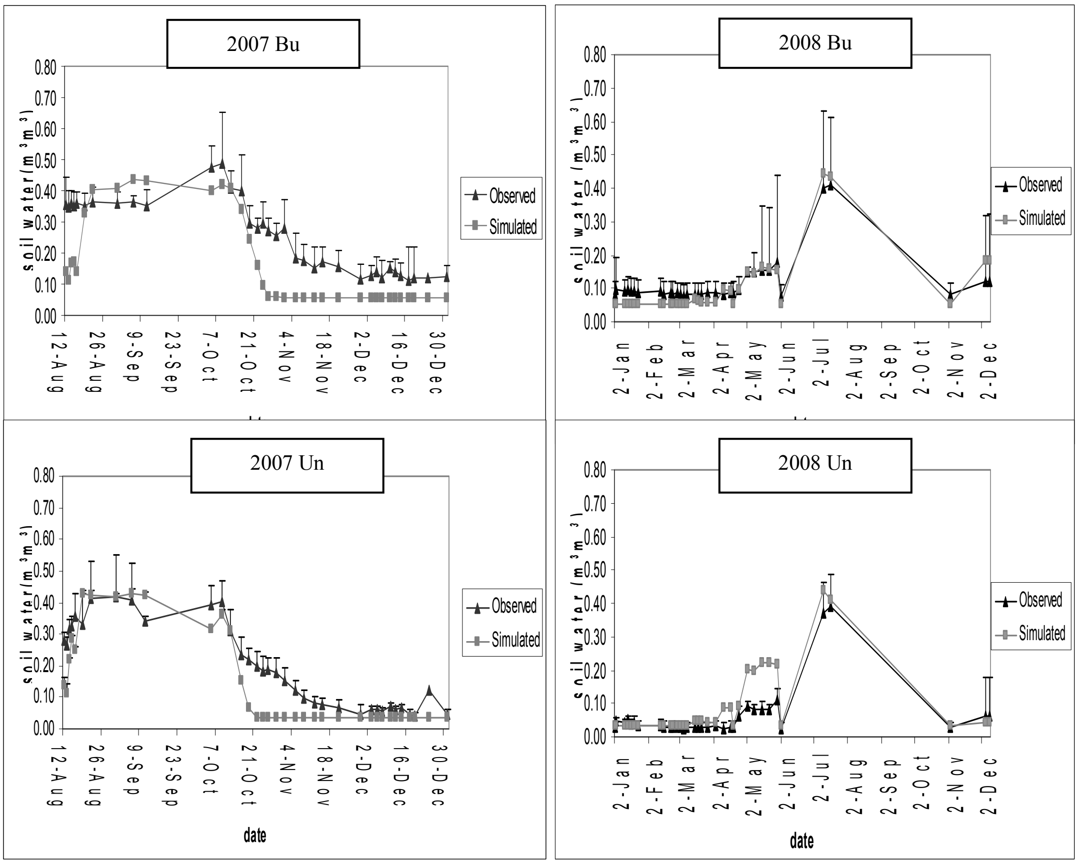


Figure 3.5: Mean simulated and measured soil water contents in 0–60 cm soil depth over two years. Bu is plots with bund; Un refers to plots without bund.

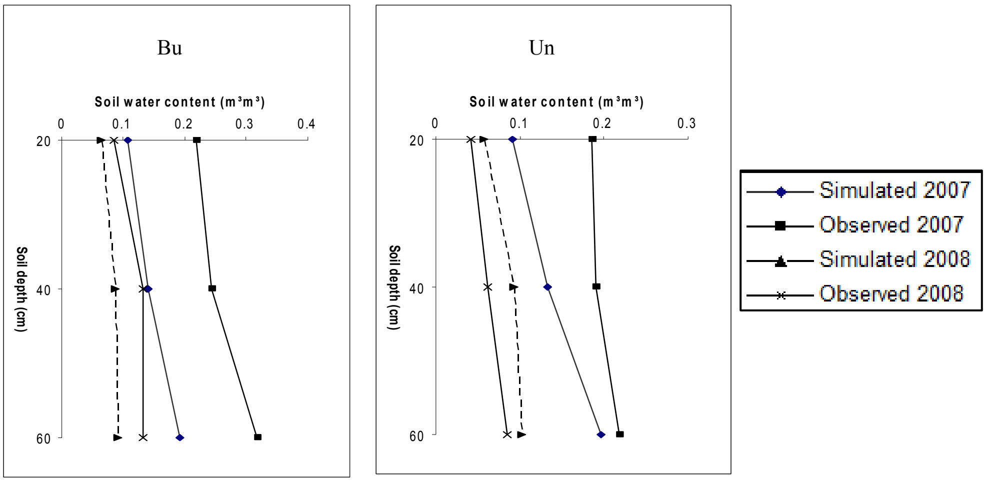


Figure 3.6: Vertical distribution of mean annual soil water content for bund (Bu), without bund (Un).

In 2008, the covered data collection period included the dry season. On average over the entire year, the model slightly underestimated soil water content in different depths under bund condition (Fig. 3.6) whereas for no bund, the model showed slight overestimation of soil water content through all depths in the profile. However, the difference between simulated and observed soil water content was not significant. The simulation results confirmed the calibration results of Wang et al. (2011). In fact, with a long-term experiment on the Loess plateau in China, though the difference between the simulation and measurement of available soil water was not significant, soil water was slightly overestimated in extreme drought years and was slightly underestimated in extreme wet years (comparable to bund condition in 2007 and 2008).

The regression equations given in Fig. 3.7 demonstrate a scattered distribution of simulated versus observed soil water contents for two years. The best agreement between observed and simulated values was found for the no bund treatment as confirmation of trends observed in Fig. 3.5 and 3.6. With regard to different depths, the model explained more variability for the deeper layers. In general, the model was less precise than presented in Wang et al. *(*2011) who reported R^2values of 0.82 to 0.96 at different layers down to 2 m depth compared to 0.48 to 0.68 in our study. However, the estimation of Wang et al. (2011) was made with long-term data collected on a monthly basis. Over the two years, the model underestimated soil water content in all treatments by 3 to 7 m^3 m^{-3} as shown in Table 3.5.

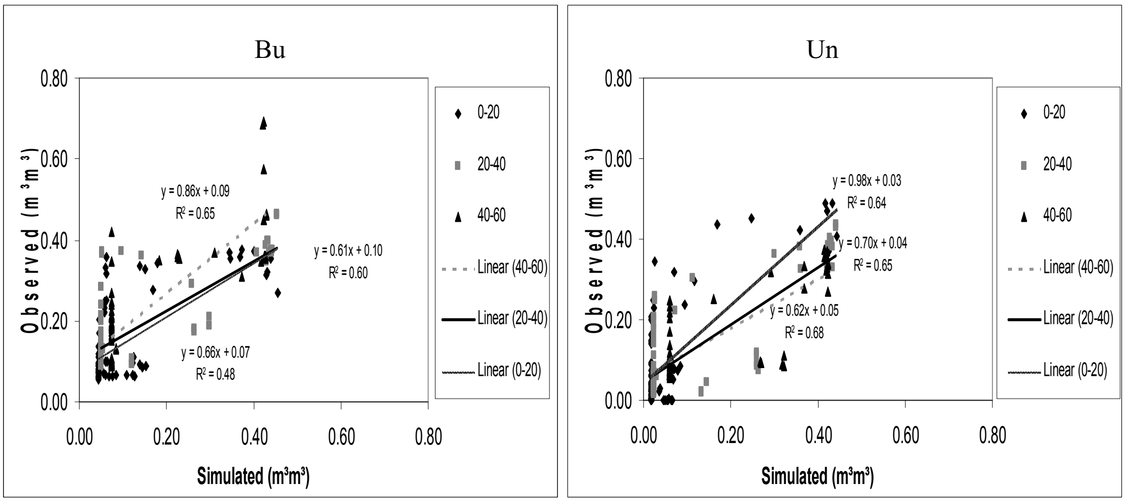


Figure 3.7: Comparison between the measured and simulated soil water contents in bund and no bund plots at 20, 40 and 60 cm soil depth (Solid line is linear relationship, R²: coefficient of determination).

Table 3.5: Estimation of mean soil water content over 2 years (2007 and 2008), mean residuals error (ME) and mean relative error (MRE) for EPIC simulation under bund and no bund condition.

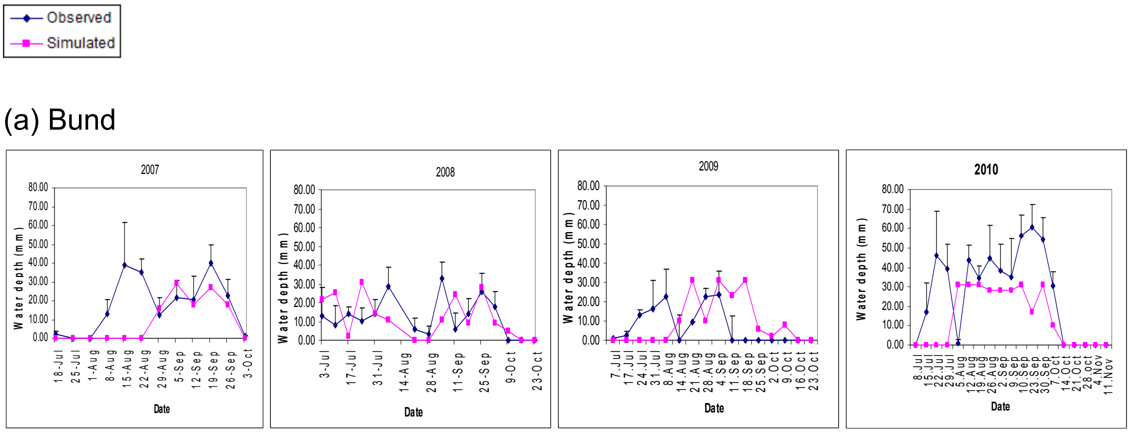
				Soil water mean (m³/m³)					
Depth				Bund				No bund	
	n	ME	MRE	Simulated	Observed	ME	MRE	Simulated	Observed
0-20	70	-0.03	-0.22	0.11	0.15	-0.07	-0.53	0.08	0.15
20-40	70	-0.04	-0.33	0.14	0.18	-0.07	-0.53	0.11	0.18
40-60	70	-0.06	-0.31	0.15	0.22	-0.00	0.00	0.15	0.15
0-60	70			0.13	0.19			0.11	0.16

3.3.3. Simulation of water table dynamics

Temporal evolution of the level of ponded water in the rice plots was influenced by the amount of groundwater storage, rainfall events and soil moisture conditions. Water levels for both observation and simulation looked similar in all treatments during submergence of plots (Fig. 3.8).

However, the occurrence of a ponded water table was slightly delayed during the simulation in years 2007, 2009 and 2010 in fields with bund. The higher groundwater storage capacity (Table 3.3) was responsible for this delay in the simulations because a part of the rainfall during the early stage was used for filling the groundwater aquifer. External factors may also have contributed to explain the difference between simulation and observations in the plots with bund. Belder et al. (2005) suggested that, at lower slope positions, continuously subsurface flow from surrounding fields can make the groundwater table rise to shallow depths. However, this type of lateral fluxes between slope elements can not be represented by a one-dimensional model like EPIC.

(a) Bund



(b)No bund

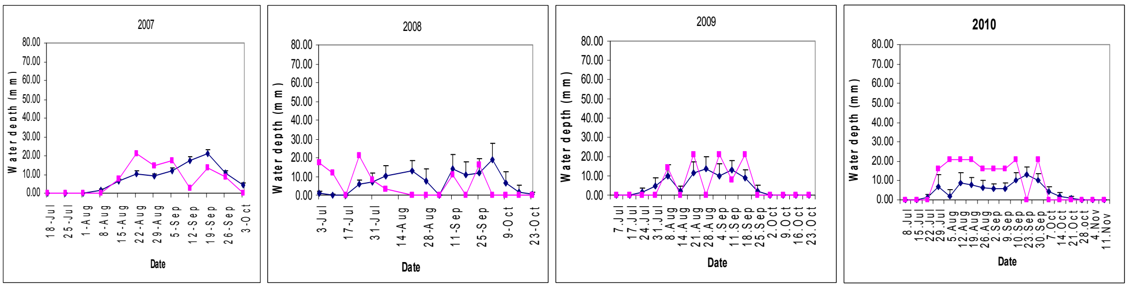


Figure 3.8: Simulated and observed temporal evolution of ponded water level over 4 years: (a) plots with bund, (b) plots without bund.

Mean ponded water level during the experiment period was given in Table 3.6. Best agreement between simulation and observation with respect to ME was obtained for no bund condition in the years 2007, 2008 and 2009. Under bund condition, 2008 only yielded an acceptable value of mean absolute error. The observed delay in Fig. 3.8 explained the larger ME and lower R^2 in others years. The model underestimated the ponded water level in most years except in 2009 for both treatments and in 2010 for no bund plots. Year 2010 presented the highest ME in terms of absolute values. In this year, the highest rainfall amount was recorded, i.e. 1400 mm against the average of 1200 mm. By setting a maximal depth for the watertable in Table 3.3, this constrains the simulated water level in case of excessive amount of rain as it is the case in the plots with bund. The effectiveness of bund in this year was shown by the statistical difference with a P-value less than 0.05 (Chapter 2). At the same time, the gap between simulated and observed water level in no bund field was higher by the assumed higher runoff in 2010. Thus, in 2010, the model seemed to underestimate the water loss process in no bund plots. Without the particular year 2010, no bund average water level is 7.3 mm in observation versus 7.6 mm in simulations and with bund average water level is 12.0 mm versus 10.3 mm (Table 3.6).

Table 3.6: Comparison of simulated and observed average ponded water level in mm during 4 years (2007, 2008, 2009 and 2010). The numbers with the same letters within the same year are not statistically different among each for pairwise comparison. n: number of pairs for observation and simulation at a specific date. X_{mean}: observed water level during the growing period from 16 plots of observation. X_{sdmean} is the mean of the standard deviation of the observations. Y_{mean} is the mean of simulations during the growing period.

	n	x_{mean} (mm)	x_{sdmean}	y_{mean} (mm)	R^2	A	β	ME (mm)
				Bund				
2007	12	17a	7	9	0.18	0.32	3.29	-8.3
2008	16	12a	7	12	0.10	0.35	7.70	-0.2
2009	16	7a	5	10	0.01	0.14	8.51	2.5
2010	19	26a	8	14	0.34	0.37	4.01	-12.4
				No bund				
2007	12	8b	1	7	0.38	0.69	1.67	-0.7
2008	16	7a	7	6	0.01	-0.05	5.87	-1.2
2009	16	7a	5	10	0.45	1.10	0.01	2.5
2010	19	4b	2	14	0.51	2.49	2.79	9.5

3.3.4. Simulation of crop growth development and grain yield

3.3.4.1. Leaf Area Index

LAI development is simulated according to the number of cumulated degree-days triggered by the planting density and the biomass accumulation. In EPIC, biomass accumulation depends on reduction factors which take into account possible stresses like a lack of nutrients, water or with environmental constraints such as aluminum toxicity.

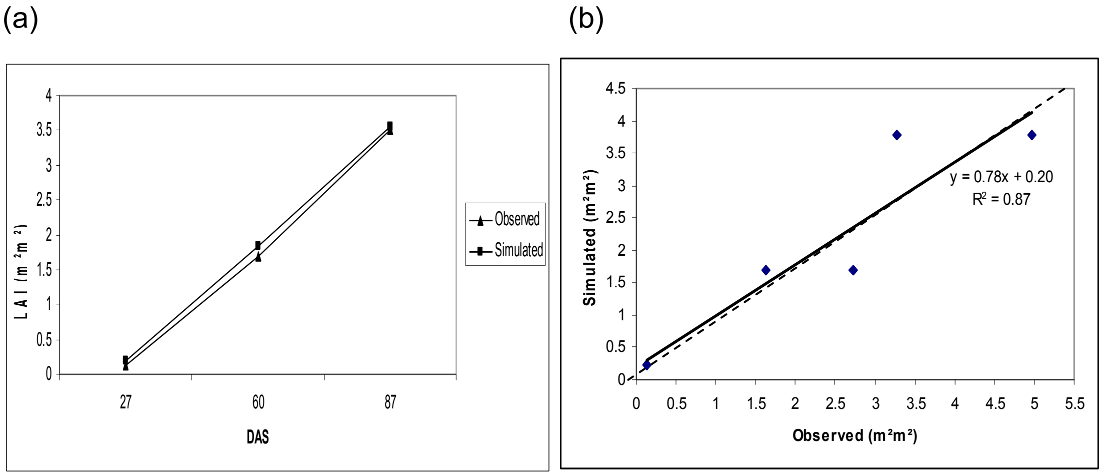


Figure 3.9: (a) Observed mean LAI over four treatments and simulated values (b) regression between simulated and observed LAI (points represent LAI values from 27, 60 and 87 DAS, solid line is linear relationship, R² is the coefficient of determination).

In the calibration process DLMA, the DLAP1 and the DLAP2, were used as parameters to control LAI growth from emergence to maturity. Fig. 3.9 shows the comparison between the simulated and observed mean LAI value at three growth stages (21, 58 and 87 DAS). The goodness of fit of the simulations is shown by an overall determination coefficient of 0.87.

When comparing measured and simulated LAI in bund and no bund treatments (Fig. 3.10), the correlation showed higher coefficient of determination in no bund (0.97) than in bund treatment (0.67). For no bund plots, the average absolute mean difference between the observed and simulated values was approximately 0.30 and that for bund condition was 0.40. Furthermore, there were slight differences between fertilized and unfertilized treatment. In no bund plots, it appears that the model overestimated the LAI in unfertilized plots at the middle stage of the crop development. In no bund plots, simulated LAI at 27 and 87 DAS showed the best goodness of fit with observations.

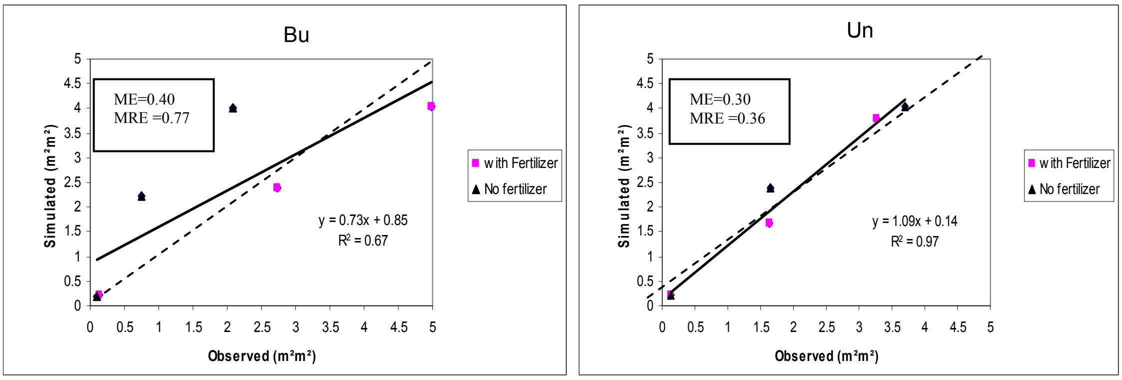


Figure 3.10: Regression between observed and simulated LAI of NERICA-L26 grown in 2010 under different hydrological conditions and fertilisation rate (R² is coefficient of determination of the regression equation, ME: mean residual error, MRE: mean relative error) Bu is plots with bund; Un refers to plots without bund.

Many studies discussed the reliability of the EPIC model under stress environment: particularly the tendency of the model for underestimating LAI growth was demonstrated in Srivastava and Gaiser (2009). They showed that there could be a tradeoff between water stress and N-limitations. The lack of nutrients seemed to have a smaller impact on model simulations compared to the observations. In this experiment, an overestimation of LAI by the model was obtained only plots with bund and without fertilizer application (Fig. 3.14). The analysis of iron concentration in 2010 showed that there iron toxicity might occur in plots with bund and without fertilizer application. The current version of the EPIC model does not consider Fe stress. Indeed plots in bund and without fertilizer yielded the highest iron concentration in leaves, being well above the critical threshold of 500 ppm at both 38 DAS and 60 DAS. Previous works (Kirk, 2004, Becker and Asch, 2005) pointed out that in West African inland valleys; *in-situ* Fe toxicity is aggravated by the depletion of nutrients and reducing the rice plants' ability to exclude $Fe^{2+.}$

3.3.4.2. Total above ground biomass development

The results of the calibration for the above-ground biomass are illustrated in Fig. 3.11 for all treatments from 2007-2010.

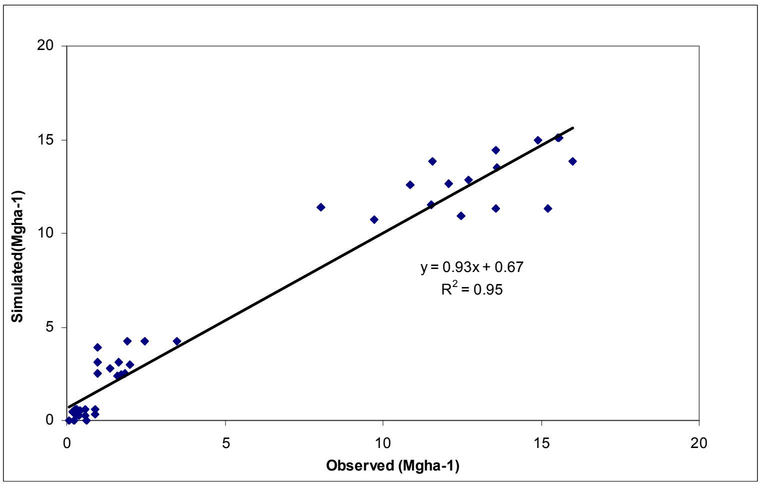


Figure 3.11: Observed and simulated total aboveground biomass over 4 years (solid line is linear relationship between simulated and observed total above ground biomass, R^2: coefficient of determination).

Fig. 3.11 shows relatively high goodness of fit between the observed data and the simulations. In all years, the comparison of simulated and observed biomass accumulation indicated a satisfactory representation of biomass accumulation at harvest over all treatments (Fig. 3.12 & Fig. 3.13). However, across the different treatments, the model slightly overestimated the above-ground biomass at 60 DAS in each year. This can be related to the bias observed in LAI at middle stage (Fig. 3.9). There is consistency with the overestimation of LAI. Plots with fertilizer presented model underestimation in 2010 at harvest. Some underestimations were reported by Srivastava and Gaiser (2009), He et al. (2006) and Cabelguenne et al. (2006) for the model for diverse crops under optimal N input. The authors suggested an overestimation of nitrogen demand by the crops at different growth stages. The goodness of fit in the simulation of above-ground biomass at maturity was higher in no bund plots with an R^2 value of 0.51 compared to plots with bund (R^2= 0.27). The MRE and ME in every treatment summarized well the trends observed (Table 3.7 and Figure 3.13).

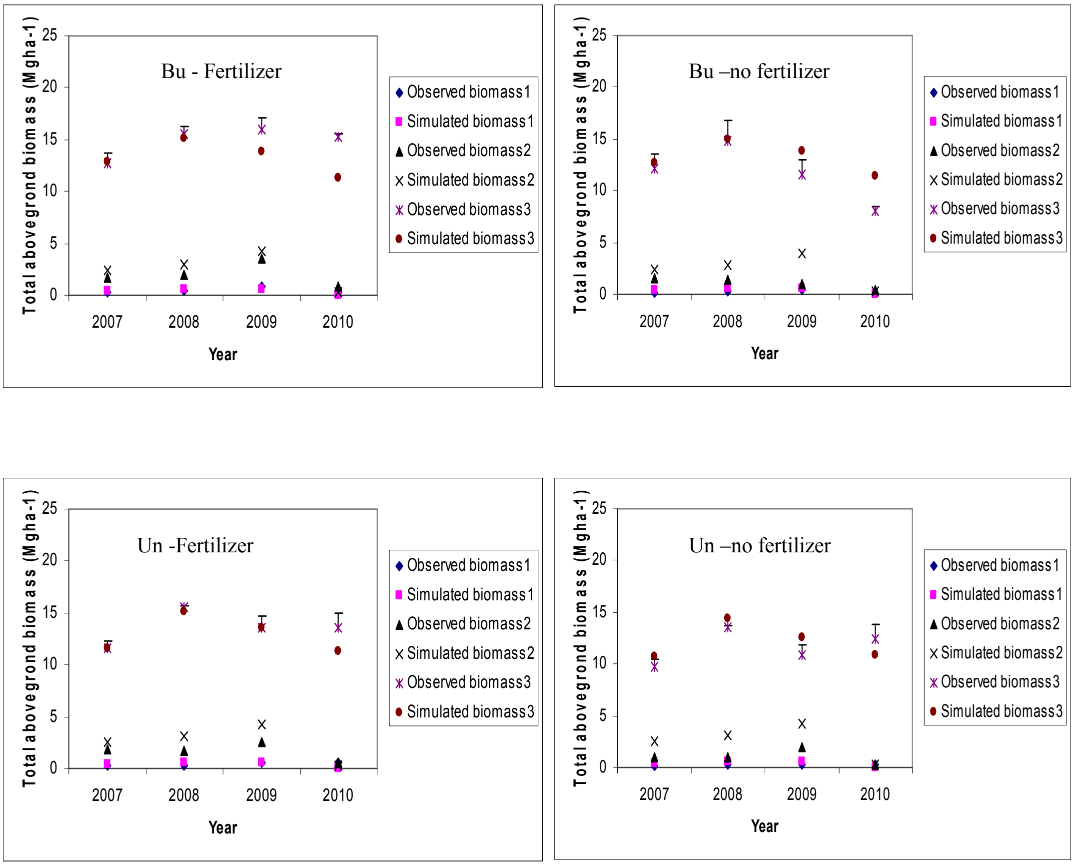


Figure 3.12: Observed and simulated total aboveground biomass depending on treatment and year (biomass 1=biomass at 38 DAS, biomass 2= biomass at 60 DAS and biomass 3 = biomass at maturity) Bu is plots with bund; Un refers to plots without bund.

Table 3.7: Means of observed and simulated total above-ground biomass and rice yield over 4 years with respect to bund and fertilizer application.

	Bund		No bund	
	Fertilizer	No fertilizer	Fertilizer	No fertilizer
Total aboveground biomass at maturity (Mgha^{-1})				
Observed (n=16)	14.86	11.64	13.57	11.66
Simulated (n=4)	13.27	13.21	12.87	12.18
ME (Mgha^{-1})	-1.60	1.57	-0.70	0.52
MRE (%)	-0.10	0.17	-0.05	0.05
Grain yield (Mgha^{-1})				
Observed (n=16)	4.98	3.81	4.69	3.92
Simulated (n=4)	5.07	5.03	4.93	4.66
ME (Mgha^{-1})	0.65	1.22	0.23	0.73
MRE (%)	0.16	0.45	0.06	0.18

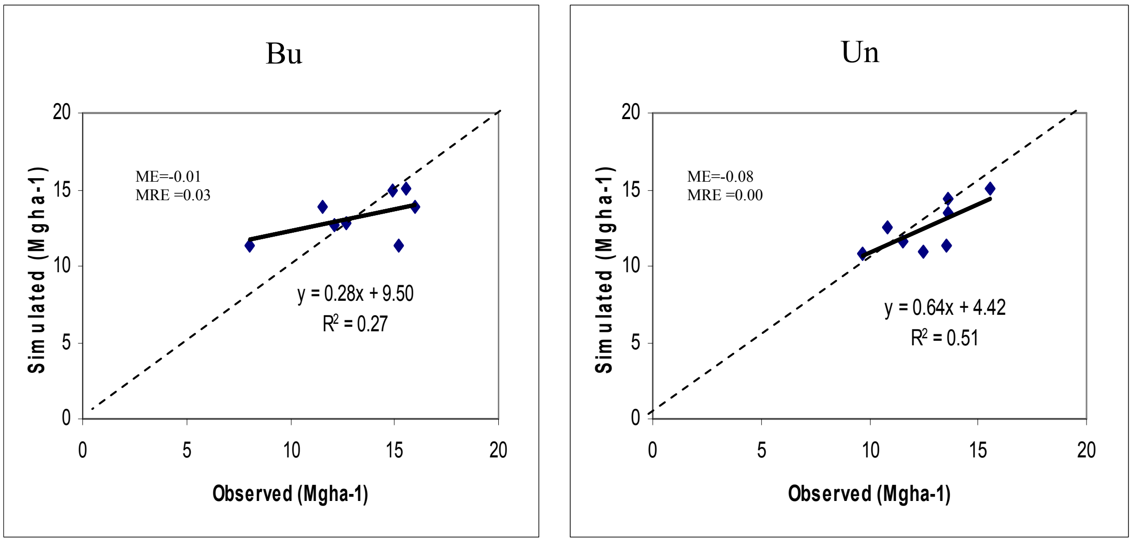


Figure 3.13: Regression between observed and simulated total aboveground biomass of NERICA-L26 at maturity over 4 years under different bund conditions and fertilizer rates (R² is the coefficient of determination of the regression equation. ME: mean residual error, MRE: mean relative error). Bu is plots with bund; Un refers to plots without bund.

The model overestimated the biomass at maturity in plots with bund and without fertilizer in 2010. The highest MRE was observed in these plots. This overestimation of plant biomass in 2010 can be attributed to the effects of iron toxicity (Fig. 3.14).

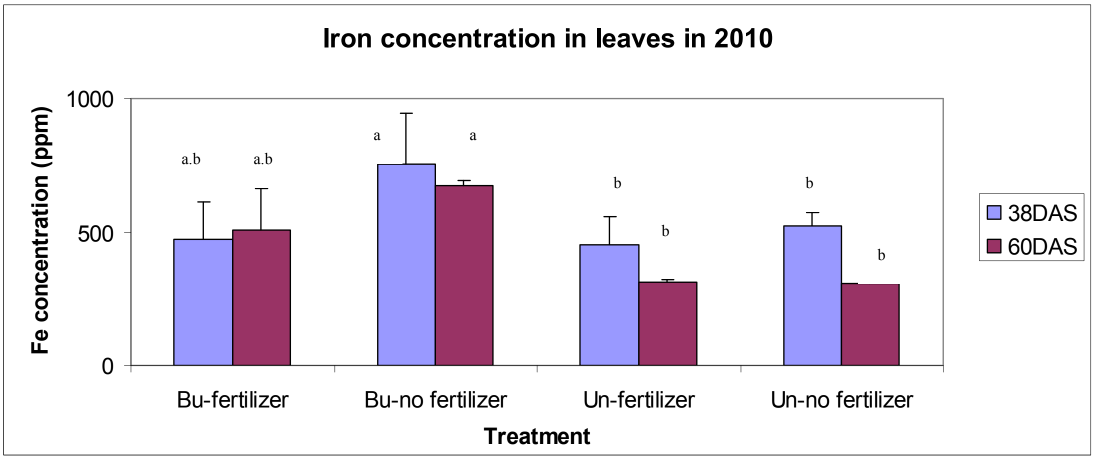


Figure 3.14: Mean iron concentration in rice at 38 and 60 DAS in different treatments in 2010 (treatments with the same letters are not statistically different at P=0.05).

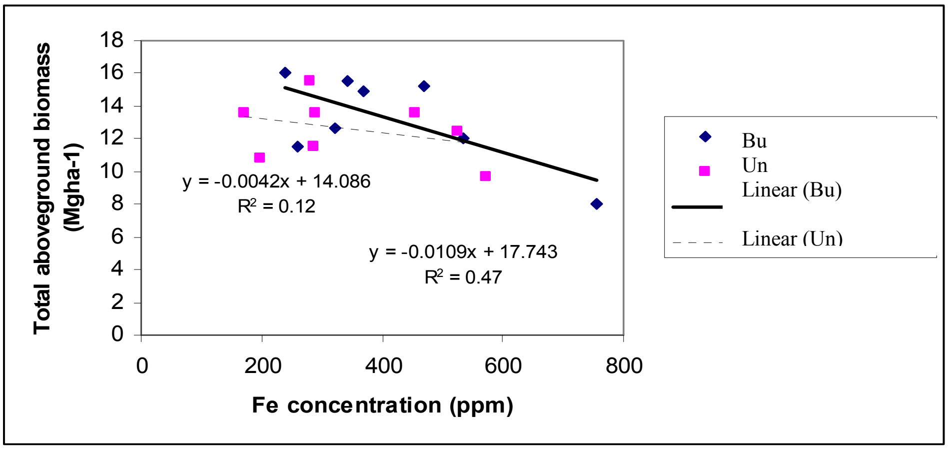


Figure 3.15: Regression between observed aboveground biomass of NERICA-L26 with Fe concentration in leaves at 38 DAS over 4 years under different bund treatments (R^2 is the coefficient of determination of the regression equation Bu is plots with bund, Un refers to plots without bund).

The relationship between the iron concentration and the total above ground biomass is more pronounced under bund than under no bund condition as shown in Fig. 3. 15 when all years were cumulated. Because of the longer period of flooding, the plots with bund are subject to toxic concentrations of reduced substances such as reduced iron (Fe^{2+}) (Dobermann, 2004). Therefore, in the case of iron toxicity during the vegetative stages a reduction of plant height and dry-matter accumulation can be observed particularly with the tiller formation and the total shoot biomass (Becker and Asch, 2005).

3.3.4.3. Grain yield

The grain yield was obtained in the model from a conversion of the total aboveground biomass by a factor of harvest index.

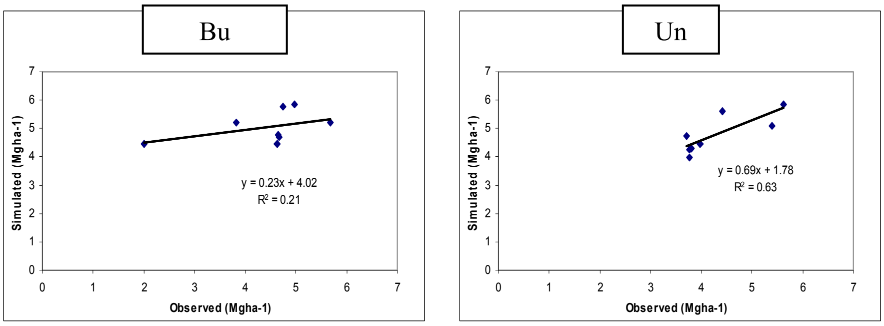


Figure 3.16: Regression between observed and simulated grain yield during 4 years (2007-2010) under bund and no bund conditions.

Overall R^2 after calibration was 0.23 and 0.65 for with and without bund plots respectively for grain yield (Fig. 3.16).

Rice yield simulation in average for the 4 years ranged from 4.66 $Mgha^{-1}$ to 5.07 $Mgha^{-1}$ against 3.81 $Mgha^{-1}$ to 4.98 $Mgha^{-1}$ in the observations (Table 3.7). This suggested an overall trend of overestimation of the model. The overestimation of the model (ME>0) in no fertilizer and bund is the consequence of an overestimation of biomass production which is related to the effect of iron toxicity, not represented by the model. Indeed, a critical MRE value was obtained only for plots without fertilizer (Table 3.7). The case of occurrence of iron toxicity during the late vegetative or early reproductive growth phases is associated with fewer panicles per hill which can contribute to considerable yield reduction (Becker and Asch, 2005).

4.Pedoclimatic affects on improved upland rice varieties in different agroecological zones of Benin republic

4.1. Introduction

Rice cropping at large scale was introduced in 1960 in Benin Republic. It is becoming next to maize, cassava and sorghum a popular staple food crop. The interest for rice has increased due to incentive from governmental and international policies (Bonou, 2006). Upland rice is cultivated on smallholdings. Meanwhile, a review of the land evaluation showed that there existed very strong disparities in soil nutrient availability within the same agroecological zone inside the country (Igué et al., 2004). This increases the challenge to develop upland rice varieties with higher yield potential and yield stability under highly variable soil conditions.

At present, the variety development programmes target their objective for developing varieties for suitable areas with introduction of breeding lines that present favourable traits such as water stress tolerance in low-input environments. The adopted upland NERICA varieties showed relatively high yields which vary in a controlled environment from 4.0 to 7.0 Mgha^{-1} (Akintayo et al., 2008). Since then the test of the interspecific crosses was done either for understanding the ability to overcome drought (Asch et al., 2005) or to tolerate temporary inundation via flash flooding (Kawano et al., 2009) or for low nitrogen environment (Saito & Futakuchi, 2009, Oikeh et al., 2008). Beside the 18 released varieties, 10 new varieties are assessed through the Participatory Varietal selection (PVS) in order to identify genotypes that perform well across or within a specific target environment. Basically, the PVS consists of trials in collaboration with farmers in order to identify promising cultivars for further evaluation by the farmers themselves (Obilana and Okumu 2005). Two agroecological zones in Benin with three pilot sites each were chosen for NERICA testing and dissemination i.e. Ganpkétin/Erokowari/kpakpazoumé and Tanguiéta/Pingou/Kobli.

Since leaf photosynthesis rate depends on genotype parameters such as leaf N content and relative crop growth rate in rice cultivars (Yoshida et al. 2007), Yoshida and Horie (2010) reported large variations in dry grain yield for 9 rice genotypes grown at 7 locations in Asia. In addition, Saito et al. (2010) evaluated 14 rice genotypes (lowland and upland) across several lowland locations in Benin and determined a G x E (Genotype x Environment) interaction on grain yield. Those previous records confirmed our hypothesis that the yields are influenced by the changes in growing environment and the plant heredity. However those studies were conducted with no water limitation during the cropping period. Our study rather aimed in identifying the effect of environmental factors on grain yield in on-farm trials e.g.

with moderate access to fertilizer under pure rainfed conditions in different agro ecological zones of the West African Savanna.

4.2. Material and Method

4.2.1. Site general characteristics

For the purpose of varieties testing and dissemination, the National Agricultural Research Institute (INRAB) conducted a series of trials from 2007 to 2009 with the cooperation of local farmers. Six sites were used and located in (Table 4.1):

Pingou, Kobli and Tanguiéta (Atacora District) are located in Sudanian -Guinean Savanna Zone which extends in the country from 8° up to 11° North. The zone presents a semi-humid tropical climate with a weak mono-modal to bi-modal rainfall distribution (Thamm et al. 2005, Röhrig 2008). The 30 years annual rainfall average is 1013 mm (Fig. 4.1).

Kpakpazoumé, Gankpétin and Erokowari (Collines District) are located in the Guinean Zone which extends from the coast up to about 8° North. The climate is tropically wet with usually two rainy seasons, a longer one from May to July and a shorter one from September to November with about 250 rainy days altogether (White 1983). The 30 years annual average is 1171 mm.

Daily weather parameters (precipitation, air temperature and moisture) were also collected from synoptic weather stations located nearest to the trials.

The area is located in the Southern sedimentary basin as a majority by ferrallitic soils formed on the sandy to sandy-clay material. All the sites are charaterized by tropical soils (Alfisol) in which ferric hydroxid particles are associated with aluminium oxides (Azontonde, 1991). The soils represented about 70% of the soils in Benin and across the transitional zone to the sudanian climate.

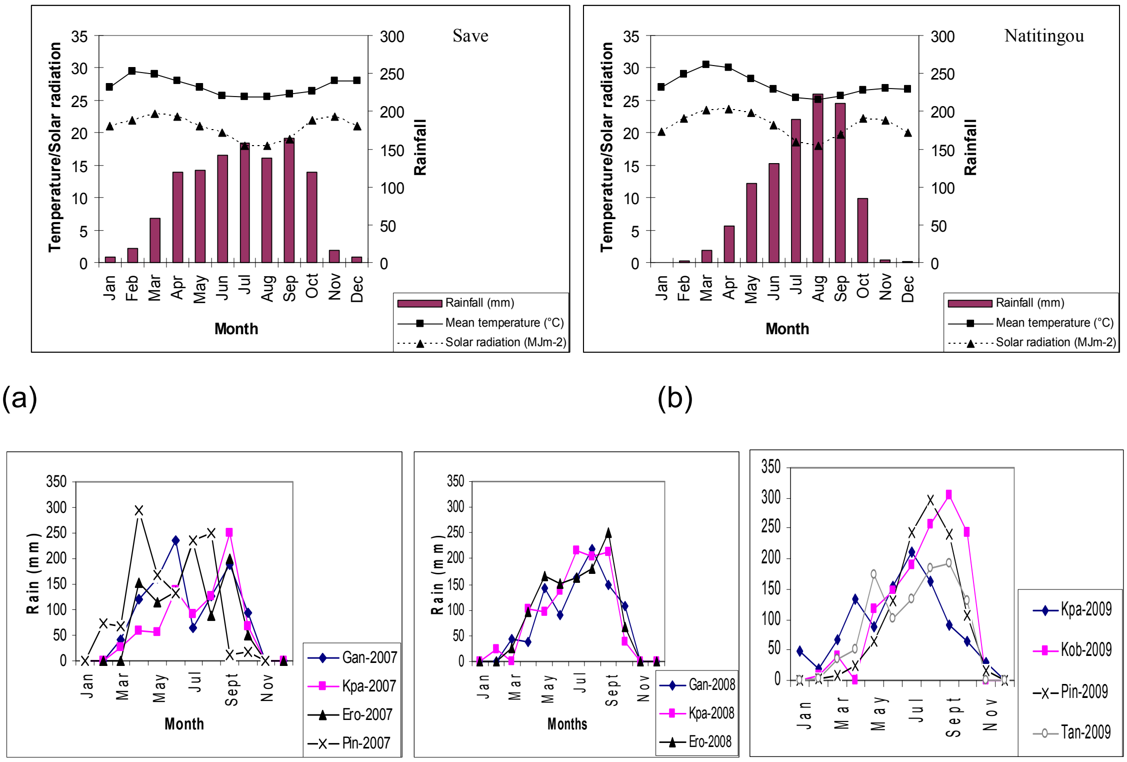
Table 4.1: Experimental sites used for upland vraieties evaluation in Benin Republic. Gan is Gankpétin, Kpa is Kpakpazoumé, Ero is Erokowari, Pin is Pingou, Tan is Tanguiéta and Kob is Kobli.

	Locations										
	Gan		Ero		Kpa			Tan	Pin		Kob
Coordinates	7° 42´N 2° 14´E		7°51´N 2°07´E		7° 55´N 2°15´E			10°37´N 1°26´E	10° 45´N 0° 59´E		10°29´N 0°59´E
Soil type (FAO)	Ferric Alisol		Ferric Acrisol		Plinthic Luvisol			Alisol	Dystric Plinthisol		Luvisol
USD classification	Alfisol		Alfisol		Alfisol			Alfisol	Alfisol		Alfisol
Landscape position	lowland		lowland		upland			upland	upland		lowland
Year	07	08	07	08	07	08	09	09	07	09	09
Rain in growing cycle (mm)	617	712	617	709	685	930	569	641	646	902	993
Sowing date (Jul-)	18	17	19	22	17	21	16	30	20	20	28
Crop residues[1]	nd	nd	nd	1	nd	nd	1	1,0	nd	0	1,0
Crop intensity[2]	nd	nd	nd	3,8,7,0	nd	0,1	8	1,2,3,6	nd	3,4,5,7	0,1,7,3

nd :not determined

1: Code crop fallow residue: 0: grass fallow, 1: grass fallow + rice residue,

2: crop intensity is associated with previous crop sequence for 3 years before the season. Crop includes: rice or maize or sorghum. 0: grass + cowpea at any sequence, 1: grass grass grass , 2: grass grass crop, 3: grass crop grass, 4: grass crop crop, 5: crop grass grass,, 6: crop grass crop , 7: crop crop grass, 8 : crop crop crop .



(a) (b)

(c) (d) (e)

Figure 4.1: (a) and (b): Meteorological conditions in Benin Republic. Synoptic station data from 1975-2005. (a) Savé refers to Gankpétin, Kpakpazoumé and Erokowari. Natitingou refers to Pingou, Tanguiéta and Kobli. (c), rainfall in 2007, (d) rainfall in 2008, (e) rainfall in 2009. Gan is Gankpétin, Kpa is Kpakpazoumé, Ero is Erokowari, Pin is Pingou, Tan is Tanguiéta, Kob is Kobli.

4.2.2. Experiment description

The experimental design on each site is arranged as a simple RCBD. It is comprised of 3 varieties: two improved and one traditional variety used as control. The traditional variety was subject to modification depending on the site and the year. This was the main reason that it was not taken into account in the present evaluation. The block was repeated with 2 farmers. The improved cultivars included 10 interspecific progenies from *O. sativa* × *O. glaberrima* derived from the Africa Rice collection.

A uniform recommended management level was applied. Each cultivar was sown on individual plots of 3m x 15m surrounded by bund. Tillage and plowing were carried out at the depth of 20-25 cm. Two weeding were made during the growing cycle. Sowing was direct with a spacing of 10cm x 30cm. NPK (16-16-16) fertilizer was applied as basal fertilizer the day of sowing at rate of 200 kgha^{-1}. 100 kgha^{-1} of urea was applied at 40 DAS (days after sowing). 228 plots were analyzed after removing plots with total yield failure.

In some plots, rice residues were left on the field during the fallow period (Table 4.1). Information of crop intensification is given for 76 sites and allowed to score the cropping intensity from 0 to 8. 0 corresponds to less intensified, 8 represents highest intensification with consecutive 3 years of rice cropping before the seasons.

4.2.3. Data collection

In each site, one representative field was selected for soil description in 2009 during the fallow period for Kpakpazoumé, Pingou and Erokowari and in 2011 for Kobli and Tanguiéta. Topsoil samples are randomly collected from the fields at 5 points at 0–20 cm depth. Secondly it was dug a profile per site down to root zone depth. The samples were sieved (2-mm mesh) before analysis. The pH was determined using a soil-water ratio of 1:2. The organic carbon and organic N were analysed using the elemental analysis for Kpakpazoumé, Pingou and Erokowari. The dichromate oxidation method of Walkley and Black was used for Kobli and Tanguiéta. Exchangeable bases (Mg, K, Ca and Na) were extracted with 1 mol L^{-1} NH_4 Acetate; Ca and Mg in the extract were measured using the atomic absorption spectrophotometer (AAS) while Na and K were determined by flame photometry. The potential cation exchangeable capacity was determined by extraction with 1 mol l^{-1} $BaCl_2$.

4.2.4. Statistical analysis

Data analysis consisted of running analysis of variance with a general linear model, of Principal Component Analysis (PCA) and correlation analysis at a 95% confidence level. Means separation was performed with Tukey Least Significant Difference (LSD) method at 0.05 probability level. SPSS (version 16.0) was used to perform analyses.

4.3. Results and discussion

4.3.1. Soils characteristics

The physicochemical properties of the topsoil (0-20 cm) layer of the locations are presented in Table 4.2. Soil texture classes were dominated by sandy loam texture except in Kobli which presented the highest clay content. The soils were characterized by moderate to acid pH. Southern sites were more acidic and presented lower pH values than northern sites. There were no large differences for nitrogen among the sites. The soil organic carbon content was highest in Kobli and lowest in Erokowari.

Table 4.2: Soils description from 0-20 cm layer.

	Gankpétin[1]	Erokowari	Kpakpazoumé	Tanguiéta	Pingou	Kobli
Material content						
Sand (%)	88	55	66	72	70	38
Clay (%)	6	10	29	12	7	26
Texture class	SL	SL	SL	SL	SL	LS
Chemical properties						
pH (H_20)	5.60	4.70	5.79	5.70	6.30	7.30
Corg (%)	1.20	0.78	0.91	0.98	0.84	1.34
N (%)	0.10	0.05	0.06	0.04	0.06	0.06
CEC (cmol kg^{-1})	5.10	5.93	8.45	12.00	7.03	21.00
Bases (cmol kg^{-1})						
K^+	0.24	0.20	0.03	0.05	0.16	0.13
Ca^{2+}	2.75	0.39	0.31	4.17	0.36	6.51
Mg^{2+}	0.61	--	--	0.98	3.67	5.23
Na^+	0.08	0.08	0.24	0.15	0.79	0.26

1. Igué (2006)

4.3.2. Agronomic responses

The General Linear Procedure model with mixed effect (Table 4.3) across 11 cropping seasons showed that upland rice productivity in Benin depends strongly on soil type. Site x year interaction was also highly significant, while variety effect was not significant.

Table 4.3: F ratios from the combined analysis of variance across 6 experiments for rice traits evaluated for 10 varieties. d.f.: degree of freedom; DDF: Denominator Degree of Freedom of covariance parameters; ns, not significant at the <0.05 probability level.

Source of variation	d.f.	DDF	F probability
Variety	9	161	ns
Site	6	161	<0.0001
Year	2	161	ns
Variety x Site	42	161	ns
Site x Year	3	161	<0.0001
Variety x Year	14	161	ns
Variety x Site x Year	65	161	ns

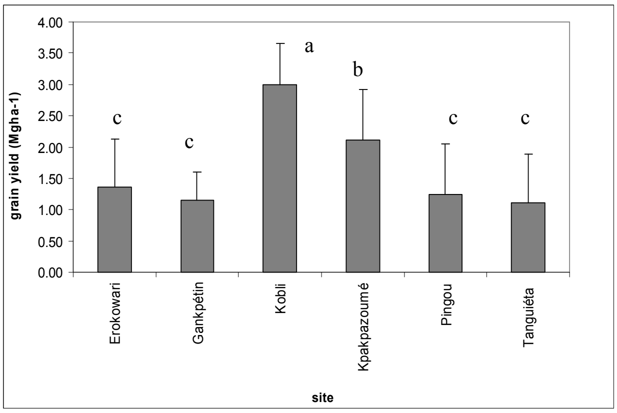


Figure 4.2: Rice yield in 6 experimental sites of Benin. The numbers followed by the same letters are not different at p<0.05.

Sites could be ranged into 3 classes (Fig. 4.2), Kobli exhibited higher potential for rice than in the other experiments. Low to moderate yield was obtained in Kpakpazoumé. Low yielding sites comprised Tanguiéta, Pingou, Erokowari and Gankpétin.

Table 4.4: Grain yield distribution across years 2007, 2008 and 2009. Figures with same letter are not statically different across the year**.**

	2007			**2008**			**2009**		
Site	**n**	**Mean ($Mgha^{-1}$)**	**Cv (%)**	**n**	**Mean ($Mgha^{-1}$)**	**Cv (%)**	**n**	**Mean ($Mgha^{-1}$)**	**Cv (%)**
Gankpétin	20	1.08d,e	26.85	18	1.20d,e	46.67		-	-
Erokowari	20	1.76c	43.18	18	0.92d,e	51.09		-	-
Kpakpazoumé	20	1.49c,d	59.73	20	2.39b	25.41	12	2.68 a,b	16.42
Pingou	20	1.97bc	43.15		-	-	30	0.76e	20.54
Tanguiéta		-	-		-	-	30	1.11d,e	70.27
Kobli		-	-		-	-	20	3.00a	22.00
Total/average	**80**	**1.58**		**56**	**1.50**		**92**	**1.88**	

Grain yield per site across all years and sites was presented in Table 4.4. Mean grain yields of the 10 rice genotypes ranged from 0.76 to 3 $Mgha^{-1}$ across the experiments. The higher yield was obtained in 2009 in Kobli and Kpakpazoumé. In 2008, Erokowari presented yield below 1 $Mgha^{-1}$. In 2007, the yield ranged from 1.08 to 1.97 $Mgha^{-1}$ across 4 sites where Pingou was the highest. In sum, there is an increase of yield from 2007 to 2009.

Table 4.5: Correlation matrix including variable grain yield, soil characteristics at 0-20cm and rainfall during the growing season. Numbers in bold are significant at $p<0.001$.

	Sand (%)	Clay (%)	N (%)	Corg (%)	Rain (mm)	Grain yield (Mgha^{-1})
Grain yield	**-0.50**	**0.51**	0.20	**0.52**	**0.29**	1
Rain	**-0.43**	**0.63**	**0.22**	**0.53**	1	
Corg	**-0.56**	**0.79**	**0.45**	1		
N	**0.16**	-0.03	1			
Clay	**-0.65**	1				
Sand	1					

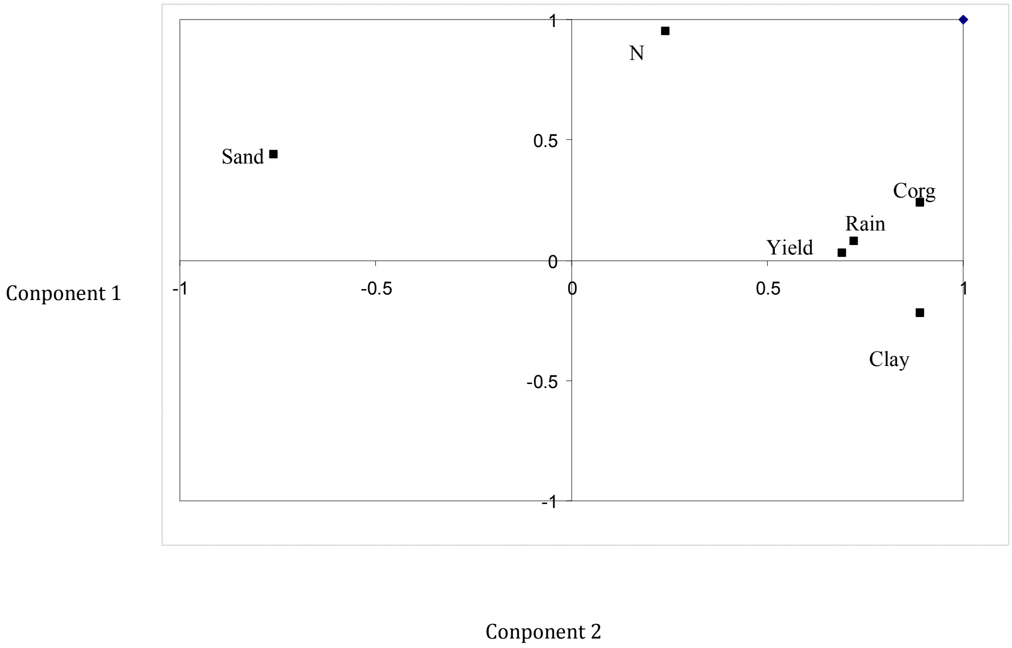


Figure 4.3: Scatter plot for Principal Component Analysis of rice yield, seasonal rain and soil characteristics. (Axis I is the first principal component. Axis II is the second principal component).

The internal relationship of seasonal rainfall amount, soil texture, soil organic C and N at 0-20 cm, with grain yield is illustrated in Table 4.5. The grain yield appeared significantly correlated in positive term with soil organic carbon, clay content and rainfall amount during the cropping season. Correlation between rice yield and sand content was negative. The principal component analysis was performed with the same variables. Fig. 4.3 shows the results of this analysis. The first principal component explained 53% and the second principal component explained 21% of the variation. In the second principal component (Axis II) the coefficient of rain, organic carbon and N content showed a positive value, while clay and sand content were more loaded on the component I suggesting that the first principal component explains the soil texture variability. Therefore, clay versus sand was plotted in the negative portion of Axis I. This graph confirms that increase of grain yield conferred to high amount in organic carbon, nitrogen and rain, but sand content adversely affected grain yield.

4.3.3. Discussion

In general West African farmers are experiencing low rice productivity in rainfed rice (Lançon et al. 2001). The average yield of this study on upland rice fits with national average estimated at 2 Mgha^{-1} (MAEP 2011). In the same line with this study, Saito and Futakuchi (2009) estimated the average grain yield across all upland cultivars in low fertility (low C_{org} content) to be 54% of that in high fertility soils (156 vs. 340 Mgha^{-1}) under irrigation. In the study through the PVS, interspecific genotypes were evaluated to cope with local farmer's conditions which include in addition to low inherent soil fertility, the occurrence of drought or flood. This multisite evaluation didn't show any type of interaction between variety and environment. Using the same approach, Mandel (2010) found smaller genetic variance for grain yield under low-input conditions in India as confirming the results in our study. Several kind of stress may limit varietal selection progress under unfavourable environments (Banziger and Cooper 2001).

Many studies reported that nutrient deficiencies in rice are very common in West Africa (Oikeh et al. 2009, Okeleye et al. 2006). The difference in grain yield was attributed mainly to soil C_{org} and clay content. The situation of Kobli in the lowland with highest yield allowed rice to respond favourably to the N and water contributed from the slope. For instance, Bognonkpe and Becker (2009) evaluated that N uptake is higher in plots adjacent to uplands with fallow vegetation compared to plots cultivated with maize. The other sites such as Pingou and Tanguiéta presented the lowest grain yield and which is linked to soil fertility degradation, because they have been extensively used formerly for long-term cotton culture. In addition, the region is characterized by rare fallow land because of the strong pressure on the land (Saidou et al. 2004). Indeed, the clearing of natural vegetation and its replacement by intensive annual cultures such as cotton should result very quickly in an intense mineralization of the organic matter (Saïdou, 1992). A decrease of soil fertility from one year to another during three consecutive seasons was observed to not be fully able to be corrected with 80N-and 100P kgha^{-1} application (Dingkuhn et al. 1998). In our study, the supply in NP elements was far less.

All the sites in the Guinean zone (Erokowari and Gankpétin) reported the lowest yields (Fig. 4.2). Previous works reported that a bimodal rainfall zone is subject to a short cessation of the rainy season during the middle season particularly during the reproductive phase of rice crop. It was reported that this water shortage is often the source of N-uptake reduction during the vegetative stage and the reproductive growth stages of rice crops particularly during the midseason (Kamara et al. 2010, Oikeh et al. 2008). The year 2007 for the southern sites (Gankpétin, Erokowari and Kpakpazoumé) showed clearly bimodal pattern for rainfall (Fig.4.1). However, the rainfall in August and September was still high, thus the grain yield cannot be linked to the water shortage. Furthermore, Koné et al. (2009) proved that there was also a significant ($P = 0.004$) decreasing effect of Zn (28%), N (34%) and K (36%) exclusion on the mean grain yield in the Ferralsol soils in south of Benin. These results attested the existence of Zn and K deficiencies which may reduce the sustainability of upland rice production. The high correlation of soil texture with grain yield confirmed the relationship between water capacity retention and soil management. In Guinean zone dominated by Ultisols and Alfisols the water retention is a main limitation to cultivation, in particular in coarse-textured and moderately deep or shallow soils (Andriese and Fresco, 1991). In addition negative correlation among sand and organic matter contents existed.

5. Multisite evaluation of the EPIC model for NERICA rice cropping in different agroecological zones of West Africa

5.1. Introduction

The operation of crop growth models is of interest for extrapolating results gained on experimental stations. Beside, simulation modelling represents a research tool for assessing climatic change patterns and their impacts on crop growth and yield. Modelling a cropping system requires to understand the complex crop-water-soil interaction and to suggest some empirical parameters which are applicable to diverse conditions and environments. However, the attempt to use crop growth models under extremely unfavourable growth conditions i.e. water scarcity combined with low soil fertility or with indigenous management practices remains a challenge in tropical cropping systems such as in Africa or in Latin America (de Barros et al., 2004, Gaiser et al., 2010a).

Indeed, for the rice crop that has a relatively long history in modelling, model development is now geared to the issue of resources limitation due to expansion of rainfed rice systems. For instance, the water and nitrogen modules in the latest version of ORYZA2000 formerly developed for estimating potential rice production suggest repeated model simulations with real-world data in order to increase the confidence in the suitability of the model for a certain purpose (Bouman and van Laar, 2006). Even the agroecological system models such as the Environmental Policy Integrated Climate (EPIC) which addresses crop simulation in response to weather and nutrient cycling, is still not widely used to explore management strategies (Probert, 2004). As result, in rainfed low-input systems such as smallholdings in West Africa, models developed for optimal management conditions fail to meet the needs of researchers and extension workers (Palm et al., 1997). This is a key issue in Africa where about 80% of the rice production depends on rainfed conditions.

Although the basic use of crop models was to calculate crop growth and development for a single field, there is increasing interest in studies that concern multiple fields evaluation (Leenhardt et al., 2007, Hartkamp et al., 1999). This depends on the assumption that field scale model can be useful for evaluating management strategies at a broader scale. In rainfed upland systems in West Africa, rice yield is seldom above 2 Mg ha^{-1}. The constraints in West Africa include rainfall uncertainty, weeds and limited soil nitrogen availability. Indeed, soil nutrient availability for upland rice cultivation has also been described to be related to land use and ecology (Becker and Johnson, 2001). It is therefore, important for crop modelling targeted on upland rice to be tested on various environmental and management conditions to provide more confidence for further upscaling exercises.

The objective of this study was a multisite calibration and validation of the EPIC model for upland NERICA rice in contrasting agroecoystems; and the identification of site-specific model sensitive parameters. Therefore, we analyzed the sensitivity of the crop model to fertilizer and water inputs with data from experimental and on-farm fields in the Guinea and Sudan agroecosystems of Benin and Nigeria (West Africa). The EPIC model was chosen due to its capacity to consider the effect of abiotic stresses due to limiting water and nutrients such as nitrogen and phosphorus on rice productivity.

5.2. Material and Methods

5.2.1. Study area

Table 5.1: Dataset for calibration and validation of crop growth simulation. GY: Grain Yield, TAB: Total Aboveground Biomass, LAI: Leaf Area Index, C refers to data used for Calibration and V for Validation.

Site No	Location	Latitude Longitude	Elevation (m)	Year	Variables for simulation	Activity	Reference
1	Ikenne	6°54´N 3°42´E	71	2004	GY; TAB	C	Oikeh et al., (2008)
2	Bohicon	7°11´N, 2°04´E	77	2006, 2007	GY	V	Sokei et al. (2010)
3	Niaouli	6° 44´N 2° 07´E	81	2005, 2006	GY	V	Koné et al. (2008)
4	IITA	6° 20´N 2° 20´E	457	2006, 2007	LAI; TAB; GY	C	Saito and Futakuchi, 2009)
5	Pingou	10° 45´N 0° 59´E	100	2009, 2010	GY	V	
6	Kpakpazoumé	7° 55´N 2° 15´E	174	2009, 2010	GY; TAB	C	
7	Tchankpéhoun	10° 45´N 0° 59´E	187	2009, 2010	GY; TAB	C	
8	Tohoué	6° 25´N 2° 40´E	14	2009	GY; TAB	C	

The model evaluation followed a calibration and validation process. Experimental data were collected from 8 experiments carried out in 2004, 2005, 2009 and 2010 in Benin and Nigeria, West Africa (Table 5.1). The locations are listed from South to North: IITA (The International Institute for Tropical Agriculture, Cotonou) (4), Tohoué (8), Ikenne (1, Nigeria), Niaouli (3), Bohicon (2), Kpakpazoumé (6), Tchankpéhoun (7) and Pingou (5). The calibration dataset was obtained from sites 1, 4, 6, 7 and 8. Validation plots were from sites 2, 3 and 5. The experimental sites ranged from the humid forest, Guinea savanna, to the Sudan savanna agroecosystems (Table 5.2) with bimodal rainfall distribution in the humid forest and Guinea savanna, and a monomodal rainfall distribution in the Sudan savanna. The annual precipitation is over 1400 mm in the humid forest with declining rainfall northwards. There is regionally higher rainfall close to the Atacora mountain range for the case of Pingou and Tchankpéhoun locations (Röhrig, 2008). The length of growing season decreases also from South to North (250 to 130 days). In general, the rainfall distribution allows cultivation of two crops per year in the southern areas (Igué, 2000).

Table 5.2: Pedoclimatic conditions of test sites used for model calibration and validation.

Site	Climate zone	Rainfall[1] (mm)	Synoptic station	Station	Soil type FAO/US classification	Texture[2]	Soil organic carbon (%)[2]	Reference for soil profile
1	Guinean	1287	FAO	Ibeju-Ode	Typic Haplustult/ Ultisol	S	0.86	Heuberger (1998)
2	Guinean	1208	Bohicon	Bohicon	Haplic Alisol/Alfisol	SL	2.38	Atchade (2006) CENAP
3	Guinean	1065	Cotonou	Niaouli	Acrisol/Alfisol	S	1.89	Atchade (2006) CENAP, Koné et al. (2008)
4	Guinean	1352	Cotonou	IITA	Haplic Alisol/ Alfisol	S /SC	1.96/0.7	Atchade (2006) Saito and Futakuchi (2009)
5	Soudan-Guinean	1103	Nati-tingou	Matéri	Dystric Plinthisol /Alfisol	SL	0.84	-
6	Soudan-Guinean	1209	Savé	Kpakpa - zoumé	Dystric Plinthisol /Alfisol	SL	0.91	-
7	Soudan-Guinean	1103	Nati-tingou	Matéri	Luvisol/Alfisol	LS	0.82	-
8	Guinean	1082	Cotonou	Porto-Novo	Dystric Cambisol / Inceptisol	S	0.65	-

1. Rainfall in site 1, in 2005, in site 2 is average 2007 and 2008, in site 3 is average 2005 and 2006, in site 4 is average 2006 and 2007, in site 5 and 7 are average 2009 and 2010, in site 6, average 2009 and 2010, site 8 refers to 2009,
2. Texture and soil organic carbon in 0-20cm or 15 cm depth.

5.2.2. Model data input and source

Table 5.3: Description of the experiments with field operation. N1 and N4 refer to NERICA1 and NERICA4 respectively.

Site	Year	Variety	Planting density (cm x cm)	Amount of inorganic fertilizer (kgha^{-1})			Sowing date	Irrigation application
				N	P	K		
Research station								
1. Ikenne (Oikeh et al., 2008)	2004	N1	20x20	0	0	25	16 Jun	no
				30	0	25		
				60	0	25		
				120	0	25		
				0	26	25		
				30	26	25		
				60	26	25		
				120	26	25		
2. Bohicon (Sokei et al., 2010)	2007	N1	20x20	60	13	25	29 May	No
	2008			0	0	0	31May	
3. Niaouli (Koné et al., 2008)	2004	N4	20x20	0	0	0	3 Jun	no
	2005			100	100	100	5 May	
				0	100	100		
				100	0	100		
4. IITA (Saito and Futakuchi, 2009) (Sone et al., 2009)	2006	N1	20x20	50	13	25	19 Sep	Yes
	2007			50	13	25	27 Feb	
On farm –research								
5. Pingou	2009	N4	30x10	66	14	27	4 Aug	No
	2010			34	-	-	13 Jul	No
6. Kpakpazoumé	2009	N1	30x10	63	14	27	14 Jul	No
	2010			66	17	33	15 Jul	No
Farmland								
7.Tchankpéhoun	2009	N1	30x10	39	14	27	28 Jul	No
	2010			35	7	13	14 Jul	No
8. Tohoué	2009	N1	30x10	44	16	25	27 May	Yes

Crop management dates are summarized in Table 5.3. For the experiments in sites 1, 2, 3 and 4, the field layouts have been described in previous studies (Oikeh et al., 2008, Saito and Futakuchi, 2009, Sokei et al., 2010, Koné et al., 2008). For 5, 6, 7 and 8, the experimental design varies according to the location. Plots of 3 m x 15 m were used in Kpakpazoumé and Pingou. The farmland in Tohoué occupied 1250 m² and 5000 m² in Tchankpéhoun. In all the experiments, NERICA1 or NERICA4 variety was used.

Soil information was provided from soil profiles dug during the fallow period in 2009 for sites 2, 3, 4, and 8. Topsoil samples were randomly collected from the fields at 5 points of 0–20 cm depth. Secondly it was done along a profile per site down to root zone depth. The samples were sieved through 2-mm mesh before analysis. The pH was determined using a soil-water ratio of 1:2. The organic carbon and organic N were analysed using the elemental analysis for samples from Kpakpazoumé, Pingou and Erokowari. The dichromate oxidation method of Walkley and Black (1934) was used for samples from Kobli and Tanguiéta. Exchangeable bases (Mg, K, Ca and Na) were extracted with 1 mol L^{-1} NH_4 Acetate; Ca and Mg in the extract were measured using the atomic absorption spectrophotometer (AAS) while Na and K were determined by flame photometry. The potential cation exchangeable capacity was determined by extraction with 1 mol L^1 $BaCl_2$.

Atchade (2006) reported chemical and physical characteristics of soil profiles in IITA, Niaouli and Bohicon (Cana Sud) from 2005. The top soil properties (0-15cm) were adapted according to Saito and Futakuchi (2009) at IITA. Two fields were used at IITA: one with low soil fertility ($IITA_{low}$) and the other with high soil fertility ($IITA_{high}$). Soil data in Ikenne was obtained from Heuberger (1998). The profiles were described during the fallow period at Kpakpazoumé, Pingou and Tchankpéhoun in 2009. Ikenne and Niaouli have sandy textured topsoil (Table 5.2). However, except Tohoué, all the sites have loamy to clayey subsoil (Alfisols and Ultisols).

The soils were usually acid with low nitrogen content except in Bohicon and $IITA_{high}$. In the 0-15 cm soil depth, soil organic carbon content of the locations was classified in the order:

Bohicon>$IITA_{high}$>Kpakpazoumé>Pingou>Ikenne>Tchankpéhoun>Niaouli>$IITA_{low}$> Tohoué.

Daily meteorological data (maximum and minimum air temperature and global solar radiation) were collected from the synoptic weather station which was as nearest as possible to the fields (Table 5.2). For synoptic data in Ikenne, the model weather generator was used from FAO climate database (LocClim, 2002) for monthly mean temperature. Solar radiation at Ikenne was derived from Apkabio and Etuk (2003) and the Hargreaves (Hargreaves and Samani, 1985) method was used for potential evapotranspiration (ETP) estimation. For all other sites, Penman Monteith Method was applied. Daily rainfall was retrieved from the closest rainfall gauge.

5.2.3. Modelling with EPIC

The version 3060 of the EPIC model (Williams, 1990) was used to simulate rice productivity. The EPIC model is a field-based model designed to simulate crop production based on information about soil, crop rotation and management system. A full description is presented in the model documentation by William et al. (1990). Among various subroutines, the model considers N and P cycling by flows between inorganic and organic stocks.

For N mineralization, EPIC couples C and N cycling in the soil. Simulated C and N compounds in EPIC are stored in either biomass, slow, or passive soil organic matter pools. Direct interaction is simulated between these pools as the function of soil moisture, temperature, nutrient content and clay content functions (Izaurralde et al., 2006, Gaiser et al., 2010a).

For P mineralization, two sources of mineralization are considered: the fresh organic P pool, associated with crop residue and microbial biomass and the stable organic P pool, associated with the soil humus. The mineral P is then transferred among three pools: labile (which comprises fertilizer), active mineral and stable mineral. Flow between the labile and active mineral pools is governed by the equilibrium equation that implies the mineral P flow, the amount in the active mineral P pool and P sorption coefficient defined as the fraction of fertilizer P remaining in the labile pool after the initial rapid phase of P sorption is completed.

5.2.4. Model evaluation

The evaluation of the model was done by producing linear regressions between measured and simulated variables and calculating the correlation coefficient R^2. The different comparison methods in Table 5.4 that highlight the feature of data and the model response were also used. The mean error (ME), mean relative error (MRE), mean absolute error (MAE), and root mean square error (RMSE) were presented where n was the sample number, x the observed, and y the simulated value. The MRE is positive when the model overestimates values compared to the observed values. The negative sign relates to underestimation. The root mean square error (RMSE) estimates the precision and reliability of the prediction for single yield estimation points. Model efficiency is used to assess the predictive power of the model taking into account the variability inside the observation dataset.

Table 5.4: Measure of agreement between a model and observed data.

Name	Equation	Optimum value
Mean error	$\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)$	0
Mean relative error	$\mathrm{MRE} = \frac{1}{n}\sum_{i=1}^{n}\frac{(y_i - x_i)}{x_i}$	0
Mean absolute error	$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}(\lvert y_i - x_i \rvert)$	0
Model efficiency	$\mathrm{EF} = \frac{\left[\sum_{i=1}^{n}(x_i - \bar{x})^2 - \sum_{i=1}^{n}(y_i - x_i)^2\right]}{\sum_{i=1}^{n}(x_i - \bar{x})^2}$	1
Root mean square	$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2\right]^{0.5} \times \frac{100}{\bar{x}}$	0

5.3. Results and discussion

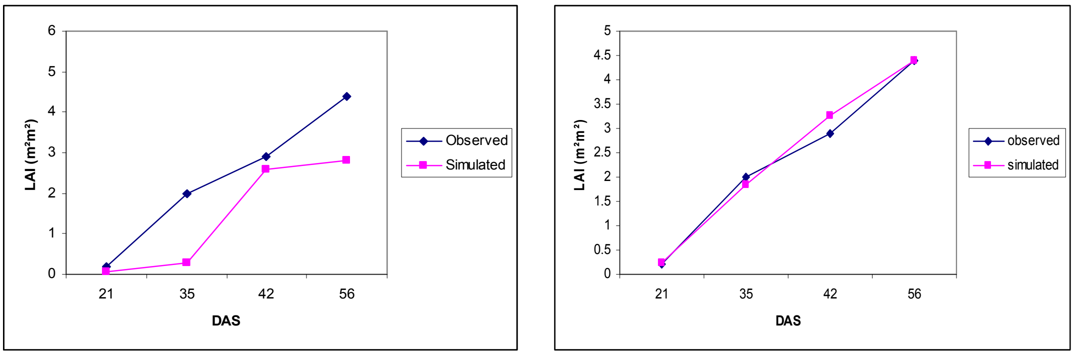
5.3.1. Calibration of crop parameters

The calibration and validation runs started with a warm up period of 8-9 years in order to stabilize the soil organic carbon pools in the model. The approach used for the calibration was to modify some initial values of the model parameters in order to iteratively fit simulation values as close as possible to the observed yield values. Therefore, we adjusted the default crop parameters for rice to the NERICA varieties, because they are short duration low management plant types that are adapted to resource-limited smallholder production systems (Dingkuhn 1998). However, no varietal distinction was taken into account in the crop file. The NERICA 1 and 4 passport data published by the Africa Rice Centre (2008) represented no feature for distinguishing the two varieties in the crop file of the EPIC model such as the number of days to maturity which determine the Potential Heat Unit (PHU) or flowering age.

In the process of LAI calibration, the parameters DLAP1 and DLAP2 were used to control the crop growth. Félix (2006) considered that the sub-model of EPIC for LAI development is based on a strong amount of empiricism, as the mechanism that controls the rate of development of LAI is not yet well understood. Therefore, DLAP1 was changed from 30.01 to 30.20 and the DLAP2 from 70.95 to 60.95 for the two varieties. The plant population density was also modified from 125.600 to 50.600 in PPC1 and 250.600 to 250.900 in PPC2.

Table 5.5: Parameter setting for rice in the EPIC crop file: original defaults and values after calibration (WA, biomass-energy conversion factor; HI, potential harvest index; WSYF, minimum harvest index; LAImax, maximum leaf area index; PPC1/PPC2 & PPT1/PPT2, DLAP1, DLAP2: LAI development parameters linked to plant density).

Parameters	Explanation	Original	Used in the parameterization
WA	Radiation use efficiency (kg ha^{-1}/MJm-^{2})	25	25
HI	Harvest index (decimal fraction)	0.50	0.55
PHU	Potential heat unit (degree days)	1500	1500
WSYF	Minimum harvest index under water stress condition (decimal fraction)	0.25	0.01
LAI max	Potential maximum leaf area index (m^{2}m^2)	6	6
DLAP1	First point on optimal leaf area curve .Percentage of heat unit	30.01	30.20
DLAP2	Second point on optimal leaf area curve .Percentage of heat unit	70.95	60.95
PPC1/PPC2	1st point of plant population density for crops (plants m^2)/Fraction of potential leaf area index at 1st point (decimal fraction)	125/600	50/600
PPT1/PPT2	2nd point of plant population density (plants m^2)/PPT2 Fraction of potential leaf area index at 2nd point (decimal fraction)	250/900	250/600



(a) (b)

Figure 5.1: Comparison between simulated and observed leaf are index (LAI), (a) situation before and (b) after calibration.

The model outputs and the observations with regard to the LAI before and after the calibration were graphically compared. Figure 5.1 shows that the model first underestimated the values of LAI with a negative mean relative error of -0.28 (Table 5.6). After calibration, the average relative difference between the observed values and the simulated LAI was approximately 6% with a model efficiency of 98%. The LAI development was satisfactorily calibrated similar to Yoshida et al. (2007) using a complex and detailed phenological model as a function of relative crop growth rate, leaf nitrogen content and air temperature. The LAI was estimated under full irrigation at relatively high soil fertility level (Org C = 19.6 g kg^{-1} and total nitrogen up to 2.2 g kg^{-1}). The observed value was average of 5 cultivars including NERICA1 grown under high soil fertility conditions (Saito and Futakuchi, 2009). The authors did not detect any difference in rice cultivars in LAI at 42 and 56 days after seeding (DAS), and no traits from the early vegetative stage were observed to relate to grain yield. The relative increase in LAI at 30 % of the PHU (DLAP1) compared to the default value is in line with the high weed competitiveness feature reported for NERICA varieties (Ekeleme et al., 2009).

5.3.2. Calibration of soil parameter

Before calibration, the model showed low sensitivity to the supply of inorganic N and P on a highly weathered and strongly acid low-activity clay soils at Ikenne (Fig. 5.2), as the experimental layout was made to test the effect of fertilizer application in the humid forest agroecosystem on Ultisols (Table 5.3). Leenhardt et al. (2006) suggested the use of pedotransfer functions to estimate soil properties during the simulation process as a solution for unavailable data. However, Gaiser et al. (2010a) using sensitivity analysis estimated the fraction of microbial biomass across some different soil types under cropland in West Africa. The fraction of biomass in the soil organic matter pool (FBM) triggers the mineralisation of soil nitrogen, which is the main growth constraint in low-input smallholder systems in West Africa.

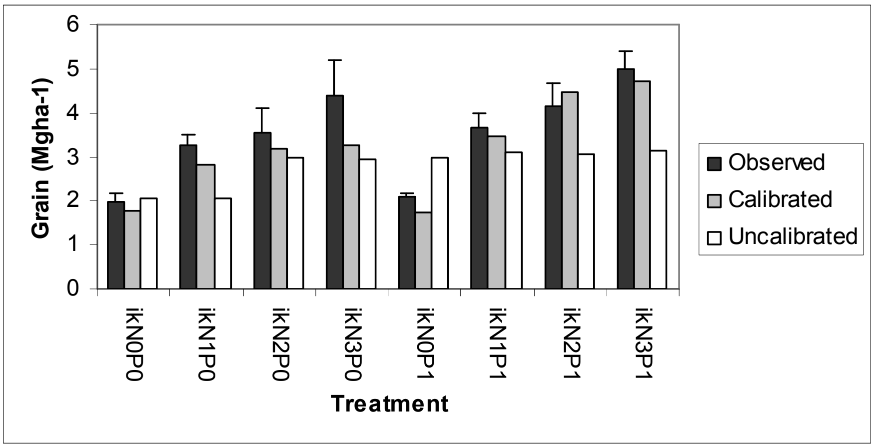


Figure 5.2: Model sensitivity to supply of N and P before and after calibration for Ikenne site in 2004 (N0, N1, N2, N3 is 0, 30, 60 and 120 kgNha^{-1}, P0 and P1 is 0 and 26 kgPha^{-1} respectively).

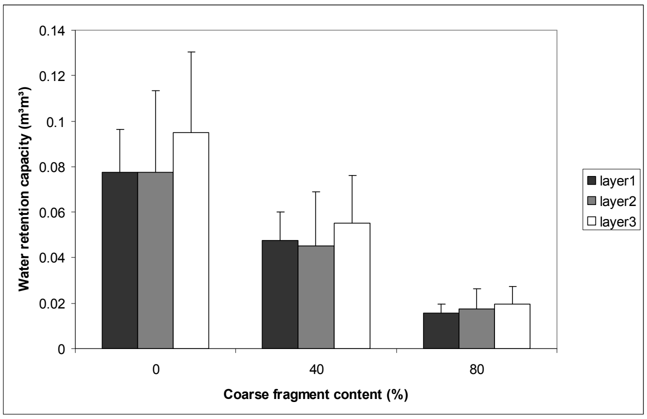
Gaiser et al. (2010a) set a value of FBM to 0.01, which is more realistic for West African savanna soils instead of the default value of 0.04 that is more representative for soils with high organic matter content (Niu et al., 2009). The recommended value of 0.01 was therefore, used for all sites. In addition, the fraction of humus in the passive pool expresses the proportion of carbon (and nitrogen) in the soil organic matter pool that has a low turnover rate. It was set to 0.99 making less nitrogen available to the plant, thus generating more response of the crop to additional nitrogen supply.

More sensitivity of yield to P fertilizer application in the model was found when initial labile phosphorus concentration in the first layer (0 – 15 cm) for the acid Ultisol was set to a value of 0.05 ppm. Labile phosphorus (CSP) is considered to correlate with P uptake (Sharpley, 1985). The labile P concentration factor allows optimum uptake rates when CSP was above 20 ppm which was the default value used as critical labile P concentrations for a range of crops and soils.

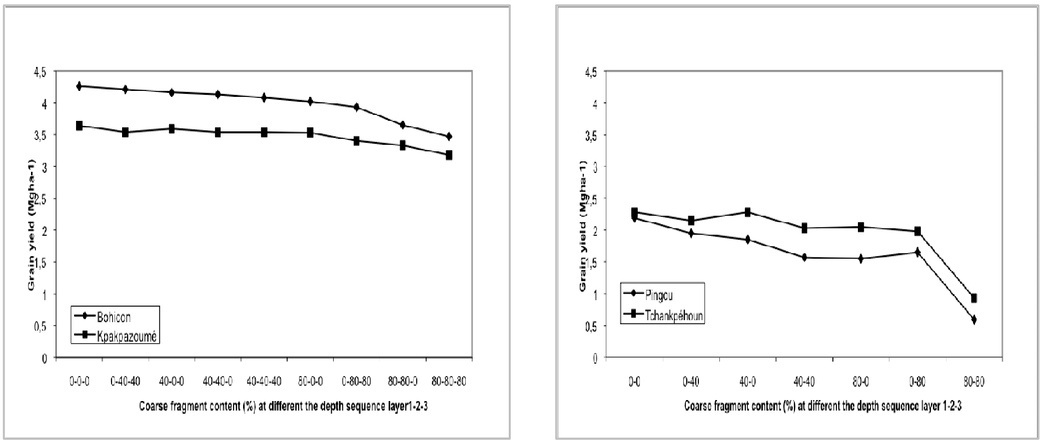
The soils in Ikenne are classified by USDA as Typic Haplustult (Chromic Ultisols, FAO classification). They are considered to be low in CEC and bases due to the translocation of the clay to the subsoil and high leaching. They present a high P sorption to Fe- and Al-hydroxides in the subsoil (Mokwunye, 1979) or kaolinite in the clay fraction (Wisawapipat et al., 2009). Daroub et al. (2002) in developing a soil-plant P model for highly weathered soils recorded for maize an overestimation of the P uptake by the model. Apparently, their model was not able to reproduce P fixation which is much higher than in less-acid soils found in temperate climates.

The analysis of rainfed upland system refers also to the evaluation of the water availability which depends on soil texture. The coarse fragments (CF) influence soil physical hydraulic properties. In EPIC model, the role of this parameter addresses directly to the water erosion engine but it has soil functioning oriented for estimation of water retention capacity at the same stand as the bulk density. In fact, Chow et al. (1997) observed that by incorporating 10 to 30% CF into the plough layer of the Northern American Podsol, it increased significantly the soil bulk density and this increase reduced the porosity and soil water retention capacity. In our study, the sensitivity analysis of CF was done at 4 sites where substantial CF was identified in soil profile to show the influence of this parameter on grain yield.

Figure 5.3 shows at 2 to 3 soil layers across 4 sites (Bohicon, Kpakpazoumé, Pingou and Tchankpéhoun), variation in CF ranged from 0 to 80%. It appeared that a strong influence of CF was obtained when all the layers were concerned by the limitation in water storage capacity and grain yield showed the higher sensitivity to CF at the upper layers.



(a)



(b)

Figure 5.3: Sensitivity analysis of coarse fragment content on: (a) mean water retention capacity of the soil layers at Bohicon, Pingou, Tchankpéhoun and Kpakpazoumé (b) grain yield depending on the variations of coarse fragment content at different soil layers (Bohicon: layer1=0-15cm, layer2=15-33cm, layer3 =33-76 cm; Kpakpazoumé: layer1=0-20cm, layer2=20-50cm, layer3=50-67 cm; Pingou : layer1=0-20cm, layer2=20-40cm; Tchankpéhoun: layer1=0-14cm, layer2=14-30cm).

5.3.3. Calibration results for total aboveground biomass and grain yield

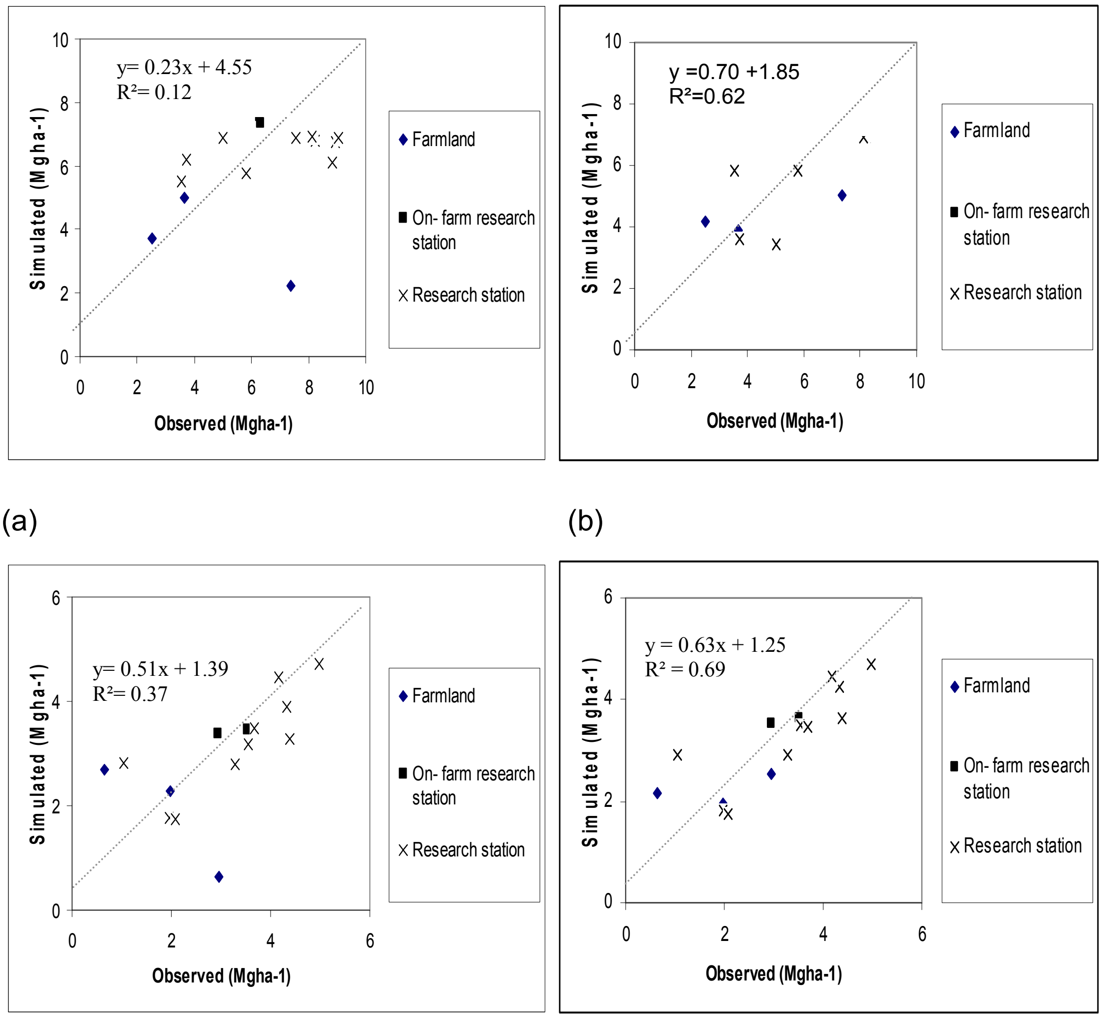
Figure 5.2 shows that the model reflects after calibration, the effect of N and P application on NERICA yield on Ultisols when P and N are limiting. This is in accordance with Nigerian humid forest agroecosystems where high split application of 90 to 120 kg N ha^{-1} has been recommended for e rice cultivars to optimize yields (Enwezor et al., 1989). The model results showed that 7 out of 8 treatments did not significantly differ from the observed yield of NERICA.

The P stress has been simulated adequately to allow the expression of nitrogen stress among the treatments with application and without application of P. By simulating adequately the processes in P deficient soils, the model agrees with the results of Sahrawat et al. (1995), suggesting that P fertilization of acid-tolerant upland rice cultivars can significantly improve the productivity of Ultisols.

Table 5.6: Mean simulated and observed rice LAI (m²m²), total above ground biomass (TAB), grain yields in $Mgha^{-1}$ as well as mean error (ME in $Mgha^{-1}$), mean relative error (MRE), mean absolute error (MAE), model efficiency (EF) and mean root square error (RSME) before and after model calibration over 6 sites.

Sites	n	Obs.	Sim.	ME	MRE	MAE	EF	RMSE
Before calibration								
LAI (m²m²)	4	2.38	1.48	-0.89	-0.28	0.90	0.37	50.84
TAB($Mgha^{-1}$)	15	6.33	6.04	-0.30	0.04	1.55	0.09	30.15
GY($Mgha^{-1}$)	15	3.03	2.97	-0.06	0.23	0.71	0.32	33.13
After calibration								
LAI (m²m²)	4	2.38	2.44	0.06	0.06	0.14	0.98	8.39
TAB($Mgha^{-1}$)	15	6.33	6.33	0.00	0.05	1.55	0.61	21.10
GY($Mgha^{-1}$)	15	3.03	3.15	0.11	0.24	0.47	0.67	23.01

Before the calibration and across all five sites, grain yield and total aboveground plant biomass had an RMSE of more than 30% (Table 5.6). Farmland fields contributed most to overestimation of the model by a magnitude of 88% on average for the 2 years (Fig. 5.4). For the calibration at Tchankpéhoun, the plant density was reduced from the theoretical plant population to the measured plant density at maturity. During the two seasons, many hills were missing thus reducing the total yield observed. Affholder (2001) pointed out that a model developed in high input environment such as the US where the planting density is very homogeneous need numerous modifications to be applied under the conditions of West Africa where high variability of plant densities at sowing is a big factor influencing variability in productivity. Oikeh et al. (2009) didn’t show relationship between the grain yield and NERICA plant density, whereas density effects appeared only for tiller and panicle densities. In the study of Oikeh et al. (2009), the seasonal differences in rainfall distribution and moisture availability might have reduced the simple effects of N and spacing (plant density) on NERICA grain yield. In our study, Tchankpéhoun got adequate monomodal rainfall supply for the two years.



(a) (b)

(c) (d)

Figure 5.4: Scatter plot between observed and simulated total above ground biomass before (a) and after the calibration (b), grain yield before (c) and after calibration (d).

After calibration, the goodness of fit of the model was improved for both total aboveground biomass and the grain yield (Fig. 5.4). We obtained lower RMSE after calibration, indicating that a higher fraction of the measured variations were accounted for by the model (Table 5.6).

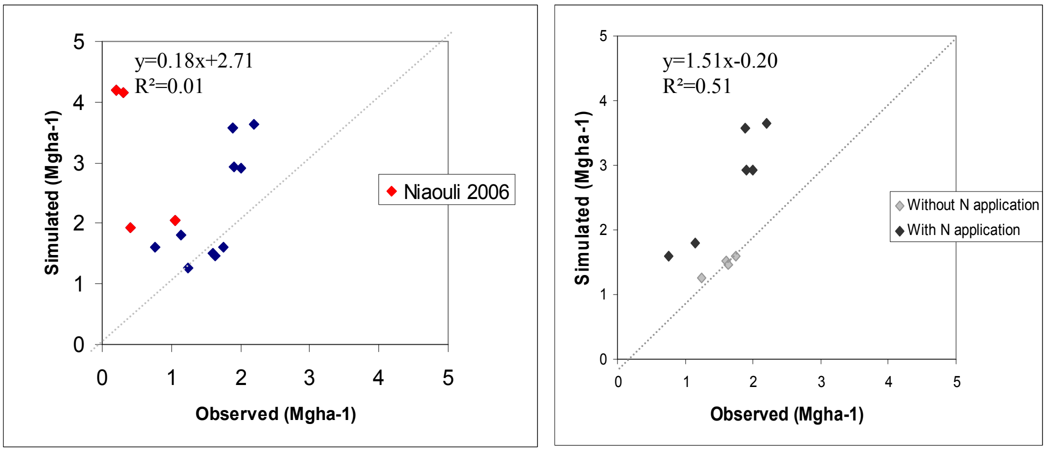
5.3.4. Model validation

The calibration of the EPIC model for upland rice was focused on nitrogen and phosphorus as main constraints to crop growth. The validation was carried out on 3 sites (Niaouli, Bohicon and Pingou) over 2 seasons. At Niaouli the experiment focused on different levels of N and P inputs, at Bohicon NPK application was tested, and Pingou was an on-farm field experiment (Table 5.3).

Table 5.7: Validation of the EPIC model with respect to yield of rice in Mgha^{-1}. Obs. is observed and sim. is simulated value, n is the number of pair of observed and simulated grain yield, a is the regression slope. The mean error (ME in Mgha^{-1}), mean relative error (MRE), mean absolute error (MAE) and mean root square error (RSME) are calculated over 3 sites.

	Grain yield (Mgha^{-1})					
N	Obs.	Sim.	ME	MRE	MAE	RMSE (%)
14	1.3	2.5	1.2	3.0	1.2	116.30

The validation of the model showed a relatively high gap between averages simulated (2.5 Mg ha^{-1}) and observed yield (1.3 Mg ha^{-1}). The mean error was 1.2 Mg ha^{-1} whereas the mean relative error was 3.0 which showed a very large overestimation of the simulated yields at plot level. The variation of the individual plots was also quite high resulting in root mean square error of 116.30%. The observed mean grain yield was lower than the average in the calibration, suggesting various stress effects. Indeed some causes of rice failure have been attributed to floods and drought for NERICA evaluated at five locations with similar pedoclimatic conditions as those in experiments in Benin Republic (JAICAF, 2007). Therefore, before the use of the model to assess the impacts of and adaptations to climate variability and climate change in spatial studies, there is need for improvement in the amount and quality of available data collection.



(a) (b)

Figure 5.5 : Scatter plots for NERICA validation, (a) represents model validation for all plots, (b) refers to plot without the particular year Niaouli 2006.

A scattered plot of the observed and simulated values of sites used for model validation presented in Table 5.5, showed that the average yield in plots used for validation was relatively low. This was due to crop failure in 2006 in Niaouli where the average yield was below 1 Mg ha^{-1} leading to the model overestimation. In fact, the experimental design was originally set up to evaluate the tolerance of NERICA varieties to drought with nutrients application. Niaouli is located in the sub humid zone with bimodal rainfall pattern. The mid season rainfall pattern associated with the sandy topsoil texture induced severe drought stress. The soil type "*terre de barre*" was described by Azontonde (1991) as soil with good physical hydraulic characteristics but with low water storage and their structure can be rapidly destroyed when there is no proper technique for maintaining organic matter.

The sensitivity of NERICA varieties to water stress is well documented. Akinbile et al. (2007) showed that with NERICAs, yield decreased under optimal satisfactory conditions almost linearly with evapotranspiration, thus indicating that water application remained the dominant factor at all the stages of production. In EPIC model, the potential harvest index (HI) was adjusted daily according to water stress suffered by the crop (Williams, 1995). During the calibration, the sensitivity of the model was increased by setting the water stress impact (WSYF parameter) which allowed harvest index to drop to 0.01 in case of severe drought. The effect of water stress could only be limited to HI reduction. Fuji et al. (2004) reported that some NERICA lines showed high dry matter production under drought condition among other rice cultivars and this have been correlated with stomata conductance (R=0.63**). However, an intensive rain of short duration followed by long dry spells which occurred during the flowering period, led to increase in sterility and decrease in grain weight (Xue et al., 2008, O´Toole and Moya, 1981). De Barros et al. (2004) observed a slight overestimation of grain yield by the EPIC simulations and attributed this to high rates of floral abortion caused by the dry spells during the flowering periods because this factor was not considered in the model.

After removing the plots with crop failure induced by the drought in 2006 in Niaouli, the goodness of the fit of the model improved from 0.01 to 0.51. Table 5.8 lists the simulation results for the remaining plots. Pingou also had yield below 1 Mg ha^{-1} in 2010 which was lower than the preceding year. In this year, a shallow groundwater was observed during the wet season at sowing (end of July) which was followed by transplanting. Therefore, the first possibility for the model overestimation was that the model could not consider transplanting shock that caused a delay in phenological development resulting in reduced vegetative period in the field. However, there are no reported analyses on the negative impact of flooding on upland NERICA. In contrast, high developmental plasticity of NERICA1 to recovery from short and intense moisture stress at the seedling emergence stage had been reported by Fofana (2008), and also midseason drought escape under low N was reported by Oikeh et al. (2008). .

Table 5.8: Validation data results without Niaouli 2006, with reference to fertilizer treatment, year and observed grain yield, + symbol refers to presence and - the absence of fertilizer input.

Year	Site	Treatment (fertilizer)		Grain yield (Mgha^{-1})	
		N	P	Observed	Simulated
2007	Bohicon	-	-	1.64	1.49
2008	Bohicon	-	-	1.24	1.36
2007	Bohicon	+	+	2.20	3.74
2008	Bohicon	+	+	1.88	3.67
2009	Pingou	+	+	1.14	1.80
2010	Pingou	+	+	0.73	1.60
2005	Niaouli	-	-	1.60	1.51
2005	Niaouli	-	+	1.75	1.60
2005	Niaouli	+	-	1.90	2.62
2005	Niaouli	+	+	2.00	2.92

The presence of ferric cuirasses in Pingou might have resulted in low saturated conductivity at the mid-soil depth, thus increasing the submergence and runoff risk. The relatively high soil moisture might have caused the low yield because sowing was done only by direct seeding in 2009. Indeed Ogunremi at al (1986) demonstrated direct-seeded rice was adversely affected by the transient flooding conditions during the seedling stage on Ultilisol in Southern Nigeria. The grain yield obtained decreased with increasing penetrometer resistance.The tendency of overestimation of yield response to fertilizer was observed in Bohicon and Niaouli (Figure 5.5). Even at Niaouli in 2005, where the experiment received relatively high amount of NP (100kg ha^{-1}), the observed yield was lower than the modelled yield.

Under limiting water conditions, there could be less capacity of the crop to continue taking up water which could probably reduce transport to the roots through mass flow. Undeniably, some traits of upland rice (japonica type) related to less adventitious roots per hill result in relatively weak ability in N uptake (Zhang, 2008). In addition, a severe drought that occurred just after the application of the first split of N could have induced urea loss resulting from the lack of N dissolution, thus reducing grain yield (Oikeh et al., 2008).

6. General discussion

6.1. Rice productivity in rainfed lowland and upland systems

In the present study, grain yield and total aboveground biomass of rice were assessed in West African production systems under different ecological conditions. The average grain yield in inland valley experiment with lowland rice variety was higher compared to the average of grain yield obtained in upland experiments (4 $Mgha^{-1}$ vs. 2 $Mgha^{-1}$) using at both sides moderate fertilizer application. The impact of land management was investigated in both systems. It was shown for the inland valley system, that grain yield responded to bund through water level fluctuation, fertilizer application, N and Fe availability at two slope positions, while in the upland system, soil fertility as related to organic carbon contents and rainfall were decisive for the increase of grain yield. In chapter 4, the upland system was evaluated by a simple correlation model analyzing the potential effect of environmental factors, but without taking into account soil variability. In this chapter, I will discuss the potential effects of e.g. fallow residue management and cropping as they varied between farms.

6.1.1. Relationship between water level, soil parameters, N and Fe uptake by the plant in inland valley system

With the first experiment in this thesis (Chapter 2), the spatio-temporal variability of the total aboveground biomass and grain yield was assessed for lowland rice cropped in an inland valley. A large variability was observed with regard to soil characteristics among plots and with variables such as Fe and N uptake, water level, total dry matter and grain yield over 4 years. A multi- regression analysis using stepwise elimination of factors with lower effect was run and allowed to limit the effect of heterogeneity of soil characteristics to soil carbon content and CEC (Table 6.1). The study showed that differences in yield response to landscape and management are due to the interaction of water level, Fe and N uptake by rice. In the upslope position, the grain yield was negatively correlated with the Fe concentration (in leaves) whereas downslope its correlation with leaf N content, CEC and soil organic carbon was positive.

Table 6.1: Pearson **c**orrelation coefficient between yield, nutrients and water level in the first month for NERICAL-26 grown under 2 toposequence positions.

	LWM1	Fe	N-Uptake	CEC	Corg	Grain (Mgha^{-1})
			Downslope			
N in plant (%)	0.32**	-0.64**	0.65**	0.14	0.09	0.30*
LWM1 (cm)		-0.13	0.17	0.09	-0.00	0.54**
Fe concentration (ppm)			-0.55**	0.00	-0.01	0.07
N-Uptake (kgha^{-1})				0.15	0.03	0.18
CEC (cmol kg^{-1})					0.74**	0.36**
Corg (%)						0.31*
			Upslope			
Nplant (%)	0.21	-0.14	0.41**	-0.07	-0.04	0.20
LWM1 (cm)		0.29*	-0.11	0.19	0.19	0.06
Fe concentration (ppm)			-0.47**	-0.03	-0.15	-0.37**
N-Uptake (kgha^{-1})				-0.01	0.14	0.49**
CEC (cmol kg^{-1})					0.88**	0.07
Corg (%)						0.20

Data for the 4 years were combined for calculation of the coefficient. Level of significance: significance at *$p<0.05$, **$p<0.01$. LWM1: Ponded water level at first month of growing period (cm), C$_{org}$: organic carbon (%), Nplant: N content in plant at 38 DAS (%).

Additional visual score was made in 2007 and showed the symptoms of Fe toxicity such as bronzing on some leaves at vegetative phase. Inland valley swamps are known to provide the soil and water conditions to develop iron toxicity in rice (Virmani 1979). Becker and Asch (2005) reported that in inland valleys with low clay content, symptoms usually occur very early in the rice plant's development and are associated with the onset of interflow from the slopes. In upslope, a significant relationship was observed between the water level and Fe concentration in leaves at 30 to 38 DAS. Audebert (2005) confirmed the effect of the redox potential and oxygen content on the incidence of iron toxicity while pH has a normal value for rice farming that does not contribute to the processing of ferric ion into ferrous ion, which is easily absorbable by the plant but toxic at high concentration. Fe toxicity may produce yield losses of 43 % over 42 varieties. It affects growth and development such as height, number of tillers per m² and number of panicles per m².

In both positions, the N uptake of rice a 38 DAS was also negatively affected by iron toxicity. According to Inthapanya et al. (2000) the occurrence of iron toxicity in plots with fertilizer created a nutrient disorder limiting the response to fertilizer application. However, on our site in the upslope position and plots with bund, the fertilizer in all the recorded years was limiting the Fe uptake by rice. Previous studies provided further evidence that the application of P, K and Zn in conjunction with N is an effective way of reducing iron toxicity (Sahrawat et al., 1996, Yamauchi, 1989; Yoshida, 1981). The application of nutrients such as P, Zn and K strengthens the rice plant, “dilutes” toxic Fe^{2+} via enhanced biomass growth, and especially bivalent cations may also act as competing ions. Some authors suggest that P could enhance oxidizing potential of the rhizosphere decreasing the availability of ferrous iron (van Breemen & Moorman, 1978).

Indeed on toxic field, Diatta and Audebert (2005) observed that N alone may contribute to enhance the productivity only slightly from 4.47 $Mgha^{-1}$ to 4.59 $Mgha^{-1}$, but in combination with P the yield was enhanced up to 6.7 $Mgha^{-1}$.

In downslope plots, a relationship among standing water in the first month, plant N concentration and grain yield was demonstrated by correlation analysis. However, Fe concentration affected grain yield negatively only in upslope plots. The application of 60kg of N was most likely not sufficient to counteract the negative effects of Fe^{2+} on N uptake in upslope plots, whereas in the downslope plots higher soil N content may have provided more mineral N by mineralization from organic N. Thus, the N supply in downslope plots was sufficient to counteract the negative effect of high Fe concentrations. The contribution of the other macronutrients such as P and K should be investigated later on.

6.1.2. Relationship between grain yield, soil fertility (Corg) and crop intensity in upland systems

In chapter 4 the response of improved upland rice varieties grown under different agroecological conditions of low-input agriculture in West Africa was shown. Yield turned out to be related to soil organic carbon and clay contents as well as seasonal rainfall. In addition, management of residues and cropping sequences prior to the experiments were varied between farmers and was supposed to be a controlling factor. In some plots, rice residues were left on the field during the fallow period (Table 4.1). Information of crop intensification was given for 76 sites and allowed to score the crop sequence from 0 to 8, where 0 corresponds to less intensified system, 8 represents highest intensification with consecutive 3 years of rice cropping before the starting of the experiment.

Table 6.2: Correlation coefficients between cropping intensity and grain yield, crop residues and organic carbon at 0-20 cm (76 plots were considered). (* = correlation coefficients are significantly different at $p<0.05$).

	Grain yield ($Mgha^{-1}$)	C_{org} (%)	Crop intensity	Residues
Residues	0.12	-0.10	0.06	1
Crop intensity	0.04	0.30*	1	
C_{org}	0.51*	1		
Grain yield	1			

Table 6.2 shows correlations between cropping intensity, grain yield, Corg content and residue application during the fallow period. Crop intensity did not appear to be significantly correlated with grain yield. However rice yield was slightly higher in the field following 3 consecutive years for rice cropping than in the year after fallow. In the cropping pattern in both Atacora and Collines region, Saidou et al. (2004) found that the cereals may benefit from the residual effect of fertilizer applied to the previous crop.

A positive relationship was also observed between soil organic C and crop intensification which is in contrast with results from Becker and Johnson (2001) who showed that the soil N supplying capacity was lowest in the bimodal Guinean savanna zone and declined with crop intensification (-26% in average across sites). But Igué (2006) reported after 6 years of rice cultivation in Gankpétin (one of the sites covered by the study) an increment of soil organic matter content from 1.23% to 3.15%. Nitrogen, phosphorus and potassium availability changed positively as well. Indeed, rice shavings amendment was found in Ultisols not to generate significant differences in the pH whereas it has been shown to increase organic matter and nitrogen concentration during 2 years (Mbagwu et al., 1992). The use of crop residues may have contributed to the maintenance of soil fertility but apparently not in our case.

6.2. Modelling the rainfed lowland and upland with EPIC

6.2.1. Simulation outputs

LOWLAND SYSTEM

As the exploitation of lowland inland valleys for rice production requires improved understanding of the effect of management practices on soil water and nutrient dynamics on rice yield, the crop model EPIC (Environmental Policy Integrated Climate) was applied to the upslope of inland valley situated at Dogué in order to capture processes involved in crop growth and yield in temporarily inundated rice fields and assess the suitability of the model for this specific agroecosystem (Chapter 3).

From the observations above, we derived input values for soil and growth parameters required for the modelling of rice growth and development. At first we described soil moisture conditions based on experimental treatments of water control and fertilizer application. The calibration of the model EPIC0509 was made with a dataset of 4 years of rice-fallow succession in savannah inland valley. The exercise was carried out for five (5) model outputs: soil water content, ponded water level, LAI and aboveground biomass development, as well as grain yield.

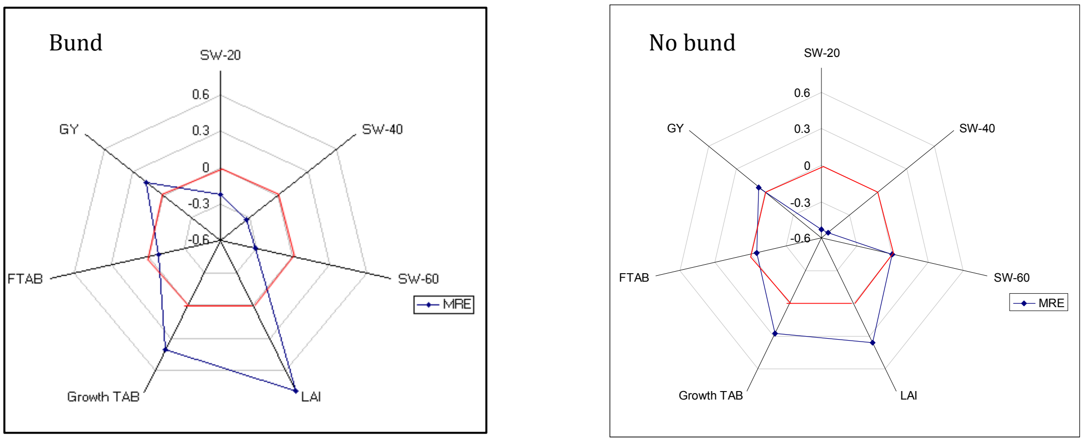


Figure 6.1: MRE summary for no bund plots. SW is soil water content at 20, 40, 60 depths, LAI leaf area index, GY grain yield, FTAB Final Total Aboveground Biomass, growth TAB : Total Aboveground Biomass at different growth stages. Note that the optimal MRE value is 0 (red line) and positive and negative deviations from 0 indicate an overestimation or underestimation, respectively, by the model.

The model simulations were presented for MRE in the plots with and without bund for simulated variables (Figure 6.1). The optimal MRE value is 0 and positive sign show an overestimation by the model. The ponded water level was not included in the evaluation because of the null value in the observations. In the no bund plots, the model simulations represented best the final biomass followed by the grain yield. The soil water content in topsoil and LAI had the highest MRE values in absolute terms in no bund and bund plots respectively. In no bund condition, this is due to the differences between simulated and observed soil water content before and after the growing cycle. In addition, the model must be improved through integration of 2 D water flows.

In plots with bund, the bias was higher for grain yield and LAI in 2010. It has been shown that the model poorly represents crop productivity in bund condition due to the occurrence of iron toxicity. However, the simulation of soil water matches the observations with bund.

UPLAND SYSTEM

From the data derived from the upland experiments, the EPIC model was calibrated and parameterized in a multisite evaluation, which is particularly important for rice production because of its high dependency on nutrients and water (Chapter 5). The results showed the accuracy of the model to simulate LAI, total above ground biomass and grain yield. In the model validation the variation of simulations for individual plots was higher than the observed variation. Large root mean square RMSE for validation (>100) suggested that robustness of the model became restricted under severe drought conditions where the rice response to N fertilizer was less pronounced.

6.2.2. Importance and limitation of the EPIC model simulations with respect to influence of water and N balance on grain yield in rainfed rice system

6.2.2.1. Water budget and relationship with grain yield

LOWLAND SYSTEM

From 2007-2010, the water-nitrogen budgets simulated by the EPIC model on a control plot (without fertilizer) are presented in Table 6.3. For the water balance, it is observed that ET and runoff processes were most important for water losses. Raes et al. (2007) formulated the sensitivity of rice grown in bund condition to water stress with relative evapotranspiration. From the waterbalance simulated by the model in Table 6.3, it can be reported that the model estimated 2066 mm of evapotranspiration, which is equivalent to the mean rate of 5.66 mm/day. This value is within the range of wetlands in subtropical and tropical zones, similar cases were recorded in rice fields (Tomar and O´Toole, 1980).

The bund contributed to reduce the runoff from 430 mm to 198 mm and percolation from 42 mm to 23 mm. Eventually, the process of percolation and runoff in no bund plots should be increased when water accumulates after reaching the saturation point. In the simulations the model showed in 3 of 4 years water stress at some days (Table 6.3). Examination of the water balance showed the highest water stress in 2007, but this could be a consequence of the underestimation of soil water found in the calibration process. The estimation of runoff in 2010 was increased by the high rain intensity but seems not to have effect on water stress.

Table 6.3: Water balance and N-loss generated in plots without fertilizer by EPIC model using climate and soil data in Dogué Research field. ET evapotranspiration, Q amount of water in runoff (Q), in subsurface flow (SSF), percolation(PRK), amount of N loss in eroded sediment (YON), runoff (QNO3), SSFN (subsurface flow), denitrification (DN), volatilization (AVOL) and number of stress days (NS : nitrogen stress, WS: water stress, PS: phosphorus stress, TS: temperature stress).

Treatment	*Year*	*Water balance (mm)*					*N-loss (kgha^{-1})*									
		Rain	ET	Q	SSF	PRK	YON	QNO3	SSFN	PRKN	DN	AVOL	WS	NS	PS	TS
No bund																
	2007	1126	1873	91	5.7	50.0	1.7	1.6	0.6	27.4	8.6	18.4	25	3	0	0
	2008	1255	2473	477	7.1	53.1	17.6	5.2	0.8	12.9	6.6	22.9	0	3	0	0
	2009	1237	2147	399	7.5	36.1	5.0	3.7	0.8	9.1	7.6	20.7	8	4	0	0
	2010	1400	1771	756	4.3	30.2	12.2	7.0	0.4	3.7	3.2	18.1	7	3	0	0
	Mean	**1255**	2066	430.75	6.1	42.4	9.1	4.4	0.70	13.3	6.5	20.0	10	3	0	0
Bund																
	2007	1126	1873	79	4.7	17.5	1.0	0.7	0.7	19.0	15.9	23.0	19	0	0	1
	2008	1255	2475	79	5.8	16.3	12.0	0.7	0.8	16.8	10.9	26.1	0	0	0	1
	2009	1237	2147	44	7.5	49.5	0.8	0.3	1.6	16.9	15.2	26.6	5	0	0	1
	2010	1400	1771	592	4.7	8.7	29.7	8.2	0.6	4.3	11.6	22.6	6	0	0	1
	Mean	**1255**	2066	198.50	5.7	23.0	10.9	2.5	0.9	14.3	13.4	24.6	8	0	0	1

UPLAND SYSTEM

EPIC estimates water retention capacity from soil texture information particularly when input such as water content at field–capacity, wilting–point and soil saturated conductivity are missed. In Niaouli, Fig. 6.2 shows the relatively good agreement of the model estimation for water retention capacity at the Niaouli site. This low water retention capacity throughout different soil layers effectively allowed conditions for water stress experiment.

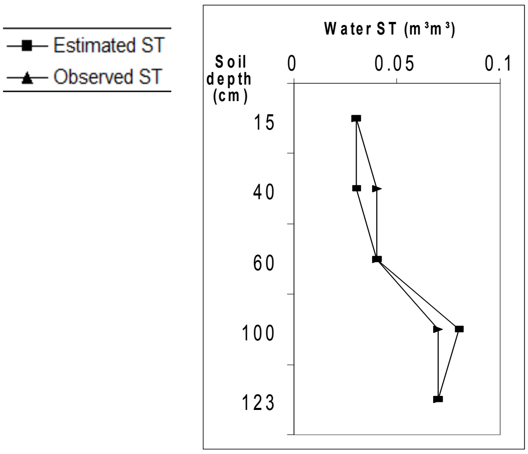


Figure 6.2: Estimation by the model compared to the measured water retention capacity at Niaouli site in the rooting zone.

However, the sensitivity analysis of the model has also shown that the coarse fragment content had a more or less high influence on the water retention capacity of soil layers. In four out of eight sites, the model was parameterized for the coarse fragment content (CF) limiting water retention capacity in different layers. A modified CF was needed for the site of Bohicon. The results of the final calibration are shown in Fig. 6.3. Indeed, the model estimation of water retention capacity required an adaptation in CF and this adaptation reduced the yield gap between observed and simulated values from 1.60 $Mgha^{-1}$ to 0.74 $Mgha^{-1}$ on the average. As a consequence, when simulating rainfed rice in uplands it appears to be a prerequisite to provide detailed site-specific soil input parameters including water retention capacity among the soil physical characteristics.

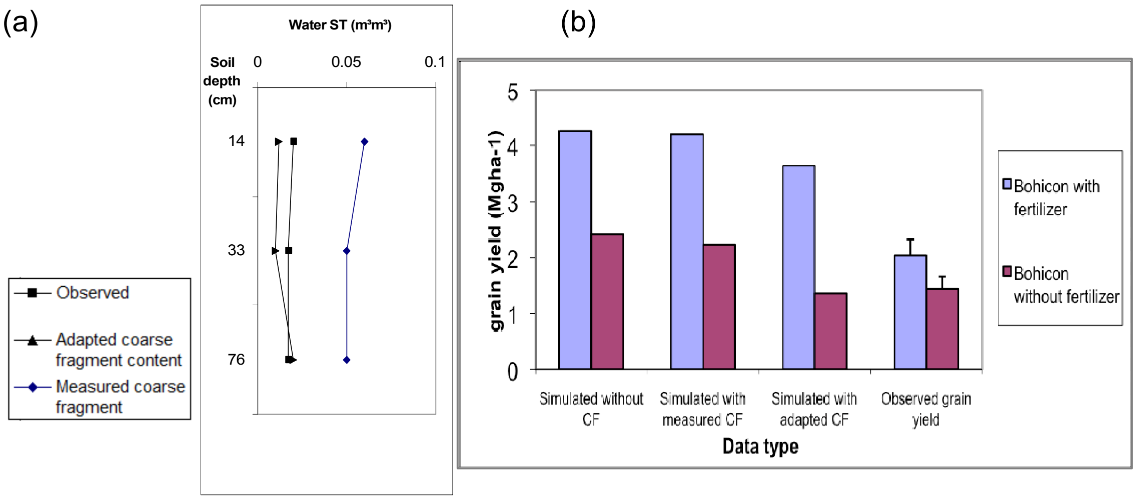


Figure 6.3: (a) Comparison between estimated and measured water retention after adjustment of coarse fragment content at Bohicon (b) effect of coarse fragment (CF) on grain yield simulation and comparison with observed grain yield in Bohicon.

6.2.2.2. Nutrient budget

IN LOWLAND SYSTEM

N loss during 2007 to 2010 of runoff almost doubled from bund to without bund with higher amounts of QNO3 (Table 6.3). Excessive soil water may limit the availability of fertilizer N by increasing the risk of loss through surface runoff and percolation (Brown and Rosenberg, 1997). The risk of N loss was estimated to range between 10 to 60 % under moist conditions (Mengel, 1985), caused by the denitrifying bacterial activity in alternatively saturated and non-saturated conditions and by leaching. In fact, Antonopoulos (2010) confirmed that in addition to leaching to groundwater, surface and subsurface runoff are significant processes of nitrogen loss from the soil system in irrigated rice flied in Greece. Gaseous losses of nitrogen (via volatilization) and denitrification being higher under condition with bund, were also substantial processes reducing nitrogen availability in the flooded compartment (AVOL and DN in Table 6.3). The nitrogen balance model used on irrigated flooded fields in southern Greece produced an average of N leaching loss of 13%. The denitrification of NO_3-N and volatilization of NH_4-N accounted for 30 % with a total N loss of 282.7kg ha^{-1} (Antonopoulos, 2010). In this lowland rice system, volatilization was estimated by EPIC to 20 Kg ha^{-1} and denitrification accounted for 10 kg ha^{-1} over a total N-loss of

60 kg ha^{-1}. The experiment in Greece was implemented with higher nitrogen input (fertilizer at 150kg ha^{-1} N in irrigation water). It can be assumed that the lowland experiment in Dogué presented lower overall depletion of N than the irrigated field in Greece even though the share of volatilization and denitrification remained similar.
The model evaluation showed that nitrogen stress seems not to be critical for the development of crop production in the presence of bund. A higher nitrogen uptake is expected in the plots with bund (Touré et al. 2010). The authors found that bunding improved the agronomic N use efficiency with an increase of rice yield of up to 40%. In the previous chapter it had been shown that the N content in plants was higher for all years in the plots with bund in upslope, being significant in 2008 and 2009. The use of relatively short-term experiments to calibrate the model shows the complexity of factors controlling the growth of plant and grain yield in lowland systems. Based on this complexity, the validation of the model remains essential for refining processes in the rhizosphere and their effects on biomass growth of rice plants under alternately flooded conditions.

IN UPLAND SYSTEM

The model was well calibrated to simulate observed crop responses to NP fertilization. However, model validation results show some overestimation of grain yield with fertilizer application. One reason might be that micronutrient availability has not been adequately addressed in the model. Several experiments conducted on highly weathered soils in Africa showed that when sufficient N and P are applied to maize, micronutrient deficiencies may appear (Gaiser et al., 1999). Voortman et al. (2000) estimated micronutrients deficiencies on about 60% of the cropland in sub-Saharan Africa. This confirms the need to consider the introduction of routines with micronutrient availability in crop models.

The general use of the model for rainfed rice production at a large scale requires identification of areas with iron toxicity, risk of drought and flooding. It should be improved to consider the impact of iron toxicity and drought on rainfed rice.

Conclusion at a glance

Conclusion at a glance

In order to assess different rainfed rice systems in West Africa by examining land position, fertilizer application, bund function, rainfall and soil characteristics, two types of analyse were performed: an empirical analysis and crop modelling. From the results, the following conclusions can be drawn:

- In upland rice, the rice grain yield was on average lower than in the lowland system, estimated at 2 Mgha^{-1} vs. 4 Mgha^{-1} with a moderate fertilizer input.

- Constraints for rice production vary under both ecological conditions:

    - In upland systems, conserving existing soil organic matter and proper management of water supply (irrigation, bund building or drainage) can to be useful for improving rice productivity.

    - In inland valleys with lowland rice, temporal and spatial variation of water ponding is seen as the key driver that determines the impact of factors such as Fe toxicity, N uptake by the plant and N loss through runoff at different topographic positions. Fe concentration in leaves was negatively correlated with the grain yield only in upslope condition and positively with the water level increase induced by bund.

- With a multi-year calibration, 2 versions of the EPIC model 0509 and 3060 were able to simulate multiple variables such as leaf area index, grain yield, plant total aboveground biomass and soil humidity conditions under fertilizer, bund and irrigation application with acceptable accuracy at field scale for both upland and lowland systems. Application of the model in each system requires specific inputs.

    - In upland systems, relevant soil parameters for calibration are different pools of nitrogen and phosphorus in the soil and coarse fragment content limiting soil water retention capacity.
    - In inland valleys, soil water retention and water table are the principal characteristic inputs for hydraulic dynamics in bund and no bund treatments.

- Generally, the model constantly overestimated rice productivity. To reduce the bias in predicting crop production, modeling the rainfed rice should consider:
    - an upgrade for simulation with bund and without fertilizer application by including an iron toxicity model routine in inland valley systems. It should also provide a routine for the effects of micronutrients on grain yield;
    - more input data with a better quality for the estimation of drought spell impact on grain yield;
    - better representation of the impact of drought periods on the reduction of harvest index and how it is linked to floral abortion; fertilizer responsiveness under severe drought condition needs to be assessed, too.

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List of figures

List of tables