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- Department of Plant Nutrition –

Rice yield gaps in West Africa

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Dedication

Ce travail est dédié:

A la mémoire de feue ma très chère maman Absa Samb arrachée à notre affection un an après l'entame de ce projet et à feu mon papa Abdou Niang parti plus tôt

A la mémoire de feu mon oncle Laba Samb qui a pris le relais de mon éducation dès l'âge de 10 ans et qui a largement contribué à ma réussite scolaire

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Summary

Rice is a staple food for many countries in Africa but the production has never satisfied the demand which largely depends on imports. Therefore, more efforts are needed for raising yield in order to reduce the gap between potential and actual farmers' yields. To increase yield, improved management options are to be considered. Thus, this thesis has estimated the range of yields and yield gaps at three rice production systems in West Africa across climatic zones, the affecting factors and has explored management options to reduce the gap between potential and actual farmers' yield. Field surveys were carried out between 2012-2014 in 22 sites located in eleven West African countries covering the main production systems and the main climatic zones. Management practices were recorded through interview, crop status from field observations and yield recorded at harvest. In central Benin, Nitrogen use efficiency was estimated at different field water status using experimental and farmer's practices' fields. Finally yield gain was estimated after implementation of GAP in selected farmers' fields. Boundary function was used to estimate attainable yield. Random forest evaluated the importance of variables explaining yield and yield gap variability.

Average yield was 4.1, 2.0, and 1.5 t/ha in irrigated lowland, rainfed lowland, and rainfed upland rice production systems, respectively, with maximum attainable yields of 8.3, 6.5, and 4.0 t/ha. The factors affecting yields were specific to each production system. Yield gaps between potential/water limited yields and actual farmers' yields ranged from 1.1 to 10.2 t/ha and from 3.5 to 10.3 t/ha in irrigated and rainfed systems, respectively. Farmers' yield was 27-51% of potential yield at optimum sowing date in irrigated system, and 17-22% of water limited yield at optimum sowing date in rainfed systems. In irrigated system, 34% of the yield gap was attributed to weeds, N fertilizer application rate and crop establishment methods. In rainfed systems, 30% of this gap was explained by rice variety, field hydrology and weed infestation at maturity stage. The implementation of GAPs in farmers' fields reduced the average yield gaps between 13 and 25% in irrigated system and between 20 and 42% in rainfed lowland system.

These results suggest that there is a large scope for increasing rice yield in West Africa. There is a need for site-specific decision support guide including targeted GAPs for an efficient use of the available farmers' resources.

Chapter 1 : **General introduction**

1. Background

Rice is one of the major staple crops for many countries in Africa (Becker and Johnson, 1999b). However rice consumption in Africa depends largely on imports. Seck *et al.* (2013) reported that African rice imports accounted for 32% of the rice word trade in 2008. To reduce rice importation and meet growing demand (6 % annually) due to increasing population of about 2.9 % per year (Population, 2015), rice production in Africa has to be increased. While rice production has steadily increased since the 1970s mainly due to expansion of cultivated area, it has never satisfied demand. In1980's, area expansion contributed to 96% of increase in rice production while yield increase contributed only to 6 % (Seck *et al.*, 2013). Although area expansion is still possible in many parts of Africa, more efforts are needed on intensification as current yield level is quite low (Becker and Johnson, 1999b) as a result of large differences between potential yields and farmers' actual yields (Wopereis *et al.*, 1999a).

After the rice crisis of 2008, many efforts to increase production have been deployed in Sub-Saharan Africa. Consequently, yield growth rate was increased from 11 kg/ha/year before 2007 to 108 kg/ha/year after the 2008 rice crisis. The contribution of yield increase to production was changed from 24 % in the period 2000-2007 to 71% in the period 2007-2012 (Seck *et al.*, 2013). However, the gap between consumption demand and production is yet to be closed. Therefore, more efforts are needed for raising yield in order to reduce the gap. To increase yield, improved management options are to be considered, they include introduction of improved varieties, application of balance fertilizer, better control of pests and diseases. To decide which management option to adopt to increase yield, it's needed to quantify the yield gap for each production system and the affecting factors.

The yield gap is the difference between the potential yields and yields achieved by farmers. Potential yield is defined as the maximum yield attained by a crop (cultivar characteristics) in a given environment (solar, radiation, temperature and CO_2 concentration during crop growth period) as determined by simulation models when pests and disease are controlled with no limitation in water and nutrients (Evans and Fischer, 1999a).

The following chapter provides an overview of the existing production systems and their spatial distributions across agro-ecological zones are provided. The potential and constraints for rice production in relations to climate, soil and other factors are discussed. The different approaches to estimate rice yield gap are highlighted. The status of knowledge on rice yield gaps in West Africa is provided followed by the research objective and the thesis outline.

2. The major agro-ecological zones in West Africa

The agro-ecological zones consist of the Sahel with a length of growing period (LGP) of 65–90 days, corresponding to arid and semi-arid zones; the dry Savannah with an LGP of 90–180 days and the moist Savannah with an LGP of 180–270 days, corresponding to the sub-humid zone; and the forest with an LGP >270 days, corresponding to the humid zone. In this thesis, we use the term ‘climatic zone’ which

2.1. The Sahel

The Sahel is the transition zone between the Sahara Desert in the North and the Sudan Savannah in the south with arid to semi-arid climate (Figure 1.1). From east to west it is extended between the Atlantic Ocean to the Red Sea with 5400 km long representing an area of about 3,053,200 km^2. In West Africa, the Sahel zone covers northern Senegal, southern Mauritania, central Mali, and southern Niger (Figure 1.1). The vegetation is mostly covered in grassland with areas of woodland and shrub. Grass cover is fairly continuous across the region, dominated by annual grass species. *Acacia* is the dominant tree species with *acacia tortilis* the most common along with *acacia Senegal* and *acacia laeta*. Other tree species include *Commiphora africana*, *Balanites aegyptiaca*, *Faidherbia, albida* and *Boscia senegalensis*. The climate in the Sahel is arid to semi-arid with strong seasonal variations in rainfall and temperature. The rainfall is about 200-600 mm a year which falls from May to October (Table 1.1). Monthly mean temperature vary from a minimum of 13-15 °C to a maximum of 38-40 °C in Senegal river delta (Haefele *et al.*, 2000).

2.2. The dry Savannah

The Sudan Savannah is a broad belt of tropical Savannah that extends east to west across the African continent, from the Atlantic Ocean in the West to the Ethiopian Highlands in the east. The Sudan Savannah is characterized by a mono-modal rainfall pattern varying from 550 to 1000 mm falling in 90-165 days (Table 1.1). The vegetation is formed with different tree species including *Combretaceae*, *Caesalpinoideae* and some *acacia* species.

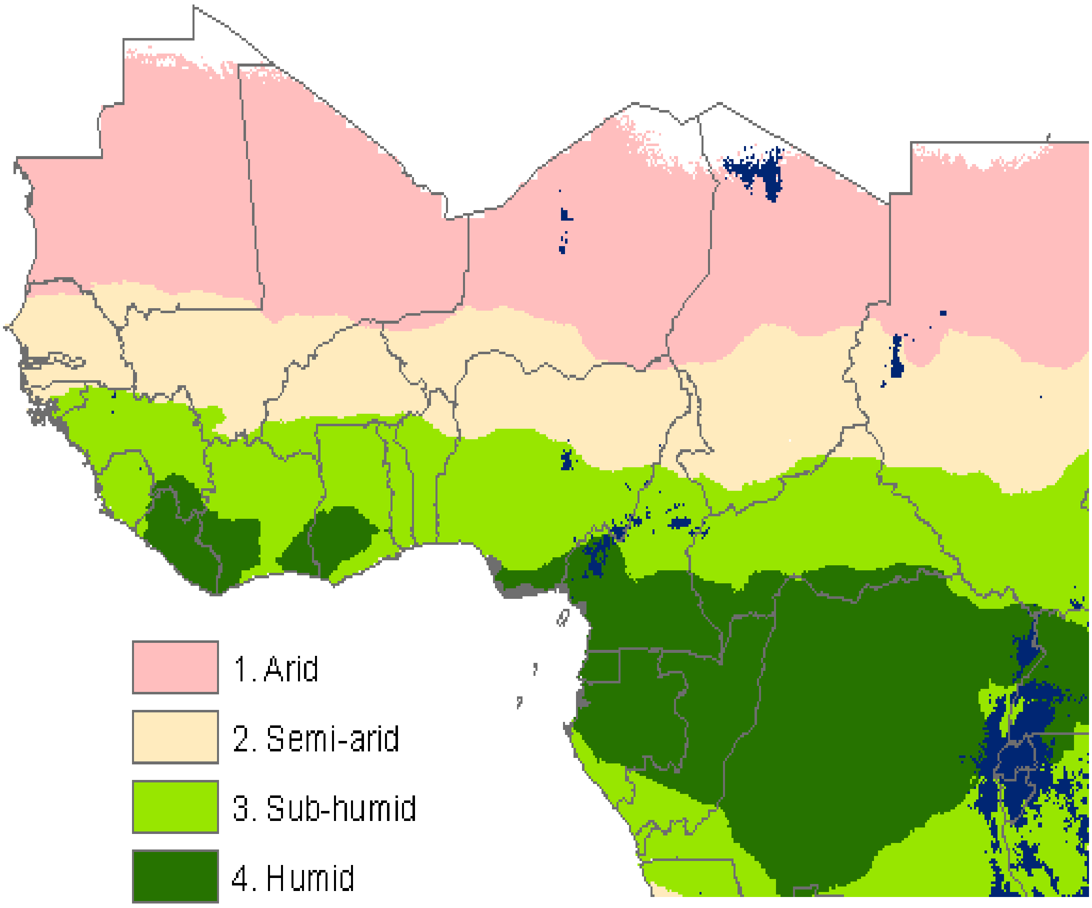


Figure 1.1: Climatic zones of West Africa

Source: modified from (HarvestChoice et al., 2016)

The main soil types found in Sudan Savannah zone are classified as Lixisol and Arenosol. They are young immature well drained soils formed of parent materials rich in quartz and crystalline rocks of basement complex and sedimentary deposits (Enewezor *et al.*, 1990). Soils are generally shallow on the upper parts of the landscape overlying a hard petroplinthite rock. The soils have low organic matter content, low cation exchange capacity and poor in nutrient content specially nitrogen and phosphorus (Windmeijer and Andriesse, 1993c).

2.3. The moist Savannah

The Guinea Savannah is a vegetation belt of around 1,575,000 square kilometers, located north-south from south of Senegal to South of Benin and running from east to west of the continent. The vegetation is characterized by a woodland Savannah consisting of an open stand of trees. The main tree species are *Daniellia oliveri*, *Lophira alata* and *Terminalia glaucescens* (Windmeijer and Andriesse, 1993c). The growing period of the Guinea Savannah zone extends over 165 - 270 days with monomodal annual rainfall distribution of about 900-1200 mm in the northern part and a bimodal rainfall pattern of up to 1500 mm in the south (Table 1.1). The soils in the Guinea Savannah are classified as ferruginous tropical, they are coarse to medium textured and generally graveled. Due to the presence of an underlying rock plinthite, soils are less deep in the upper part of the toposequence. The type of soils is dominantly Acrisol and Ferralsol with low inherent fertility in the upper and middle slopes. Because of the relatively higher rainfall, rice may occur in all parts of the landscape with a dominant frequency in the lower part with single rice cropping the most common practice because of the absence of irrigation facilities during dry periods.

2.4. The equatorial Forest

In the humid forest of West African regions, rainfall generally exceeds potential evapotranspiration for more than five months. It includes the south and center of Sierra Leone, the entire Liberia, central Ghana and the southern part of Guinea, Côte d'Ivoire, Nigeria and Cameroun. Annual rainfall is over 1500 mm with mono-modal rainfall pattern in the west, with four to six humid months (Table 1.1). Bimodal rainfall pattern is found in the transition zones of the tropical forest with a major rainy season of four to five months and a minor cropping season of about two to three months. A pseudo-bimodal pattern dominates the wetter forest regions from the center to the south, with seven to nine humid months. Soils in the equatorial forest zone are strongly weathered and are classified as Ultisols, Alfisols and Inceptisols. Oxisols and Entisols are present in smaller areas with a great potential for rice production (Moormann and Wambeke, 1978). Ultisols are generally found in the bimodal humid forest zone, they are very acidic, with low base saturation, low activity clays and very low fertility status. Alfisols are generally found in the drier bimodal and monomodal transition zones between the forest and the savannahs. The Ferralsols generally occur in the same high-rainfall belts as the Arcisols but they are more finely textured and structurally more stable. They are well drained in the upper and middle slopes, deep and poorly drained in the lower slopes. Gleysols and Fluvisols are mainly found in river floodplains and inland valleys in the bimodal and mono-modal rainfall areas. They have more mixed clay mineralogy, higher organic matter content and are more productive when excess water can be controlled.

Table 1.1: Characteristics of the major climatic zones in West Africa

Climatic zones	Length of growing periods	Annual rainfall	Rainfall pattern	Estimated area	
	(days)	(mm)		(x 1000 km^2)	%
Arid	0-90	150-550	Monomodal	1780	27.6
Semi-arid	90-165	550-1000	Monomodal	1170	18.3
Sub-humid	165-270	1000-1500	Monomodal (North) Bimodal (entral-South) Pseudo-bimodal (elsewhere)	1575	24.6
Humid	> 270	> 1500	Monomodal (West) Pseudo-bimodal (East) Bimodal (central-South)	1090	17

Source: (Andriesse and Fresco, 1991b; Windmeijer and Andriesse, 1993b)

3. Major rice production systems in West Africa

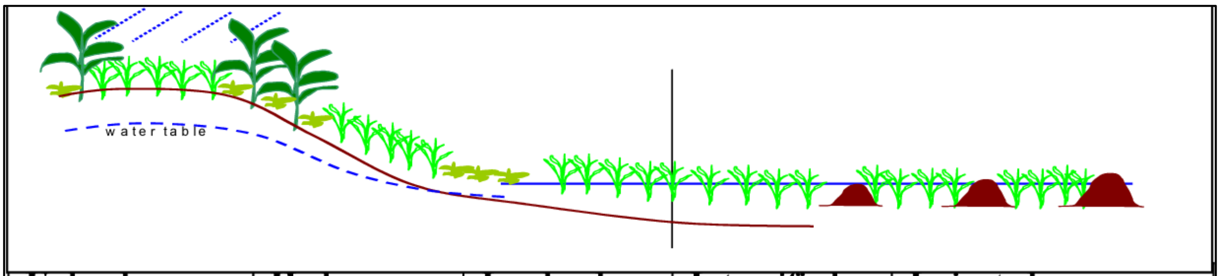
In West Africa, five rice production systems are distinguished, they are classified as rainfed upland, rainfed lowland irrigated lowland, deep water and mangrove swamp with the two latter considered as minor importance in term of surface area (Balasubramanian *et al.*, 2007a). Rice productions systems from Sudan Savannah to the equatorial forest follow the continuum from the top hills of the plateau to the bottom part of the inland valley swamps (Figure 1.2). Rainfed upland is practiced on the top of the landscape and on the middle slopes. At the end slopes, rice fields generally benefit from the hydromorphic conditions of the soil due to the shallow groundwater tables at the vicinity of the lowland. Rainfed and irrigated lowland rice are practiced in the bottom part of the landscape in flooded conditions during part or the entire growing season. The total harvested area is about 4.4 million hectares with the rainfed upland and rainfed lowland production systems representing each about 38 %. Irrigated rice accounts for only 12 % of the total area under rice cultivation (Dingkuhn *et al.*, 1998; Becker *et al.*, 2003b).

3.1. Rainfed upland

Upland rice production is practiced in unbunded fields under rainfed conditions on naturally well drained flat at the top of the topo sequence and at slopping fields without stagnant water (Datta *et al.*, 1990). Upland rice is mostly grown by subsistence oriented farmers who do not generally use external inputs. This is mainly due to the lack of means and the large surface areas used which limit the possibilities for intensification. Grain yield averages about 1 t/ha (Becker and Johnson, 2001c) with a large variation among farmers due to the quality of the land (soil variability), the rainfall distribution and the difference on management practices (sowing dates, weed control, nutrient input). The most important yield-reducing factor is weed infestation (Johnson *et al.*, 1997) followed by drought with the other factors including disease (blast), Insects (stem borers, termites), and soil conditions (soil acidity, nitrogen and phosphorus deficiency). In upland systems, crop water demand is entirely dependent on rainfall which makes this production system quite risky in arid areas. Upland rice production system is therefore more viable in humid zones from the Guinea Savannah to the humid equatorial forest where rainfall is more abundant. Rice plant may also benefit from shallow water table in addition to rainfall when grown in hydromorphic areas at the transition zone between the lower slope and the bottom part of the landscape. However, with continuous population growth, land pressure reduced fallow periods which aggravated soil degradation and soil quality decline (Bationo *et al.*, 1998). In 2009, upland cultivated rice area accounted 32% of the total rice area in Africa and occupied 35% of rice producers (Diagne *et al.*, 2013b).

3.2. Rainfed lowland

Rainfed lowland rice is grown in the lower part of the topo sequence and in inland valley swamps with bunded or unbunded fields flooded by rains and shallow ground water table (Saito *et al.*, 2013a). The total area of inland valley swamps is estimated about 20 to 40 million ha in West and Central Africa (Duivenbooden *et al.*, 1994). In 2009 rainfed lowland rice area was estimated to be about 38 % of the total area cultivated in rice in Africa which occupied 31 % of rice producers (Diagne *et al.*, 2013b). Rice yield in rainfed lowlands ranges from 1 to 3 t/ha. External inputs to enrich soil nutrient status and improving water control through bundings are ways to increase yield in lowland systems (Andriesse and Fresco, 1991a). The factors that affect rice yield in the rainfed lowlands include poor water control, drought, flooding, nutrient deficiency, iron toxicity pests and disease (bacterial leaf blight). Rainfed lowland production system is found from the Sudan Savannah to the humid forest agro-ecological zones.



Upland	**Hydromorphic slopes**	**Lowland**	**Intensified lowland**	**Irrigated lowland**
Main water supply: Rainfall	Rainfall + water table	Rainfall + water table + flood water	Regulated flood water	Irrigation

Figure 1.2: Rice production continuum

Source : modified from Defoer *et al.* (2004)

3.3. Irrigated lowland

Irrigated systems are bunded fields with dam-based, water diversion and pump irrigation from rivers in the Sahel. In the humid zones of Guinea Savannah and humid forest, irrigation is by gravity or by stream diversion of surface water and tube wells. The total area covered by irrigation is 100 000 ha in the humid forest, 150 000 ha in Guinea Savannah, 75 000 ha in Sudan Savannah and 175 000 ha in the Sahel (Becker *et al.*, 2003a). This production system occupy 26 % of the total area cultivated on rice in Africa (Diagne *et al.*, 2013b). Based on the annual flow of rivers, there is a potential water more than twenty times what is presently covered by irrigation. Poor water control, N deficiency due to leaching, soil salinity and acidity and bacterial leaf blight are the main factors affecting rice yield in irrigated lowland systems.

4. The general concept of yield gaps

Rice yield is determined by the interaction between variety characteristics, environmental conditions and management practices (Figure 1.3). The yield gap is the difference between potential yield and average farmers' yield estimated over the same spatial and temporal scale (Lobell *et al.*, 2009a). The different approaches to estimate yield gaps depend on the way potential yield is estimated. Potential yield is determined in crop growth condition without any biophysical limitations (nutrients, pests, weeds and diseases) other than uncontrollable factors, such as solar radiation, air temperature and rainfall in rainfed systems. Crop models are used to estimate potential and water limited yields in irrigated systems when water is amply supplied and in rainfed systems when water can be lacking at some points during part of the growing season (Wart *et al.*, 2013). Potential yield is determined in irrigated systems using two factors, solar radiation and temperature. In rainfed systems, water limited yield is simulated using rainfall and soil physical characteristics as additional factors.

Therefore the use of crop models validated with field experiments for the site or in the surrounding region provides a more robust approach for estimating yield potential for a site than using either approach alone. Another alternative to estimating yield potential is to survey farmer's fields and record the maximum yield achieved among a sample of farmers in the location of interest (Lobell *et al.*, 2005). The estimates are therefore more reliable when measured in farmer's fields but sample size is larger when collected only from farmer' records. This approach is appropriate in intensively rice cultivation systems, where farmers apply high levels of mineral fertilizers and appropriately control weed, pest and diseases that make farmers' yield possible to be close to potential yield. Figure 1.3 illustrates potential yield estimates of the three approaches and the level of farmers' average yield and the three yield gaps associated.

The expected range would be YGM > YGE > YGF with values likely to be close to each other in intensively managed systems but YGF would be much lower than YGM and

YGE in low input systems. In frequent nutrient, pest and disease stresses average farmer's yield are commonly less than 20% whereas in more intensive systems it can be as high as 80% of potential yield. In this study, simulated yield approach was used for estimating yield gap.

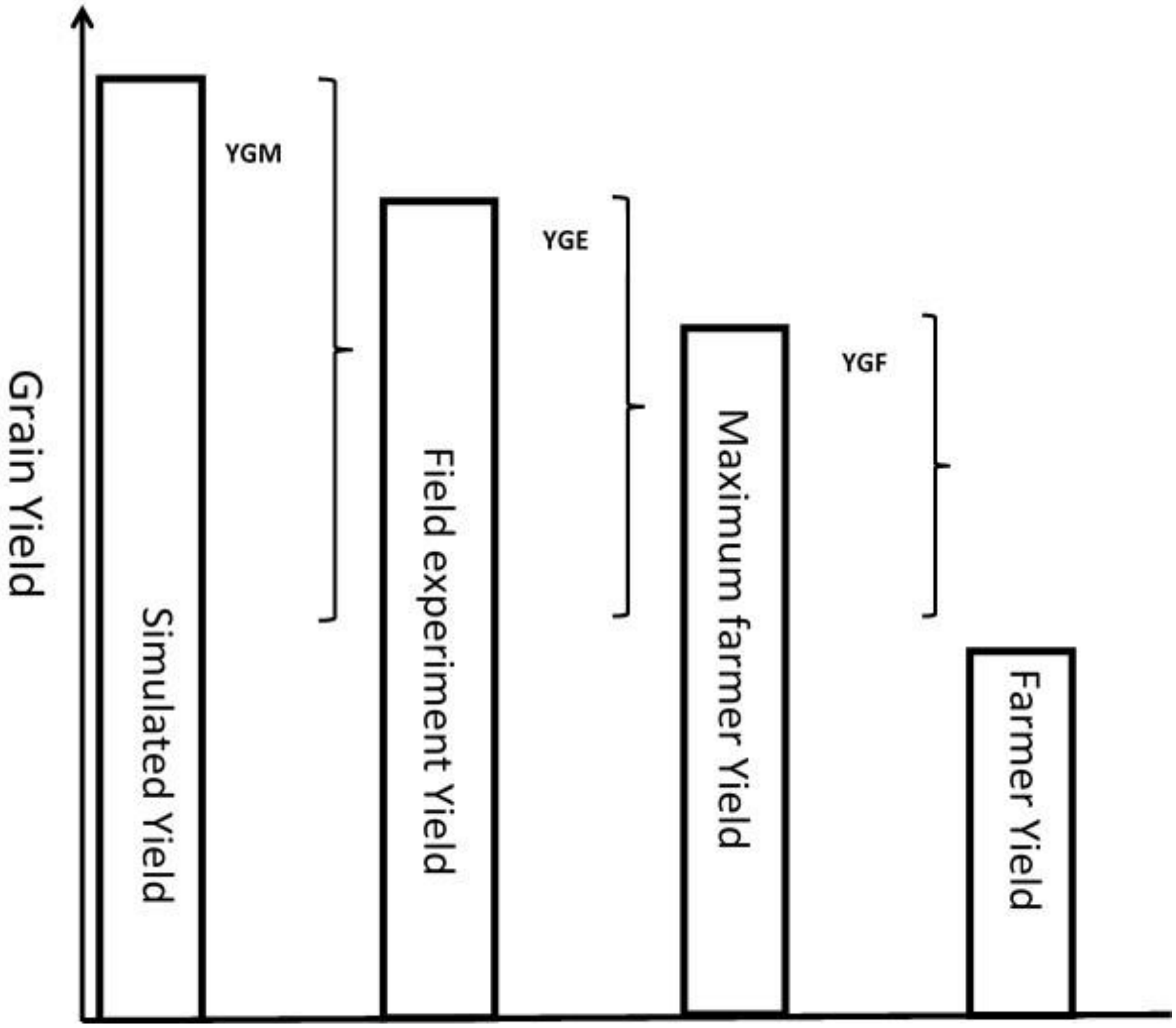


Figure 1.3: Three different approaches for rice yield gap estimation

Source: modified from Lobell et al. (2009a): YGM, model-based yield gap (potential yield simulated from a model); YGE, experiment-based yield gap (potential yield estimated with field experiments) and YGF, farmer-based yield gap (potential yield estimated with maximum of farmers' yield

5. Rice yield gaps in West Africa

AfricaRice, formerly West African Rice Development Association (WARDA) has analyzed rice yield gaps in the 1990s for 4 countries in West Africa (Côte, d'Ivoire, Senegal, Mali and Burkina Faso) from the Sahel to the Equatorial Forest zone (Becker and

Johnson, 1999b; Wopereis *et al.*, 1999a; Becker *et al.*, 2003b). Average farmers' yield was around 3.4 t/ha in Guinea Savannah; 3.6 t/ha in humid forest; 3.9 t/ha in the Sahel and 5.1 t/ha in Sudan Savannah (Becker *et al.*, 2003a). Simulated potential yield varied from 7 t/ha in the humid forest to more than 10 t/ha in the arid zones due to higher solar radiation (Becker *et al.*, 2003a). This potential is therefore constrained in some locations by extreme temperature (cold and heat) during dry season (Dingkuhn, 1993). Becker *et al.* (2003a) has reported average on-farm yields of irrigated lowland rice in different agro-ecological zones in West Africa ranging from 3.4 to 5.4 t/ha and average potential yields from 6.9 to 9.8 t/ha with an average yield gap ranging from 3.2 to 5.9 t/ha, indicating considerable possibilities for yield increase. On-farm trials in different agro-ecological zones in West Africa showed average yields of rainfed lowland rice and rainfed upland rice ranging from 1.0 to 2.2 t/ha and from 0.8 to 1.6 t/ha respectively (Becker and Johnson, 2001c; Becker and Johnson, 2001b). Potential yields have not been estimated using models for upland rice in Africa, yields in trials managed by researchers with sufficient nutrient input and without water stress (Dingkuhn *et al.*, 1998; Oikeh *et al.*, 2008; Ekeleme *et al.*, 2009; Saito and Futakuchi, 2009; Kamara *et al.*, 2010) were considered as potential yield in the upland system, they ranged between 4.0 to 5.6 t/ha. Thus, large differences exist between farmers' yields and research station's yields, suggesting that the yield gaps are likely to be high in upland conditions. Large yield gaps are noted in irrigated systems due to relatively high potential yields of irrigated lowland rice (Dingkuhn and Sow, 1995) and the low yields measured in farmers' fields. Low on-farm yields are caused by a range of biophysical and socio-economic constraints that lead to abiotic and biotic stresses of the rice crop during its growth cycle (Defoer *et al.*, 2004). The major challenge of rice research for development in Africa is to reduce rice yields gap by alleviating these stresses through genetic improvement and GAPs. Becker *et al.* (2003a) showed that improved weed control and timely N management narrowed yield gap up to 43 % in West African irrigated lowland systems in the equatorial forest zone. Becker and Johnson (1999b) has reported large yield variability in the forest zone of Côte d'Ivoire mostly due to the age of seedlings, delay of transplanting dates, fertilizer application timing, weed and water control. In the Sahel irrigated zone of Senegal, yield variability from 0.7 to 7.2 t/ha have been reported partly explained by timely application of mineral nitrogen (Dingkuhn, 1993).

6. Hypothesis and research objectives

Since the years 1990s no study has been carried out in farmers' fields to assess rice yield gap and the affecting factors. The last estimation of yield gap focused only on four countries in West Africa with only model-based method used to estimate potential yield in irrigated systems and farmer-based method in upland systems.

The objective of this study was to estimate the factors affecting rice production at farm level in the main rice production systems in West Africa across agro-ecological zones and to explore alternative management options to reduce the gap between potential and actual farmers' yield. Quantitative information on the causes of yield gap is key for identifying areas with potential to increase food supply, and for rice research prioritization

We hypothesize that (1) rice yield gap is large in low input systems; (2) improper management practices are the principal causes of the large yield gap, and (3) improving agricultural practices will increase rice production by minimizing yield-reducing factors. To test these hypotheses, the following research questions are addressed:

- What is the actual rice yield gap in different rice production systems in West Africa?
- What are the important factors affecting rice yield in different production systems across agro-ecological zones?
- What is the contribution of each affecting factor to yield gap for each production system across ecological zone?
- What are the best practices (combination of factors) that minimize yield gap?

7. Thesis outline

The thesis consists of an introduction, five chapters (Chapters 1-5) and a general conclusion. In chapter, I described the rice-growing environments in West Africa, including biophysical information and agricultural practices through literature review and data from previous works. The different approaches for yield gap estimation at field level were also described. In chapter 2, rice yield variability was assessed in each production system across agro-ecological zone and the affecting factors identified using boundary function and random forest. In chapter 3, different yield gaps were estimated using oryza2000 crop growth model and the factors affecting yield gap established using random forest and multiple regression analysis. In chapter 4, data from survey and experimental fields were used to assess rice yield variability in central Benin as affected by field water hydrology and N application rates In chapter 5, data from on-farm GAP testing are analyzed to examine if GAP can increase yield and help narrow the yield gaps. Chapter 6 presents a general discussion and conclusion of this thesis.

Chapter 2 : **Variability of yields and its determinants in rice production systems of West Africa**[1][2]

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[1] This chapter was partly presented in Tropentag conference, Vienna 2016 as:

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Variability and determinants of yields in rice production systems of West Africa

Abstract

Rice (*Oryza* spp.) is the major staple food for most countries in West Africa, but local production does not satisfy the demand. Rice is mainly grown by smallholder farmers, and are generally low with a high temporal and spatial variability. Low yields have been attributed to unfavorable climate conditions, poor soil quality, and sub-optimum agricultural practices. The objectives of this study were to assess variation in yields of three major rice production systems (irrigated lowland, rainfed lowland, and upland) across three climatic zones (semi-arid, sub-humid, and humid), and identify factors affecting the variation. We analyzed data on yield, climate, soil, and agricultural practices in 1305 farmers' fields at 22 sites in 11 West African countries between 2012 and 2014. A boundary function approach was used to determine attainable yields. Random forest algorithm was used to identify factors responsible for yield variation.

Average yield was 4.1, 2.0, and 1.5 t/ha in irrigated lowland, rainfed lowland, and rainfed upland rice production systems, respectively, with maximum attainable yields of 8.3, 6.5, and 4.0 t/ha. Yield difference between attainable and average yield tended to be higher in irrigated and rainfed lowland rice production systems. In those two systems, yields were highest in the semi-arid zone, while no difference in yields among climatic zones were apparent for upland rice. High yields were associated with high solar radiation, intermediate air humidity, multiple nitrogen (N) fertilizer application splits, high frequency of weeding operations, the use of certified seeds, and well-leveled fields in irrigated lowland rice. Minimum temperature, rainfall, building of field bunds, varietal choice, and the frequency of weeding operations were determinants of yield variation in rainfed lowland rice. Varietal choice, bird control, frequency of weeding operations, and the number of N splits affected yields in upland rice production. Improving access to inputs and improving their use efficiencies, and site-specific rice management strategies must be priority intervention areas to boost yields at regional scale independent of the rice production system and the climate zone.

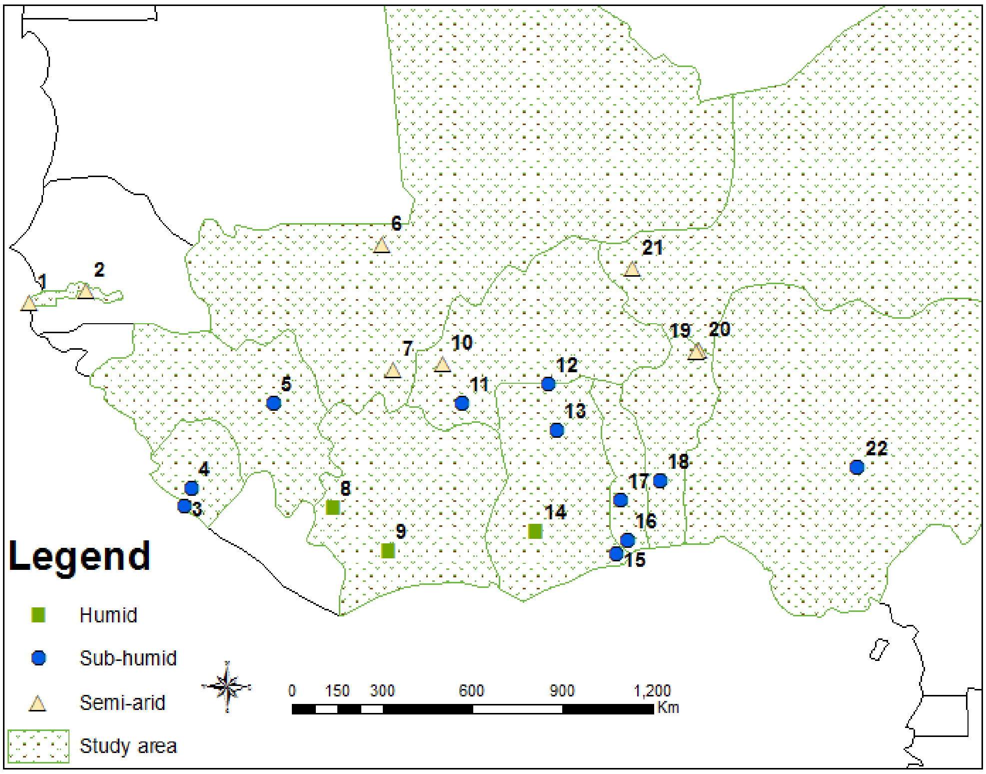
Keywords: climatic zone; boundary function; *Oryza* spp.; random forest; yield gap

1. Introduction

With six million hectares or 60% of the continent's rice-growing area, West Africa is the most important rice production region in Africa (Diagne *et al.*, 2013b). Production systems comprise irrigated lowlands, rainfed lowlands, and uplands, with deep water and mangrove rice being of only minor importance (Balasubramanian *et al.*, 2007a). Rice is grown across agro-ecological zones that are differentiated by the LGP. The agro-ecological zones consist of the Sahel with an LGP of 65–90 days, corresponding to arid and semi-arid zones; the dry Savannah with an LGP of 90–180 days and the moist Savannah with an LGP of 180–270 days, corresponding to the sub-humid zone; and the forest with an LGP >270 days, corresponding to humid zone (Peel *et al.*, 2007). In this paper, we use the term 'climatic zone' which comprises arid, semi-arid, sub-humid, and humid zones as shown in Figure 2.1.

Climate attributes such as rainfall, solar radiation, and temperature change markedly among climatic zones, with substantially higher solar radiation but also much greater temperature and humidity amplitudes in the arid than the humid zone (Windmeijer and Andriesse, 1993a). Although high solar radiation is generally associated with high yield, extreme temperatures can cause heat- or cold-induced spikelet sterility, resulting in low yield (van Oort *et al.*, 2014). These climatic conditions differentially affect soil weathering with associated changes in nutrient stocks, cation exchange capacity (CEC), and pH (Bouma and Finke, 1993). Thus, rice soils in the humid forest zone tend to be highly weathered and acidic with macronutrient deficiencies (Haefele and Wopereis, 2005) and microelement toxicities (Becker and Asch, 2005).

On the other hand, soils in the arid and semi-arid zones are mostly little weathered with generally higher CEC and soil pH, but salinity and alkalinity problems are commonly observed (Asch *et al.*, 1995; Ceuppens *et al.*, 1997; Saito *et al.*, 2013b). Irrespective of climatic zones, irrigated rice is generally produced in bunded paddy fields with irrigation, allowing for cultivating more than one crop per year. In all but the arid zone, rainfed lowland rice is grown on level to slightly sloping, unbunded or bunded fields in lower parts of the toposequence in inland valleys (Touré *et al.*, 2009).



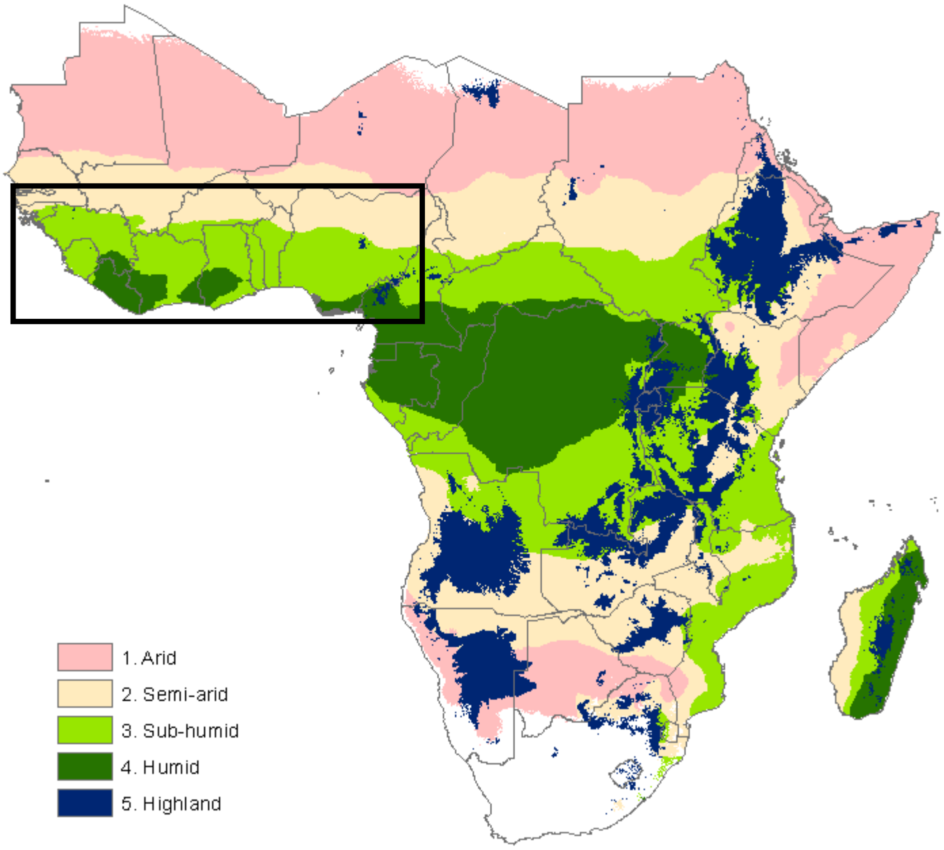


Figure 2.1: Location of study sites (top) and climatic zones (bottom) in sub-Saharan Africa. The climatic zone map was adapted from HarvestChoice et al. (2016). Numbers in the left map refer to site codes in Table 2.1

Upland rice is produced on level or sloping unbunded fields in hilly regions within the undulating inland valley landscape with low groundwater tables. Such diverse growing conditions result in large variation in yields across production systems (Becker and Johnson, 2001a; Becker and Johnson, 2001d; Becker *et al.*, 2003b) and farmers' fields within a given system (Saito *et al.*, 2013b). Apart from these climatic and edaphic properties, and the production systems themselves, farmers' rice yields are also affected by agricultural practices that are largely determined by the resource endowment of farmers that differentially influence production orientation, cropping intensity, and input use (Angulo *et al.*, 2012; Tanaka *et al.*, 2013). Large farm-to-farm variability has been observed for crop establishment date and methods (Tanaka *et al.*, 2013; 2015), varietal choice (Dingkuhn and Asch, 1999), tillage method (Becker *et al.*, 2003b), water management (Becker and Johnson, 2001d), the amount and timing of fertilizer applications (Haefele *et al.*, 2003), and the frequency and type of weed and pest control (Wopereis *et al.*, 1999b; Kent *et al.*, 2001). All these factors have been reported to affect yields and possibly explain their variability.

Most previous studies assessing on-farm rice yields, yield variation, and agricultural practices in West Africa were conducted in the mid- to late 1990s (Wopereis *et al.*, 1999b; Becker and Johnson, 2001d; Becker and Johnson, 2001a; Becker *et al.*, 2003b) with only two recent studies of irrigated lowland rice systems (Tanaka *et al.*, 2013; 2015), and most having focused on Côte d'Ivoire and Senegal. With rice being grown in all 17 countries of the region and with changing rice demand, increasing globalization effects and recent technological innovations (new varieties, mechanization, access to information and communications technology etc.), rice production systems and agricultural practices have evolved differentially in the past decade with likely implications on yields and yield variability. Furthermore, few studies in West Africa have considered climate attributes when assessing on-farm yield variation. Thus, it appears timely to re-assess the performance attributes of major rice production systems. The objectives of this study were to determine variations in yield of major rice production systems (irrigated lowland, rainfed lowland, and upland rice) across climatic zones (semi-arid, sub-humid, and humid) in West Africa, and to identify the role of climatic and edaphic attributes and of agricultural practices affecting rice yields and their variation in West Africa.

2. Material and methods

2.1. Study sites and sampling frame

The cross-sectional study of rice performance attributes and their determinants was conducted at 22 sites in 11 countries (Table 2.1). These study sites were selected by national agricultural research institutes and are considered priority intervention sites for national rice research and development. Each study site comprised of up to eight rice-producing villages, except for Bo and Kenema in Sierra Leone with 20 villages, with up to 50 farmers being randomly selected in each village (34–93 farmers per study site). The field surveys were performed during the rainy seasons in 2012, 2013, and 2014. In total, the sample comprised 1368 farmers' fields. The distribution of the sites by country and climatic zone, the sample size of farmers, and the period of data collection are summarized in Table 2.1. Climate data were collected from automated weather stations established in most of the study sites: solar radiation, rainfall, and minimum and maximum temperatures. When ground station data time series were incomplete, weather data were obtained from the online Global Summary of the Day (GSOD) or the NASA POWER database (NASA, 2016), The NASA POWER data on minimum and maximum temperatures were bias-corrected following Van Wart *et al.* (2015) and van Oort *et al.* (2014), while solar radiation and rainfall data were used directly. Daily minimum and maximum temperatures, and daily mean relative humidity were averaged over the complete rice-growing period for each individual farmer's field, and cumulative solar radiation and rainfall were calculated.

2.2. Data collection

Information on farmers' agricultural practices was collected through interviews with individual farmers. Agricultural practices considered comprised land preparation (tillage, bunding, leveling, straw management), planting material and establishment method, fertility management (amounts and frequency of fertilizer applications), and pest control (frequency of weeding operations and bird control) (Table 2.1). Within each farmer's field, a 200 m^2 survey plot was established at the beginning of the wet season. Soil samples (0–20 cm) were collected as composites (n=9) at the onset of each cropping season along two diagonal transects across the survey plots.

Table 2.1: Distribution of study sites and number of farmers' fields by production system and site.

Climatic zone	Country	Site (code)	Total number of fields (implementation/sampling year) *		
			Irrigated lowland	Rainfed lowland	Rainfed upland
Semi-arid	Benin	Malanville (20)	79 (2 & 3)		
	Burkina Faso	Hauts Bassins (10)			34 (2)
	Mali	Sikasso (7)		88 (1 & 2)	9 (1)
		Kouroumari (6)	41 (1 & 2)		
	Niger	Gaya (19)	11 (2)	38 (2)	
		Tillaberi (21)	65 (1 & 2)		
	The Gambia	West Coast (1)			70 (1 & 2)
		Central River (2)	70 (1 & 2)		
Sub-humid	Benin	Glazoué (18)		34 (1 & 2)	29 (1)
	Burkina Faso	Cascades (11)		44 (2)	
	Ghana	Navrongo (12)	32 (1 & 2)	44 (1 & 2)	12 (1)
		Savelugu (13)	6 (1)	79 (1 & 2)	
		Afife (15)	46 (2)		
	Guinea	Haute Guinée (5)			61 (2 & 3)
	Nigeria	Nasarawa (22)		52 (1 & 2)	
	Sierra Leone	Tormabum (3)		50 (1 & 2)	
		Bo & Kenema (4)		59 (1 & 2)	
	Togo	Plateaux (17)		48 (1 & 2)	
		Maritime (16)	39, 1 & 2		
Humid	Côte d'Ivoire	Man (8)			73 (2 &3)
		Gagnoa (9)	58 (1 & 3)		
	Ghana	Kumasi (14)		34 (1 & 2)	

*1=2012, 2=2013, 3=2014

Soil samples were mixed and air-dried for subsequent laboratory analysis of particle size distribution, pH (H_2O), total C and N (CN element analyzer), and extractable P (Bray-2). The grain yield at harvest was based on the average from three harvest areas of 12 m^2 each within each survey plot. After eliminating entries with missing values, a total of 1305 complete data sets for individual farmers' fields remained for use in the analysis with 10 irrigated lowland sites (447 fields), 11 rainfed lowland sites (565 fields), and 7 upland sites (293 fields).

2.3. Statistical analyses

Prior to data analysis, normality test was applied to yield values of each production system. Prior to the analysis of variance (ANOVA) of soil attributes and grain yield, non-parametric Levene's test was applied to test the homogeneity of variances (Nordstokke *et al.*, 2011). ANOVA was conducted to test for statistical significance among soil attributes and grain yields in different production systems and climatic zones. In cases of significance, mean comparisons were conducted using Scheffe post-hoc test when homogeneity of variance was assumed, or Games-Howell post-hoc test when homogeneity of variance was not assumed. Pearson's product moment correlation was used to characterize the relationships among climate variables and selected soil attributes (pH, total N, total C, extractable P, texture).

To identify the attainable yield responses to solar radiation (all production systems) and rainfall (rainfed systems only), boundary curves were fitted (van Ittersum *et al.*, 2012) with cubic smoothing splines (Daouia *et al.*, 2016) being applied for each production system. Maximum attainable yield was calculated using boundary curves and maximum solar radiation or rainfall observed. Differences between each pair of actual and attainable yields at the same solar radiation or rainfall level were determined and mean yield differences were calculated for each production system.

The relative importance of climate and soil variables on the one hand and of agricultural practices on the other hand in explaining farmers' yields were assessed separately using random forest algorithm (Breiman, 2001) implemented in the 'randomForest' package (Liaw and Wiener, 2002) in R software environment (R development Core Team, 2011).

Table 2.2: Soil and climate attributes and agricultural management practices determined in 22 study sites in West Africa.

Type	Variable	Unit or classification
Soil attribute	Clay, silt, and sand (Pipette method)	% of dry soil
	Total C and N (dry combustion elemental analysis)	% of dry soil
	pH (1:2.5 soil:water ratio)	
	Extractable P (Bray-2 method)	mg/kg dry soil
Climate variable[a]	Average daily minimum temperature	°C
	Average daily maximum temperature	°C
	Total solar radiation	MJ/m^2
	Average daily relative humidity	%
	Total rainfall	mm
Agricultural practice		
Land preparation	Straw management	Removed or returned
	Tillage method	Manual or mechanical
	Land leveling	Leveled or not leveled
	Plot bunding	Bunded or non-bunded
Planting material and establishment	Variety	Improved or local
	Source of seeds	Certified or self-grown
	Crop establishment method	Transplanting or direct seeding
Fertility management[b]	N application rate	None, low, or high
	P application rate	None, low, or high
	K application rate	None, low, or high
	Fertilizer application frequency	None, once, or more than once
Weed and pest control	Herbicide	Use or no use
	Weeding frequency	None, once, twice, or more than twice
	Bird control	Scaring/nets or none

[a] Climate values were calculated for each farmer’s field using farmer’s crop duration.

[b] Average N, P, and K application rates are based on all data points after excluding farmers who did not apply N, P, or K. Average N application rates were 100, 65, and 37 kg/ha in irrigated, rainfed lowland, and upland production systems, respectively, with 16, 13, and 9 kg P/ha and 29, 22, and 21 kg K/ha. Low fertilizer application indicates that farmer’s application rate was lower, whereas high application rate indicates that farmer’s fertilizer application rate was equal to or higher than the average.

Contributions of climate and soil variables (factors usually not changeable by the farmer) were analyzed separately from agricultural practices. In this analysis, five climate and four soil variables were categorized into two or three classes as follows:

Solar radiation (MJ/m^2): ≤2000; >2000

Relative humidity (%): ≤50; 51-70; >70

Maximum temperature (°C): ≤35; >35

Minimum temperature (°C): ≤23; >23

Rainfall (mm): ≤600; >600

Soil clay content (%): ≤30; >30

Soil available P (mg/kg): ≤10; >10

Total N content: ≤0.1; >0.1

Total C content: ≤1; >1

For agricultural practices, we used categorical variables as shown in Table 2.2. The effects of the most important climate and soil attributes and agricultural practices identified by the random forest algorithm were estimated by one-way ANOVA. Statistical analyses were performed using SPSS Statistics (ANOVA) for Windows (ver. 23.0) and R for Boundary Function and random forest approaches.

3. Results

The following sections first describe the observed variation in climatic and edaphic attributes and agricultural practices by production system and climatic zone, and subsequently present rice yields and their variability as well as their relationships with climate and edaphic attributes and agricultural practices.

3.1. Variation in climate and edaphic attributes and agricultural practices

Climatic conditions during the rice-growing season differed substantially between climatic zones (aggregated means across rice production systems). Among climate zones, average rainfall ranged from 635 mm (semi-arid zone) to over 854 mm (humid zone), whereas average solar radiation ranged from 2000 MJ/m^2 (humid zone) to 2500 MJ/m^2 (semi-arid zone) (Table 2.3). Temperature amplitudes were higher and relative air humidity was lower in the semi-arid than in the sub-humid zone. Irrigated lowland rice production environment showed higher maximum and minimum temperatures and solar radiation, and less humidity and rainfall than the rainfed environments. This is ascribed to the dominance of production systems in specific climatic zones. The semi-arid zone accounted for 60%, 22%, and 38% field plots of irrigated, rainfed lowland, and rainfed upland rice production systems, respectively. The sub-humid zone was dominated by rainfed lowland rice (65%), and the humid zone by upland rice production (44%). Solar radiation was positively correlated with maximum (r = 0.42, P<0.01) and minimum (r = 0.55, P<0.01) temperatures and negatively correlated with air humidity (r = –0.33, P<0.01) and rainfall (r = –0.50, P<0.01).

Table 2.3: Climate data during the rice-growing season: total rainfall, average daily minimum and maximum temperatures, solar radiation, and humidity by climatic zone and production system, and correlation coefficients (Pearson test) among climate variables.

	Minimum temperature (°C)	Maximum temperature (°C)	Total radiation (MJ/m^2)	Relative humidity (%)	Total rainfall (mm)
Climatic zone					
Semi-arid	24	34	2473	64	635
Sub-humid	23	31	2121	76	680
Humid	21	30	2012	77	854
Production system					
Irrigated lowland	24	34	2503	64	470
Rainfed lowland	23	32	2146	72	752
Rainfed upland	22	30	2088	80	904
Pearson's correlation test					
Min. temperature	1	0.74**	0.55**	–0.79**	–0.16ns
Max. temperature		1	0.42**	–0.95**	0.16**
Total radiation			1	–0.33**	–0.50**
Relative humidity				1	0.32**

** Correlation is significant at P≤0.01, ns correlation is not significant.

While soil pH values differed only marginally among climatic zones and production systems (coefficient of variation (CV) <13%), soil total C, total N, available P, and texture differed greatly (CV >50%). Total N, total C, available P, and sand contents tended to be highest in the humid zone, and available P was higher in upland rice soils (Table 2.4).

Table 2.4: Soil attributes (0–20 cm) by climatic zone and production system, and their inter-correlations.

	pH (H_2O)	Total N (%)	Total C (%)	Available P (mg/kg)	Clay (%)	Silt (%)	Sand (%)
Climatic zone							
Semi-arid	5.6	0.10 a	1.1 a	3.9 a	31 a	29 a	40 a
Sub-humid	5.4	0.14 b	1.5 b	3.4 a	26 b	26 b	48 b
Humid	5.4	0.20 c	2.1 c	6.2 b	21 c	18 c	61 c
Production system							
Irrigated lowland	5.7 a	0.11 a	1.3 a	2.5 a	37 a	25 a	38 a
Rainfed lowland	5.2 b	0.15 b	1.7 b	4.0 b	23 b	30 b	47 b
Rainfed upland	5.6 c	0.06 c	0.8 c	6.8 c	17 c	21 c	62 c
CV (%)	13	66	83	120	69	54	56
Levene's test P value							
Climatic zone	ns	**	**	**	**	**	**
Production system	**	**	**	**	**	**	**
Pearson's correlation test							
pH (H_2O)	1	–0.36**	–0.32**	0.24**	–0.02	–0.16**	0.10**
Total N		1	0.96**	–0.11**	0.35**	0.38**	–0.43**
Total C			1	–0.09*	0.37**	0.42**	–0.46**
Available P				1	–0.29**	–0.21**	0.31**
Clay					1	0.26**	–0.86**
Silt						1	–0.72**

Means of the same soil parameter with a different letter are significantly different between climatic zones and between production systems, ns: not significant, ** significant at $P \leq 0.01$, * significant at $P \leq 0.05$.

In general, upland rice soils were of coarser texture than lowland soils. Correlation analysis showed that sand content was negatively correlated with total C, total N, clay, and silt contents, and positively correlated with available P. Agricultural practices – land preparation, planting material and establishment, fertility management, and weed and pest control – differed among rice production systems (Table 5). More than 40% of farmers in rainfed lowland and 60% in upland rice production systems did not apply any fertilizer, while >80% of farmers applied mineral fertilizer to irrigated rice.

Table 2.5: Distribution of farmers' agricultural practices by production system and expressed as the percentage share of all fields within each system.

		Irrigated lowland (%)	Rainfed lowland (%)	Rainfed upland (%)
Land preparation	Straw return	39	36	71
	Building of field bunds	93	27	15
	Mechanical tillage	83	52	47
	Field leveling	47	23	19
Planting material and establishment	Use of improved varieties	94	71	42
	Use of certified seed	59	33	20
	Transplanting (v. direct seeding)	77	28	7
Fertility management	None, low, and high application of mineral N fertilizer	19, 48, and 33	44, 37, and 19	62, 27, and 11
	None, low, and high application of P fertilizer	27, 51, and 22	54, 31, and 15	65, 19, and 16
	None, low, and high application of K fertilizer	32, 46, and 22	58, 27, and 15	67, 21, and 12
	Single application of mineral N	20	33	20
	>1 application of mineral N	63	28	20
Weed and pest control	Use of herbicide	61	49	28
	Single weeding	23	51	46
	Two weedings	52	30	46
	>2 weedings	24	19	8
	Bird control (scaring or nets)	46	34	79

Generally, in the irrigated systems, most farmers applied advanced or recommended practices such as mechanical tillage, building of field bunds, and split application of mineral N, and used inputs such as improved varieties, fertilizers, and herbicides. Over 70% of upland rice farmers returned rice straw to the field.

3.2. Rice yield

Rice yields were highly variable, ranging from 0.03 to 8.0 t/ha (Figure 2.3). Across climatic zones, mean yields were 4.1, 2.0, and 1.5 t/ha in irrigated lowland, rainfed lowland, and upland production systems, respectively. In upland rice, yields ranged from

0.03 to about 4.0 t/ha with a >70% probability of <2 t/ha. In rainfed lowlands, yields ranged from 0.1 to nearly 6.0 t/ha with a 50% probability of <2.0 t/ha (Figure 2.2). In irrigated lowland rice, yields ranged from 0.3 to 8.0 t/ha with >60% probability of <5 t/ha. The CV of the yield was higher in rainfed systems (about 60%) than in irrigated lowlands (38%). Yield levels differed among climatic zones, with highest yields obtained from lowland production systems in the semi-arid zone.

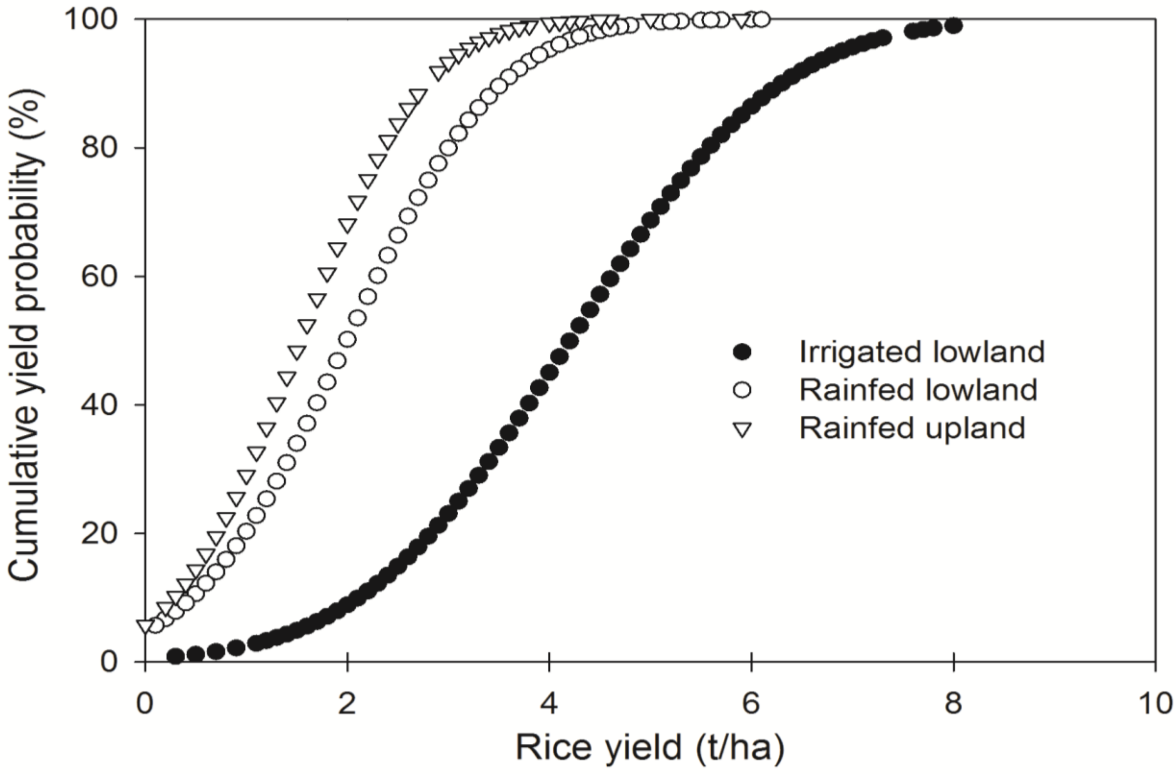


Figure 2.2: Cumulative probability distribution of rice yields per production system.

The yield variability was highest in rainfed systems of the sub-humid zone with a CV of 63%. In irrigated systems, the yield variability increased from the semi-arid (CV 29%), through the sub-humid (CV 38%) to the humid zone (CV 44%) (Figure 2.3).

Upper-limit yields tended to increase with solar radiation up to about 2000 MJ/m^2 irrespective of the production system, and increased with rainfall amounts up to 700 mm in the rainfed systems. Consequently, boundary curves were deployed using total solar radiation during the rice-growing period in all three production systems (Figure 2.4), and rainfall for the rainfed systems only (Figure 2.5).

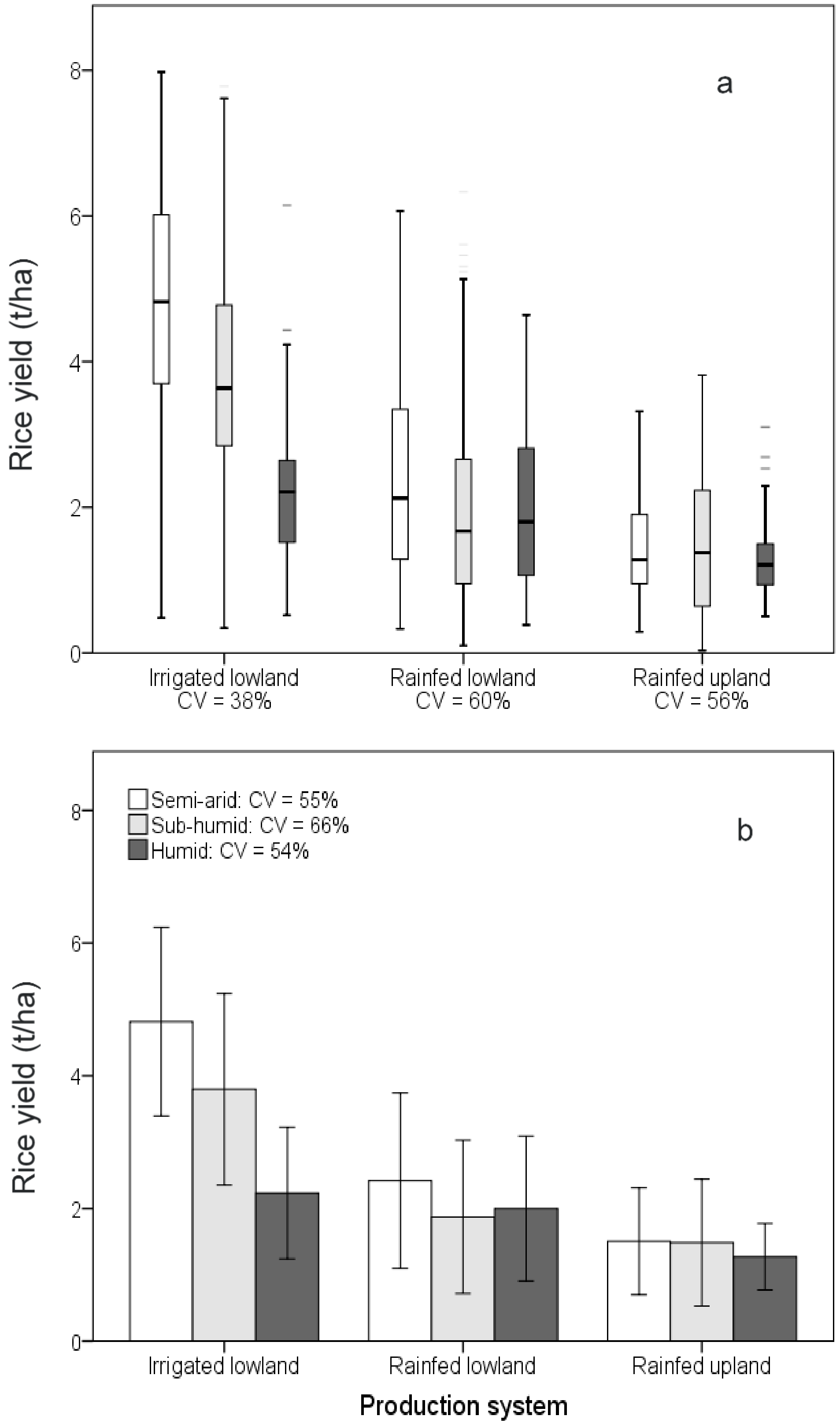


Figure 2.3: (a) Minimum, the lower quartile, the median (middle), the upper quartile, and maximum of yield, and (b) mean yield yields ± standard deviation of the mean in the main rice production systems of West Africa.

Radiation boundary curves indicate maximum attainable yields of 8.3, 6.5, and 4.0 t/ha in irrigated lowland, rainfed lowland, and upland systems, respectively, while rainfall boundaries indicate maximum attainable yields of 6.3 t/ha in rainfed lowlands and 4.0 t/ha in uplands.

3.3. Assessment of attainable yield using boundary curves

Yield difference between attainable (radiation-limited) and actual yields were 3.4, 4.2, and 2.1 t/ha in irrigated lowland, rainfed lowland, and upland, respectively. In the case of rainfall, these differences were 3.9 in rainfed lowland and 2.5 t/ha in upland systems. Largest yield difference were observed for irrigated systems in Gagnoa, Côte d'Ivoire (4.6 t/ha), Afife, Ghana (4.2 t/ha), and Central River, The Gambia (4.1 t/ha); for rainfed lowland systems in Savelugu, Ghana (5.2 t/ha), Glazoué, Benin (5.1 t/ha), and Tormabum, Sierra Leone (4.9 t/ha); and for upland systems in Sikasso, Mali (2.5 t/ha) and Glazoué, Benin (2.3 t/ha). All rainfed sites with large yield gaps are located in the sub-humid zone.

3.4. Factors explaining yield variability

Given the large differences in climate and soil attributes and agricultural practices on the one hand, and the large yield variability on the other, we exploited the observed on-farm variability by relating observed yields to climate and soil attributes and management factors. Random forest models using edaphic and climate attributes explained 56%, 12%, and 3% in yield variation in irrigated lowland, rainfed lowland, and rainfed upland systems, respectively. The four top-ranked edaphic–climatic variables explaining the observed yield variability are presented in Table 2.6 for the lowland production systems.

Upland systems are not shown as yield variation was not clearly attributable to either climatic or edaphic factors. Solar radiation and soil clay content were consistently key explanatory variables of yield variability in lowland systems. In addition, air humidity and maximum temperature were relevant variables in irrigated lowlands, while minimum temperature and rainfall explained yield variability in rainfed lowlands. Effects of the top four variables on yield are shown in Table 2.7. High yield was associated with high solar radiation and maximum temperature in irrigated lowlands and high-rainfall and low minimum temperature in rainfed lowlands.

Differences in agricultural practices explained 22–36% of variation in yield. Weeding frequency was a common explanatory factor in all production systems. The splitting of the N application was most relevant in irrigated lowland systems, while variety choice was a key factor in both of the rainfed systems (Table 2.8).

In irrigated rice, highest yields were associated with the number of splits of mineral N fertilizer application (yield gain of 1.4 t/ha), and with farmers using certified seeds, high weeding frequency, and leveling the fields (yield gains of 1.1 t/ha).

In rainfed lowlands, the building of field bunds significantly increased rice grain yields from 1.6 to 2.9 t/ha. In upland rice, bird control provided yield gains of 0.2 t/ha (Table 2.9).

Table 2.6: Main edaphic and climatic variables generated by the random forest algorithm explaining rice yield variability in lowland production systems.

Rank based on %IncMSE[a]	Irrigated lowland	Rainfed lowland
1	Relative humidity	Min. temperature
2	Max. temperature	Solar radiation
3	Solar radiation	Soil clay
4	Soil clay	Rainfall
Mean of squared residuals	0.78	0.88
% variance explained	56	12

[a] Rank 1 indicates higher % of increase in mean square error (%IncMSE) = high variable importance.

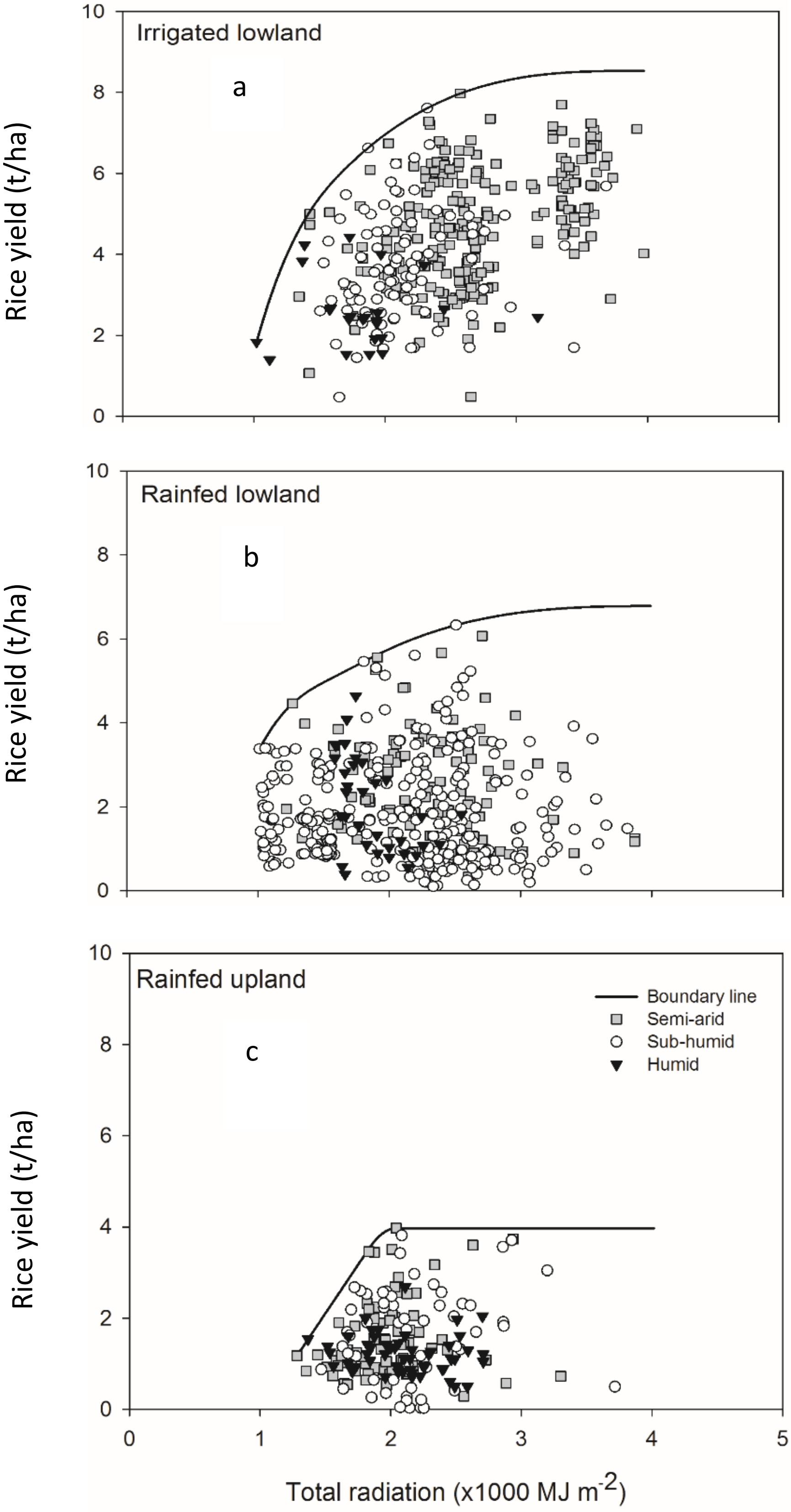


Figure 2.4: Boundary curves for rice yield response to solar radiation in West Africa. Symbols represent farmers' yields per climatic zone and lines show production system boundary curves in irrigated lowland (a), rainfed lowland (b) and rainfed upland (c).

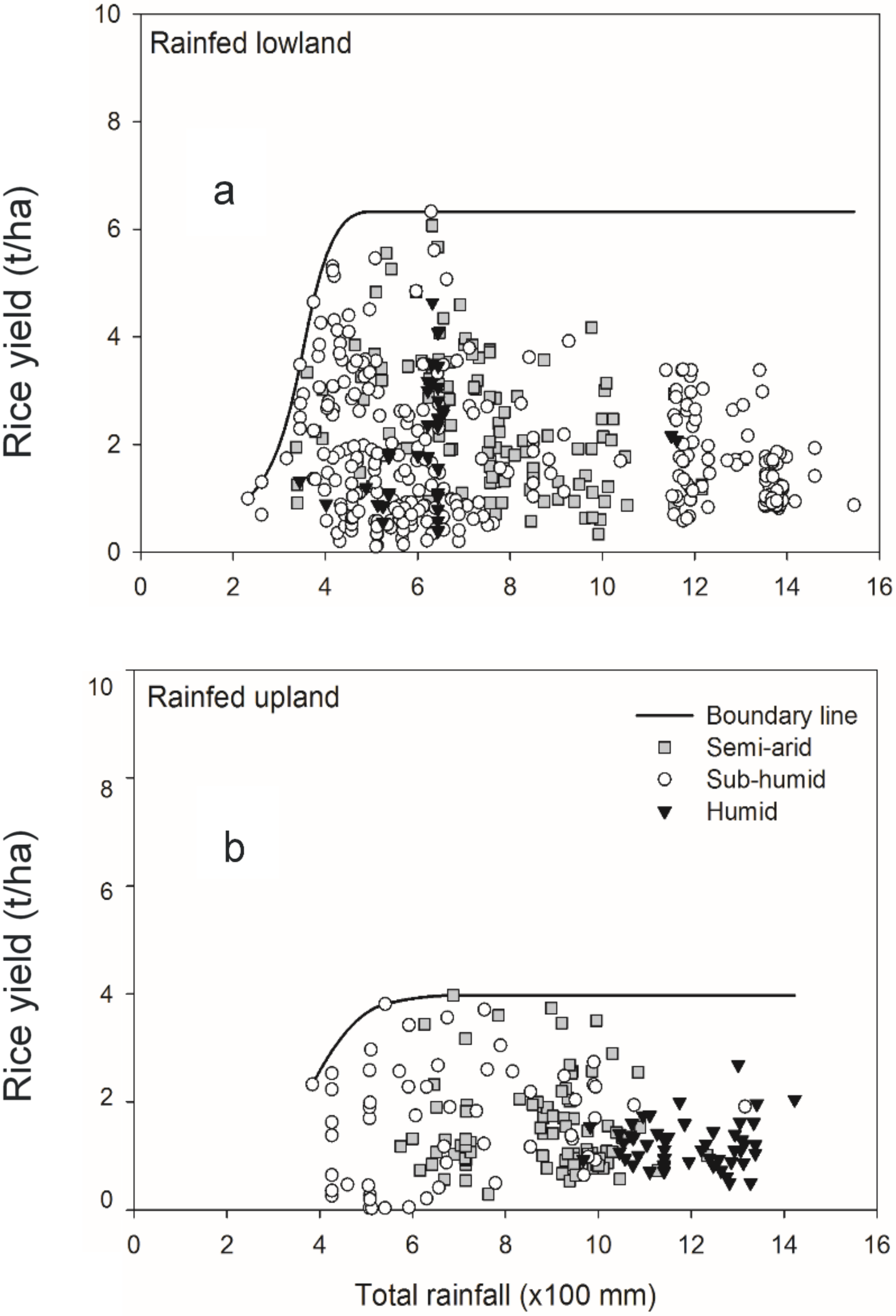


Figure 2.5: Boundary curves for rice yield response to rainfall in West Africa. Symbols represent farmers' yields per climatic zone and lines represent production system boundary curves in rainfed lowland (a) and ranfed upland (b).

Table 2.7: Mean yield comparison for the top-ranked climate and soil attributes in lowland rice production systems.

	Rice yield (t/ha)[a]	
Variable	Irrigated lowland	Rainfed lowland
Solar radiation (MJ/m^2): ≤2000; >2000	3.2a, 4.7b	2.0a, 2.0a
Relative air humidity (%): ≤50; >50 ≤70; >70	4.9a, 5.5b, 3.6c	
Maximum temperature (°C): ≤35; >35	3.6a, 5.1b	
Minimum temperature (°C): ≤23; >23		2.2a, 1.8b
Rainfall (mm): ≤600; >600		1.6a, 1.9b
Soil clay content (%): ≤30; >30	4.7a, 4.2a	1.8a, 1.9a

[a]Mean values for each variable followed by a different letter for the same production system are statistically different.

Table 2.8: Most important soil and climate attributes and farmers' agricultural practices generated by the random forest algorithm explaining rice yield variability in different production systems.

Rank based on %IncMSE[a]	Irrigated lowland	Rainfed lowland	Rainfed upland
1	Seed source	Variety	Variety
2	Mineral N splits	Weeding frequency	Weeding frequency
3	Weeding frequency	Field bunding	Mineral N splits
4	Land leveling	Straw management	Bird control
Mean of squared residuals	1.51	1.01	0.47
% variance explained	36	27	22

[a]Rank 1 indicates higher % of increase in mean square error (%IncMSE) = high variable importance.

Table 2.9: Mean yield comparison for the top-ranked agricultural practices in three rice production systems.

Variables	Rice yield (t/ha)[a]		
	Irrigated lowland	Rainfed lowland	Rainfed upland
Straw management: removed, returned		1.9a, 2.0a	
Field bunding: unbunded, bunded		1.6b, 2.9a	
Variety: local, improved		1.4b, 2.2a	1.2b, 1.6a
Seed source: own, certified	3.7b, 4.8a		
Weeding frequency: ≤1, 2, 3	3.7a, 4.2b, 4.8c	1.7a, 2.2b, 2.3b	1.4a, 1.5a, 2.0b
N applications split: 0, 1, ≥2	3.3a, 3.9b, 4.7c		1.4a, 1.3a, 1.8b
Land leveling: not leveled, leveled	3.8b, 4.9a		
Bird: none, controlled			1.2b, 1.4a

[a]Mean values for each variable following by a different letter for the same production system are statistically different.

4. Discussion

This study assessed on-farm rice yields and their variability across three rice production systems and three climatic zones of West Africa. The large observed variation in yield across and within climatic zones and production systems confirms previous reports in the region, mostly dating back to the 1990s. These studies had shown a large range in yields between 0.2 and 9.0 t/ha in irrigated lowlands in four agro-ecological zones (Becker *et al.*, 2003b), between 1.3 and 7.8 t/ha in irrigated lowlands of Benin (Tanaka *et al.*, 2013), between 0.5 and 12.0 t/ha in irrigated lowlands of Senegal (Tanaka *et al.*, 2015), between 0.2 and 6.5 t/ha in rainfed lowlands of Côte d'Ivoire (Becker and Johnson, 2001d), and between 0 and 6.0 t/ha in rainfed rice systems of Benin (Niang *et al.*, under review). Comparing the average yields of the present and the previous studies (at least those conducted at the same locations) highlights that yields have hardly improved in the past 20 years. Yield appears to have stagnated at 2 t/ha in the rainfed lowlands of Kumasi, Ghana (Ofori *et al.* (2005) and at 1.1 t/ha in the uplands of Man, Côte d'Ivoire (Becker and Johnson (2001a). They have even declined from 3.2 to 2.6 t/ha in the irrigated lowlands of Gagnoa, Côte d'Ivoire (Becker *et al.* (2003b) and from 5.7 to 5.1 t/ha in Kouroumari, Mali (Wopereis *et al.*, 1999b). As data were not collected in the same farmers' fields or even in the same villages, and as we could not consider possible climatic effects, these 20-year trends must be interpreted with caution.

Evaluating attainable yields and assessing yield responses to resource attributes by using boundary functions has previously been successfully applied to soil characteristics (Shatar and McBratney, 2004), weed control and the presence of soil-borne pests and diseases (Wairegi *et al.*, 2010), to water use and N fertilizer inputs (Tittonell and Giller, 2013), and to combinations of these factors (Casanova *et al.*, 1999; Shatar and McBratney, 2004; Wairegi *et al.*, 2010; van Ittersum *et al.*, 2012; Affholder *et al.*, 2013; Tittonell and Giller, 2013). In the present study, the application of this approach highlighted the importance of solar radiation for all the production systems and of rainfall for rainfed rice systems, and it revealed a large scope for increasing grain yields in irrigated and rainfed lowland production systems, especially those located in the subhumid zone. This confirms previous studies that showed large potential for increasing production in inland valleys of the Savannah zone (Rodenburg *et al.*, 2014b). However, the number of seasons for assessing between-year yield variations is limited in the present study and, particularly in the rainfed systems, unpredictable and variable rainfall could significantly affect yields as well as farmers' decisions to invest in yield-increasing technologies. Although we identified three priority sites (Glazoué in Benin, Savelugu in Ghana, and Tormabum in Sierra Leone) that have potential for raising yield in rainfed lowlands, there is an urgent need to assess the effect of climate variability on rice productivity in these sites. From results of climate risk assessment, different types of interventions should be considered (van Oort *et al.*, 2016). As the number of study sites in the humid zones was limited, further assessment in more and different sites is desirable to confirm the findings of this study.

Our study indicates that the random forest approach appears to be a robust analytical tool for determining factors affecting variation in rice yield. Similar conclusions have been drawn previously from assessing variability in the yield of *Ruditapes philippinarum* (Vincenzi *et al.*, 2011), of the biomass of natural wetland vegetation (Mutanga *et al.*, 2012), and also from a study on mineral prospectivity in the Philippines (Carranza and Laborte, 2015). Despite the large variation in most soil attributes in the present study, edaphic factors had little effect on yield. It is well known that the soil texture and its possible linkage with water- and nutrient-holding capacities affect rice productivity (Issaka *et al.*, 1996; Becker and Johnson, 1999a; Buri *et al.*, 1999; Becker and Johnson, 2001a; Tanaka *et al.*, 2013; Tsujimoto *et al.*, 2013). The apparently overriding role of climate attributes compared to edaphic characteristics on rice yields and their variability stands in contrast to numerous reports that blame low fertility and progressive soil degradation for low crop productivity in Africa (Sanchez, 2002; Koning and Smalling, 2005). Whereas soil fertility-related problems may thus be of lesser relevance than climate attributes and agricultural practices in the current situation, investigating other soil attributes such as micronutrient deficiency and element toxicities (Na, Fe), and their linkage with yield deserves further study. The finding of positive relationship between solar radiation and yield in irrigated systems, and between yields and minimum temperature (negative) and rainfall (positive) in rainfed lowland systems also confirm previous studies in Asia (Seshu and Cady, 1984; Islam and Morison, 1992; Peng *et al.*, 2004; Inthavong *et al.*, 2011).

In this study, we did not consider the depth of the groundwater table in individual farmers' fields as supplement to rainfall in the boundary analysis of rainfed systems. It has been reported that the depth is highly variable across and within the fields (Masiyandima *et al.*, 2003; Worou *et al.*, 2013). Consequently, observed high yields, particularly those in rainfed lowlands of drier sites, may have been related to shallow groundwater tables (Boling *et al.*, 2007). In such high-yielding fields, farmers might have applied substantially more mineral fertilizer than in the strictly rainfed and water limited fields. Consequently, best farmers' yields in rainfed lowlands most likely coincided with a combination of good water availability and higher fertilizer application rates.

Further efforts are needed to group and analyze farmers' fields according to water availability or groundwater depth. This hints at a further limitation of considering only a single factor, ignoring possible factor interactions. Thus, larger gap between attainable yield and actual yield in rainfed lowland systems when rainfall is higher is likely to be attributable to low solar radiation in high-rainfall sites. Use of crop simulation models that consider various climate attributes (Bouman *et al.*, 2001) is needed to improve the boundary function approach and will be presented in a subsequent paper.

Some major contributions of agricultural practices to rice yield variation are observed across different production systems, whereas others are production system-specific. The importance of the number of N splits in irrigated lowland rice has been highlighted in previous studies (Becker and Johnson, 1999c; 2001d; Becker *et al.*, 2003b) and appears still to be as valid and important today. The effect of leveling on yield in irrigated lowland rice, and the effect of weeding interventions irrespective of production systems confirm previous studies (Becker and Johnson, 2001d; Becker and Johnson, 2001a; Ogwuike *et al.*, 2014; Tanaka *et al.*, 2015). However, as discussed by Ogwuike *et al.* (2014), the result in this study does not imply that farmers should spend more time weeding their fields, but there is a need to develop or introduce labor saving weed management strategies (Rodenburg *et al.*, 2015).

In this study, certified seed had positive impact on yield of irrigated lowland rice, whereas this effect was not shown clearly in other production systems, possibly because the percentage of famers who used certified seed was limited in those systems. Off-types are commonly observed in farmers' fields in West Africa and have been considered to reduce yield (Diaz *et al.*, 1998). Certified seed is likely to reduce off-types and consequently increase yield in this study.

In rainfed lowlands, the importance of building field bunds remains a key concern

(Worou *et al.*, 2013; Rodenburg *et al.*, 2014b). The varietal choice is important for rainfed lowland and upland rice systems, but not in irrigated lowland systems, where improved varieties are commonly grown (>90%). It is well known that improved varieties have shown good performance in rainfed systems (Sie *et al.*, 2008; Rodenburg *et al.*, 2009; Saito and Futakuchi, 2009; Saito *et al.*, 2012). In rainfed upland systems, bird control remains as relevant in explaining yields and variability as it was three decades ago (Van Dat, 1986).

Given, on the one hand, the enormous technology progress in recent years (Fischer *et al.*, 2009) and the large number of published studies advocating substantial yield gains through the adoption of new rice varieties (Adekambi *et al.*, 2009; Yamano *et al.*, 2015) or site-specifically adapted production strategies including bunding in rainfed lowland systems (Becker and Johnson, 2001d; Touré *et al.*, 2009), and nutrient management options for irrigated lowland rice systems (Haefele *et al.*, 2003; Saito *et al.*, 2015a), and the apparently rather low productivity gains in the past 20 years on the other hand, further detailed studies to identify factors that influence the low uptake of technologies or innovations or their limited impact on productivity gains in the rice sector of West Africa are required. The present work provides the basis for identifying key production systems and guiding such studies.

From the analysis of over 1300 farmers' fields in diverse production settings of West Africa, we conclude that there is large scope for increasing yields in West Africa, especially in irrigated and rainfed lowland systems. Production system- and site-specific rice management strategies are likely to increase on-farm rice yields with largest potential impact in the rainfed lowlands of the sub-humid zone. Although improving access to inputs and their use efficiencies is essential for improving rice yield in low-yielding sites, there is urgent need to have a better understanding of the reasons why some farmers do not use advanced practices or more inputs.

Chapter 3 : **Yield gaps and their variability in major rice production systems of West Africa**

Abstract

This chapter assessed yield gaps and their variability at field level, and identify factors affecting the variation in the yield gap due to farmers' practices in representative rice production systems across climatic zones in West Africa. The yield gap is defined as the difference between potential yield in irrigated system or water limited yields in rainfed rice production systems, and farmer's yield. Potential and water limited yields at optimum crop establishment date in given site and year and farmers' actual crop establishment date were estimated using Oryza2000, while farmers' yields were assessed through surveys conducted in 824 farmers' fields in 15 sites during the wet seasons 2012 to 2014. Random forest algorithm and multiple linear regressions were used to identify causes for yield gap.

There was large variation in the difference between potential/water limited yields at optimum and actual crop establishment dates across locations and the range was between 0 and 3.9 t/ha. Yield gaps between potential/water limited yields at actual crop establishment dates and actual farmers' yields ranged from 1.1 to 10.2 t/ha and from 3.5 to 10.3 t/ha in irrigated and rainfed systems, respectively. Farmers' yield was 27-51% of potential yield at optimum sowing date in irrigated system, and 17-22% of water limited yield at optimum sowing date in rainfed systems. In irrigated system, 34% of the yield gap could be attributed to weeds, N fertilizer application rate and crop establishment methods. In rainfed systems, 30% of this gap was explained by type of rice variety, field hydrology and weed infestation at maturity stage. These results suggest that there is a large scope for increasing rice yield in this region, and barriers preventing farmers from adopting technologies including planting and weeding at right timing should be removed.

Keywords: Crop simulation model / *Oryza spp* / random forest/ potential yield /water limited yield

1. Introduction

The potential to increase rice (Oryza spp.) production in West Africa is high. Production systems comprise mainly irrigated lowlands, rainfed lowlands and uplands, with deep water and mangrove rice being of only minor importance (Balasubramanian *et al.*, 2007a). Rice is grown across agro-ecological zones (AEZ) that are differentiated by the length of growing period (LGP). The AEZs consist of the Sahel with an LGP of 65-90 days, corresponding to arid and semi-arid zones, the dry Savannah with an LGP of 90-180 days and the moist Savannah with an LGP of 180-270 days, corresponding to the sub-humid zone, and the Forest or with an LGP >270 days, corresponding to humid zone (Peel *et al.*, 2007; FAO/IIASA, 2012). In this paper, we use the term “climatic zone” which comprises arid, semi-arid, sub-humid, and humid zones. Irrespective of climatic zones, irrigated rice is generally produced in bunded paddy fields with irrigation allowing for cultivating two crops per year. In all but the arid zone, rainfed lowland rice is grown on level to slightly sloping, unbunded or bunded fields in lower parts of the topo sequence in inland valleys (Touré *et al.*, 2009). Upland rice is produced on level or sloping unbunded fields in the hilly regions within the undulating inland valley landscape with low groundwater tables. Such diverse growing conditions result in large differences in yields between systems (Becker and Johnson, 1999a; Becker and Johnson, 1999b) and climatic zones (Becker *et al.*, 2003b), but also among farmers within a given system (Saito *et al.*, 2013b).

Climatic factors such as rainfall, solar radiation, and temperature change markedly among climatic zones with substantially higher solar radiation but also much larger temperature and humidity amplitudes in the arid than the humid zone (Windmeijer and Andriesse, 1993a). High solar radiation is generally associated with high yield, while extreme temperatures can cause heat or cold-induced spikelet sterility, resulting in low yield (van Oort *et al.*, 2014). Rivers are the main water source for growing irrigated rice in the arid and semi-arid zones, while rainfall supplies water for upland and rainfed lowland cultivation in most of the sub-humid and humid zone. With opportunities for an expansion of the cultivated area being limited, the rapidly-growing rice demand resulting from demographic growth and changing consumer preferences, must be largely met by productivity gains in addition. Evaluating the capacities of different production systems will allow estimating the overall rice production potential of the region. The yield gap is defined as the difference between the (simulated) potential and farmers' actual yields, whereby the potential is usually estimated using crop growth models. Potential production constitutes the crop yield under conditions of sufficient supply of water and nutrients, optimum crop management, and in the absence of weeds, pest and disease. It is determined largely by absorbed photo synthetically active radiation and the crop phenological development (Bindraban *et al.*, 2000). Water limited yield is the potential yield if water supply falls below a threshold which decreases crop growth, and is determined by temperature, rainfall, ground water table and soil physical characteristics. Potential or water limited yields are determined by simulation models with plausible and agronomic assumptions (Evans and Fischer, 1999b). Regions with favorable climate (high solar radiation, low night temperatures and relative humidity) and with possibilities for supplying irrigation water show the highest potential. While potential and water limited yields are largely determined by the production environment (climatic attributes, irrigation infrastructure, and season/crops establishment date) and can rarely be effectively counteracted by individual farmers, the efficiency of input and resource use is related to farmers' individual production strategies. These are highly variable and may be changed through technological innovation, extension, or capacity strengthening. Consequently, farmers' yields are often highly variable between sites and productions systems, resulting not only in very large but also in highly variable yield gaps. Knowledge on the extent and determinants of yield gaps can guide the envisioned sustainable intensification (Rajapakse, 2003) and the targeting of intervention strategies.

The yield gap analysis aims to understand yield-limiting and -reducing factors and to estimate main determinants responsible for yield variability. In irrigated systems of semi-arid West Africa, Wopereis *et al.* (1999b) reported a rice yield gap of 8.7 t/ha. In the irrigated system of the humid forest zone of West Africa, average farmers ' yields ranged between 44 and 57% of the potential yield estimated from crop models (Becker and Johnson, 1999b). In irrigated lowland systems in four agro-ecolological zones, Becker *et al.* (2003b) reported a yield gap range between 3.2 and 5.9 t/ha. Large yield variability ranging between 0.2 and 6.5 t/ha was reported from rainfed lowland system in three AEZ (Becker and Johnson, 2001d). These prevailing large yield gap and yield variability could be explained primarily by age of seedlings at transplanting, the timeless of weeding operations, and water control measures. Finally, in the arid zone of

West Africa where extreme temperature can induce spikelet sterility, choice of optimum crop establishment dates was crucial to minimize yield losses and reduce the yield gap (Poussin *et al.*, 2003). These reports illustrate that yield gaps differ by production system, and that climatic attributes and crop management practices determine their extent. So far, yield gaps for rice in West Africa have rarely been decomposed into climate and management factors. Studies that did consider different climate zones (van Ittersum *et al.*, 2012; van Oort *et al.*, 2015c) did not look into management causes. Studies that focused on management causes (Becker and Johnson, 1999c; Wopereis *et al.*, 1999b) did that only in one climate zone.

We therefore see the need for site- and system-specifically differentiated yield gap analyses, for a separation of exogenously-driven (climate, water availability due to deviation from optimum sowing date) and farm endogenous (agricultural practices) yield gaps, and for the inclusion of yield gap variability in studies geared towards technology targeting. The present paper (i) assesses yield gaps in major rice production systems (irrigated and rainfed) across agro-climatic zones (semi-arid, sub-humid and humid) in West Africa, (ii) estimates the share and the variability of the yield gap caused by deviating from optimum sowing date and (iii) identify key factors affecting the yield gap in each production system, and their relative contribution to yield gap and yield gap variability.

2. Material and Methods

Data from farmers' fields' survey were combined with model simulations to estimate the yield potential and to quantify farmers' yield gaps and their determining factors.

2.1. Field data collection

Farmers' fields' survey was conducted between 2012 and 2014 with 824 farmers from 15 sites/rice production hubs, situated in 8 different countries in West Africa with 2 years of survey data per site. Sites were reduced from 22 (Table 2.1) to 15 sites with sites with one-year data excluded from the analysis. Each selected field was monitored during the rainy season using a 200 m^2 survey area within each farmer's field. In each survey field, three subplots of 12 m^2 were randomly delimited at the beginning of the season for observations, visual scoring, and yield measurement. Farmers were questioned regarding their management practices, field observations assessed soil attributes and the extent of yield-reducing factors (visual assessment of weeds, water status, lodging, bird damage), and grain yields were measured at harvest (Table 3.1).

Farmers’ practices during the cropping season were recorded, including methods of land preparation, rice variety used, source of rice seeds, crop establishment methods, crop establishment dates, fertilizer amount and timing, weeding frequency and method, and bird control. Field observations were carried out at tillering, flowering and maturity stages of the crop. They included scoring of land leveling, weed infestation (above and below rice canopy), soil water hydrology (ponded water, wet or dry soil), percentage of plants lodging, and bird damage at maturity. At harvest, grain yield was collected manually from the three harvest areas, air-dried, averaged and expressed at 14% grain moisture. Farmers’ practices and field observations were reclassified into category groups. Variety and seed sources were classified into local and genetically-improved rice varieties and into seeds obtained from own stock or purchased certified seeds. Weeding methods included the use of herbicide or other means of weed control. Straw was either “returned” (surface mulch, in situ animal feeding or incorporation) or “removed” (manual removal or burning). Weed control measures or fertilizer applications were classified into categories based on amounts of product applied or the frequency of application (Table 3.1). Upland sites were combined with rainfed lowlands to form the rainfed system as most upland fields were situated in hydromorphic zones, exposing attributes typically associated with lowland conditions (i.e. mottling of the soil).

2.2. Weather data

Climate data were collected by automated weather station in each site/rice production hub, including solar radiation, rainfall, and minimum / maximum temperatures. When ground station data time series were incomplete, weather data were extracted from the online GSOD database (Climate Prediction Center, 1987) or the POWER database (NASA, 2016) and bias-corrected for temperature (T) using the method described by Van Wart *et al.* (2015) and van Oort *et al.* (2015a). This method estimates parameters b0 and b1 using dates with available temperature from a regression equation:

Table 3.1: Variables collected in rice farmers' fields in West Africa

Variable description	Type	Data collection	Parameter
Agricultural practices			
Land preparation	Straw management before rice cultivation	Interview	1=returned to the soil, 2= removed from the field
	Tillage method	Interview	1= mechanical, 2= manual
	Land leveling	Observation	1= leveled, 2 = not leveled
	Bunding	Observation	1 = bunded, 2 = not bunded
Plant material and establishment	Variety	Interview	1= improved, 2 = local
	Sources of seeds	Interview	1= certified, 2 = uncertified
	Crop establishment method	Interview	1= direct seeding, 2= transplanting at 21 days after seeding (DAS), 3 = transplanting at 22-30 DAS, 4 = transplanting at > 30 DAS
Fertility management			
	Application rates of nitrogen (N), phosphorus (P) and potassium (K) fertilizers	Interview	kg/ha
	Frequency of fertilizer application	Interview	1 = none, 2= once, 3 = equal to or more than twice
Weed and pest control			
	Herbicide use for weeding	Interview	1 = yes, 2 = no
	Weeding frequency	Interview	1= none or once, 2 = twice, 3 = equal or more than three times
	Bird control	Interview	Scaring/nets, or none
Field and crop status			
	Field hydrology at tillering, around flowering and at maturity	Field observation	1 = ponded water, 2= wet soil, 3 = dry soil
	Weed above and below rice at tillering, around flowering and at maturity	Field observation	0 = no weed, 1 = 1-10%, 2 = 11-30%, 3 = more than 30 %
	Bird damage at maturity	Field observation	0 = no damage, 1= less than or equal to 30% damage, 2 = more than 30% damage
	Lodging at maturity	Field observation	0 = no lodging, 1= 1-10%, 2 = 11-30%, 3 = 31-60%, 4 = > 60%

T (station) = b0 + b1*T (POWER)

For dates with missing station data, the temperatures (T_{min}, T_{max} and T_{dew}) were estimated from POWER, using the estimated b0 and b1 values for bias correction:

T (station missing) = b0 + b1*T (POWER)

2.3. Model calibration and validation

The rice crop growth model ORYZA2000 (Bouman *et al.*, 2001) was used to simulate potential yields at optimum sowing date and individually for each farmer's crop establishment date to calculate reference yields and estimate yield gaps. Model equations were modified based on simulations for irrigated rice in the semi-arid zone of Senegal (van Oort *et al.*, 2015a) to better estimate cold or heat sterility, leaf senescence and early leaf growth. Full details on the model version used (ORYZA2000v2n13s14), can be found in van Oort *et al.* (2015a). Parameters for phenological development rates and base temperature for early leaf growth were calibrated per site. We applied a base temperature for development (TBD) of 14°C and an optimum temperature for development (TOD) of 31°C, assuming that development rates remain optimal above TOD (van Oort *et al.* 2011).

We further assumed that the rice varieties were non-photoperiod sensitive, allowing to apply the same development rate for the basic vegetative and the photoperiod sensitive phases. For each site, development rates were manually calibrated for the first year of observations in such a way that for a given crop establishment period for wet season rice, the simulated crop growth duration was similar to the duration recorded from field surveys. Only development rate parameters development rate at initial stage (DVRI) (for the basic vegetative phase) and development rate at juvenile stage (DVRJ) (for the photoperiod sensitive phase) were calibrated (Table 3.3) as they are reportedly most variable among rice varieties (Vergara and Chang, 1985). For the phase from panicle initiation to flowering (DVRP) and flowering to maturity (DVRR) fixed parameters were used (Table 3.2).

Table 3.2: Common input parameters for all sites for model calibration of the ORYZA2000 crop growth model

Parameter	Value	Unit	Description
TBD	14	°C	Base temperature for phenological development[1]
TOD	31	°C	Optimum temperature for phenological development[1]
TMD	999	°C	Maximum temperature for development[1]
RGRLMX	0.0085	°C day^{-1}	Maximum relative growth rate of leaf area[1]
RGRLMN	0.0040	°C day^{-1}	Minimum relative growth rate of leaf area[1]
DVRP	0.016667	day^{-1}	Development rate in panicle development[2]
DVRR	0.045455	day^{-1}	Development rate in reproductive phase[2]

[1]Source : (van Oort *et al.*, 2015a) ; [2]Source: (van Oort *et al.*, 2011). The development stage at panicle initiation is 0.65, development stage at flowering is 1.0, therefore the minimum duration for this phase (at continuously optimal temperatures) is (1-0.65)/0.016667 = 21 days and duration will be longer at sub-optimal temperatures. Duration from flowering to maturity is from development stage 1 to 2. Minimum duration is therefore (2-1)/ 0.045455 = 22 days

The value of the base temperature for leaf growth (TBLV) was set a default value of 14°C. In cases when simulated maximal leaf area index (LAIMAX) was <2, TBLV was set back to the ORYZA2000 default value of 8°C to increase simulated LAI and yield (Table 3.3). Data from the second year were used for validating simulated crop growth durations and yields in the first year. Only sites with complete weather data during the survey period were used in the simulations and calibrated parameters for each site / rice production hub are reported in Table 3.3. Reported data refer only to the most popular variety used at each site. Simulating water limited yield for each farmer's field in the rainfed systems required soil water attributes that were estimated using soil texture and soil organic carbon content using the model proposed by Saxton *et al.* (1986). Derived parameters comprised bulk density, hydraulic conductivity, and water content at saturation, field capacity and wilting point. The groundwater depth was required to simulate capillary rise in cases of rainfall deficit was not measured in farmers' fields. In upland systems sites, the groundwater table was set to a high value (1000 cm) with no possibility for capillary rise whereas in rainfed lowland it was set to a constant average value (between 10 and 40 cm) for each site based on information from national partners cross checked using model simulations and actual farmers' yields.

2.4. Reference yields and yield gaps

Different yields were measured and simulated in this study, from which we calculated the yield gaps:

- Y_{pot} = potential yield simulated using optimum crop establishment date (irrigated)
- Y_{fpot} = potential yield simulated using farmer's crop establishment date (irrigated)
- Y_{wl} = water limited yield simulated using optimum crop establishment date (rainfed)
- Y_{fwl} = water limited yield simulated using farmer's crop establishment date (rainfed)
- Y_{af} = farmers' actual yield

For Y_{pot} and Y_{wl}, we determined the optimal crop establishment date by simulating for a period of 100-300 day at 5-day increments to derive the date that provides the highest grain yield for a given site / rice production hub and year. Average soil data across fields in each site were used for determining optimal crop establishment date for rainfed systems.

Above reference yields were used to estimate different yield gaps as following:

- $YG_1 = Y_{pot} - Y_{af}$ (irrigated)
- $YG_1 = Y_{wl} – Y_{af}$ (rainfed)
- $YG_2 = Y_{fpot} - Y_{af} = YG_1 – (Y_{pot} - Y_{fpot})$ (irrigated)
- $YG_2 = Y_{fwl} - Y_{af} = YG_1 – (Y_{wl} – Y_{fwl})$ (rainfed)

($Y_{pot} – Y_{fpot}$) and ($Y_{wl} – Y_{fwl}$) are differences in potential yield or water limited using two crop establishment dates (optimum and actual dates). In irrigated systems, sub-optimum crop establishment time could cause spikelet sterility induced by heat or cold stress at critical growth stage (Dingkuhn *et al.*, 1995). In rainfed systems, it could result in water stress at any growth stage (Bouman *et al.*, 2001). YG_2 is caused by all the factors (including pests and diseases) except for crop establishment date. The conceptualization of the determination of the different yield gaps and the difference in potential yield is presented in across the 3 climatic zones (Figure 3.1).

Table 3.3: List of selected sites across climatic zones and their properties: name of most popular variety used, input parameters for the popular variety at each site, and mean simulated and observed crop growth duration of rice.

Country	Site	Climatic zone	Number farmers	Variety name	TBLV[1]	DVRJ = DVRI2	Average crop duration[3]	
							Sim.	Obs.
Irrigated systems								
Benin	Malanville	Semi-arid	79	IR841	8	0.00935	129	131
Côte d'Ivoire	Gagnoa	Humid	58	Bouaké-189	14	0.01482	117	122
Ghana	Navrongo	Sub-humid	32	Gbewaah	14	0.00798	154	156
Mali	Kouroumari	Semi-arid	42	Kogoni 91-1	8	0.01140	116	123
Niger	Tillabery	Semi-arid	65	Gambiaka	14	0.00741	147	153
Gambia	Central River	Semi-arid	70	Fourtinoo	14	0.01482	112	119
Togo	Maritime	Sub-humid	39	IR841	14	0.01482	114	123
Rainfed systems								
Benin	Glazoué	Sub-humid	34	Gambiaka	14	0.01368	132	159
Côte d'Ivoire	Man	Humid	73	Demamba	14	0.01140	156	162
Ghana	Kumasi	Humid	34	Lapez	8	0.01938	112	127
Ghana	Savelugu	Sub-humid	79	Digang	14	0.01140	139	140
Mali	Sikasso	Semi-arid	88	Sogodogochi	14	0.01596	126	128
Nigeria	Nasarawa	Sub-humid	52	Faro 44	14	0.01710	120	120
Togo	Plateaux	Sub-humid	48	IR841	14	0.01596	122	130
Gambia	West Coast	Semi-arid	70	NERICA	8	0.02166	99	97

[1] TBLV (°C): Base temperature for juvenile leaf area growth

[1,2] the assumption was made that the varieties were not photoperiod sensitive, just one development rate parameter was assumed for the vegetative phase, DVRJ (day^{-1}): development rate in juvenile phase, DVRI (day^{-1}) was the same as development rate in photoperiod sensitive phase. The development stage at emergence and panicle initiation is 0 and 0.65, therefore the minimum duration for this phase (at continuously optimal temperatures) is (0.65-0)/DVR. For example, the minimum duration for this phase for the common variety in Tillabery is (0.65-0)/ 0.007413 = 87 days and duration will be longer at sub-optimal temperatures.

[3] Simulated (Sim.) is the average simulated duration from emergence to physiological maturity averaged over farmers' crop establishment dates in 2 years. Observed (Obs.) is the average recorded duration from crop establishment (in the nursery in case of transplanting) to harvesting, averaged over the same crop establishment dates as simulated ones.

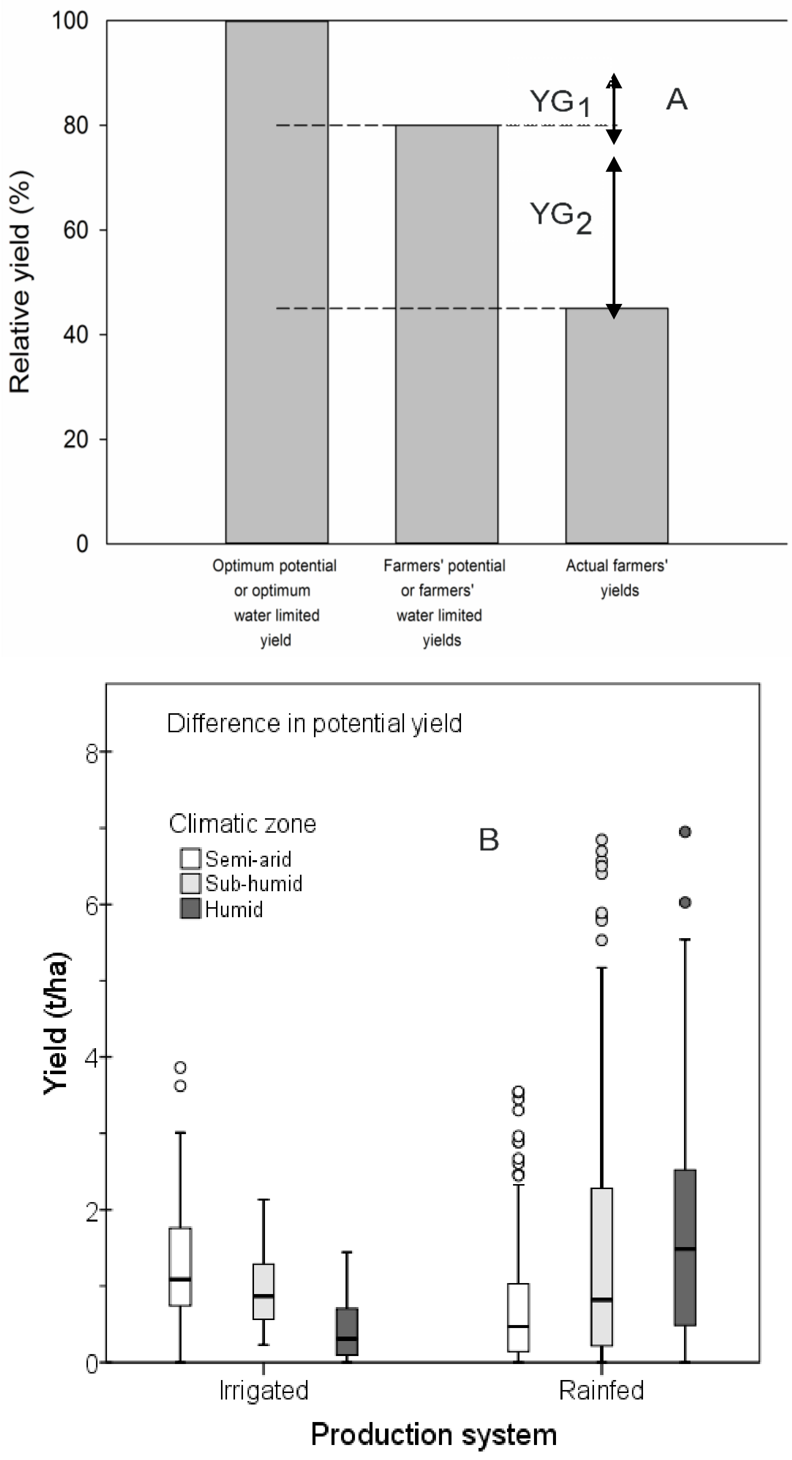


Figure 3.1 : A. Conceptual presentation for determining different yield gaps: 1. YG1 gap between simulated optimum potential (or water limited) and farmers' actual yield; 2. Potential yield difference is related to the deviation from the optimal crop establishment date or difference between simulated potential (or water limited) yield at optimum sowing date and farmers' potential or water limited yield at farmers' crop establishment dates; 3. YG2 gap is related to all other factors than crop establishment date or difference between the simulated yield (potential or water limited) at actual crop establishment date and farmers' yields. adapted after Lobell et al. (2009b). B. Difference in potential yield range in the 2 production systems

The data may also contain variables that are highly correlated between them as a result of instable model. In the presence of correlated variables, the mean squared error does not increase because of the presence of the other variable that carries the same information. The value of the prediction error after permutation is close to the value of the prediction error without permutation with small importance. First, we removed practices when their consequences on the field were assessed or measured with field observations. For example, bunding and land leveling were removed because water status was measured. Weeding frequency and herbicide use were subsequently removed from the model for weed scores and bird control for bird damage. In irrigated system water status was removed from the variables because measured water score was at least wet in more than 95% of the cases. To remove the effect of other irrelevant and correlated variables from the model we used the technique of Recursive Feature Elimination (Guyon and Elisseeff, 2003). This requires eliminating the least relevant variable in the RF classification and to repeat the classification procedure until a stable model was obtained. Between two correlated variables the most important variable had higher importance and the other variable tended to be the least important variable and can be removed from the model.

3. Results

The following section presents the results of the model calibration the distribution of yield gaps and their variability by production systems, climatic zones and sites, and the relative importance of management factors in explaining the yield gap YG_2.

3.1. Calibration and validation results

Simulated crop growth durations in different production systems across climatic zones for different rice varieties have been plotted against the observed crop durations in the first observation year (calibration) and in the second year (validation) which shows a reasonable to good accuracy of the simulation (Figure 3.2).

3.2. Relationship between actual and simulated yields

In addition, simulated potential (irrigated systems) and water limited yields (rainfed systems) were plotted against actual farmers' yields across production systems and climatic zones (Figure 3.3).

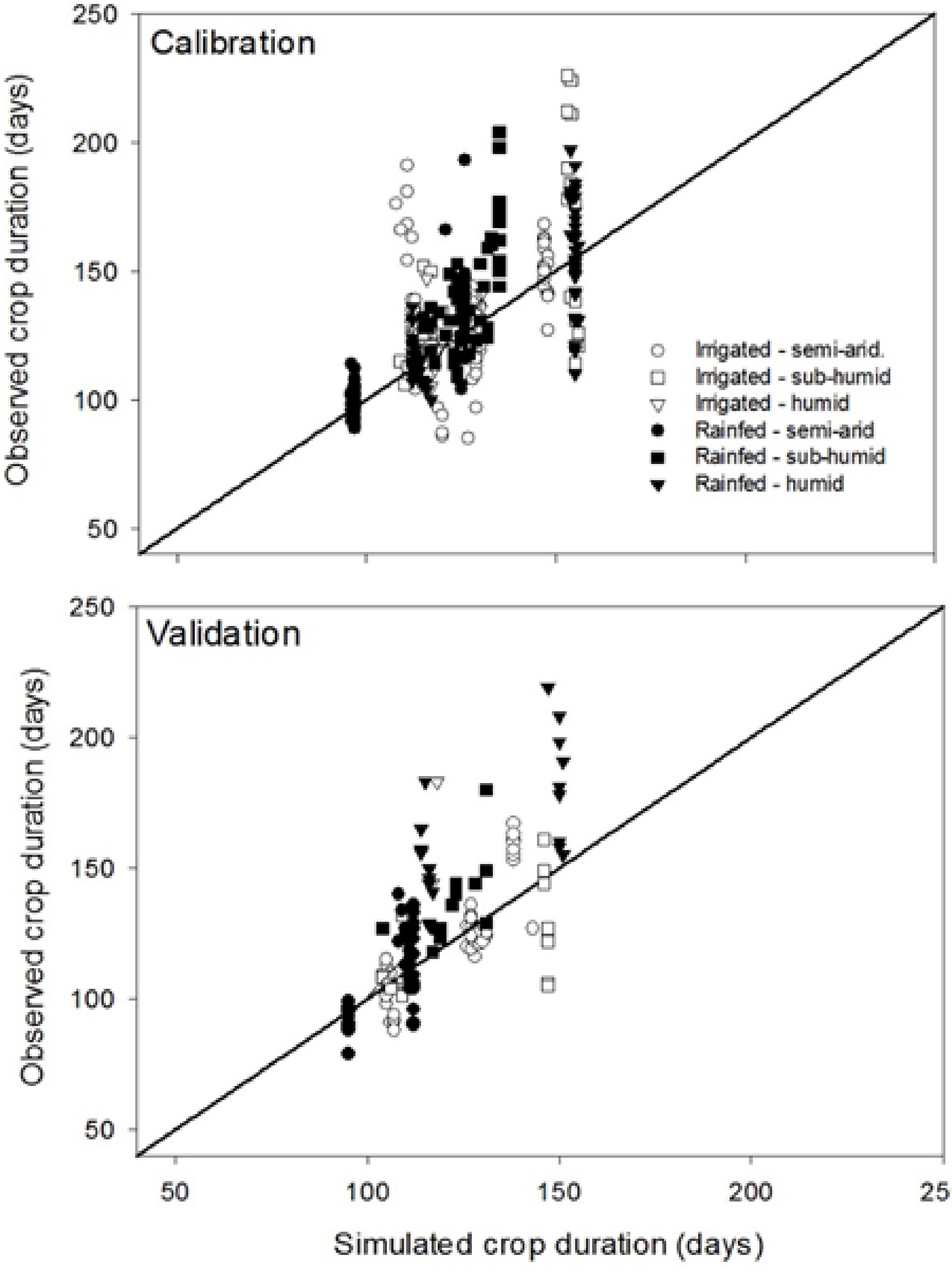


Figure 3.2 : Crop growth duration of farmers' varieties, 1. Calibration in irrigated R^2 (semi-arid = 0.20, sub-humid = 0.37 and humid = 0.10), and rainfed R^2 (semi-arid, = 0.68, sub-humid = 0.49 and humid = 0.53). 2. Validation irrigated R^2 (semi-arid = 0.75, sub- humid = 0.42 and humid = 0.10) and rainfed R^2 (semi-arid = 0.51, sub-humid = 0.39 and humid = 0.41).

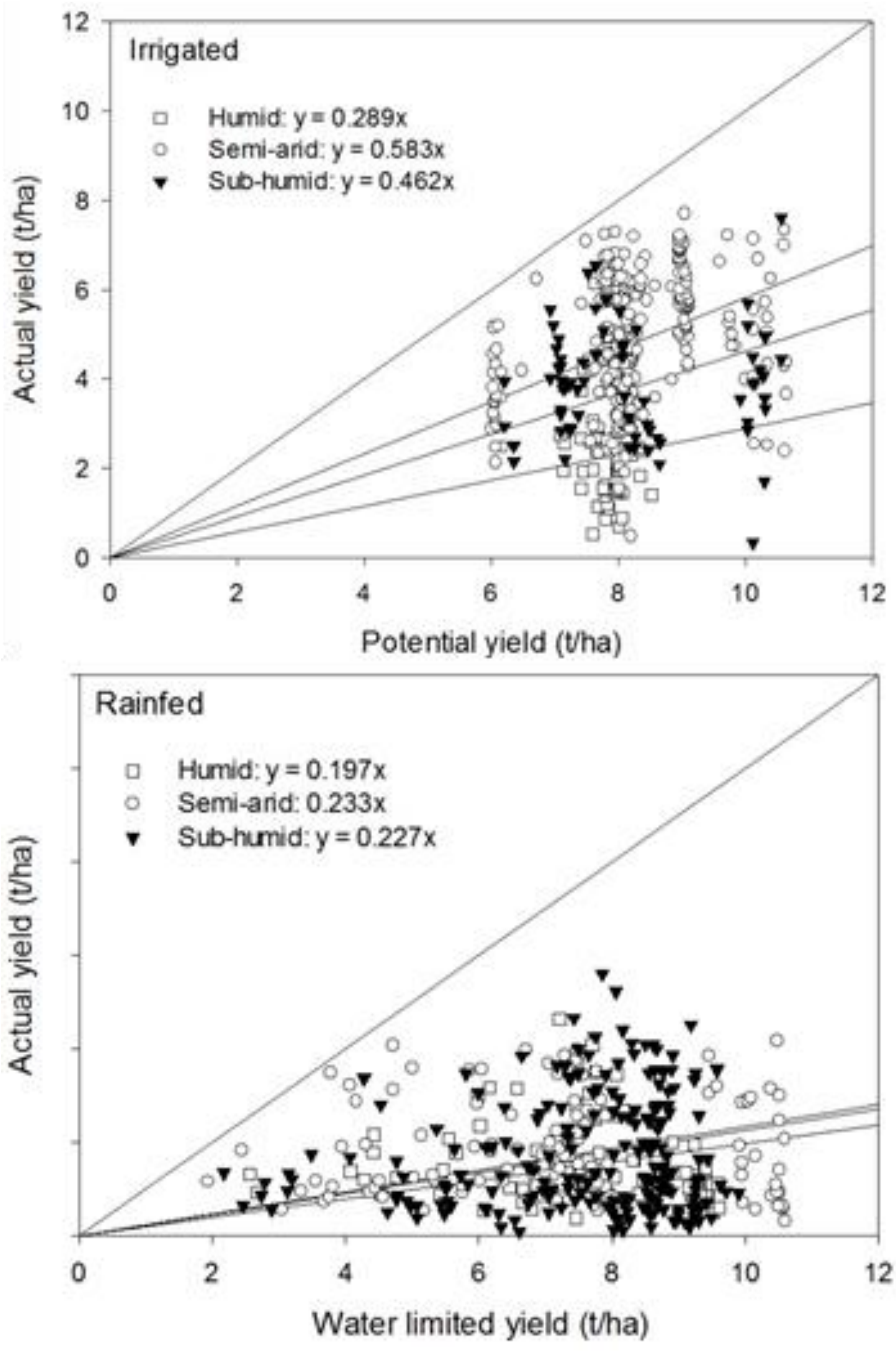


Figure 3.3 : Relation between actual farmers' yields and potential yields in irrigated (left) and water limited yields in rainfed system (right) at farmers' sowing dates at each production system across climatic zones.

The graphs show the range of the yield gaps and indicate large difference between the irrigated and the rainfed production systems with yields in irrigated system being closer to the 1:1 line than in rainfed systems and similar trends being apparent for semi-arid, humid and sub-humid climatic zones. Generally, the scatter underlines the large variability in grain yields, ranging from 0.5 to 8 t/ha in irrigated and from 0.1 to 6 t/ha in rainfed production systems. Slope of regression lines in irrigated systems indicate that actual yields are 42% below potential in the semi-arid zone (1-0.58 t/ha), 54% in the sub-humid zone (1-0.46 t/ha) and 71% in the humid zone (1-0.29 t/ha). In rainfed systems, actual yields are 77% below potential in semi-arid and sub-humid and 81% in humid zones (Figure 3.4). Hence, most farmers operate far from the potential and the gaps due to poor management practices and to unaccounted yield-reducing factors being very large.

3.3. Extent and variability of yield gaps across zones and systems

The different rice yield gaps show a large variability in all systems with a range of potential differences due to deviation from optimal sowing dates (YG_1) between 1.1 and 10.2 t/ha in irrigated system and between 3.5 and 10.3 t/ha in rainfed system (Figure 3.1). The range of the difference in potential yield was more important in rainfed systems (0-6.9 t/ha) than in irrigated systems (0-3.9 t/ha). The difference in potential yield due to the deviation from optimum sowing date was relatively more important in semi-arid zone and in humid zone in irrigated and rainfed systems respectively. Similarly, it was lower in humid zone and in semi-arid zone (Figure 3.1 B). In irrigated systems, YG_1, and YG_2 differed significantly between climatic zones. YG_2 was higher in humid zone and lower in semi-arid zone. In rainfed systems, YG_1 was different between zones with higher mean values recorded in humid zone and lower mean values in semi-arid zone. However, similar values were recorded for YG_2 between climatic zones.

In overall, average yield was 59, 49 and 29 % of the farmers' potential yield in irrigated system and 51, 44 and 27 % of the optimum potential yield. Similarly, it was 27, 24 and 22 % of the farmers' water limited yield and 22, 20 and 17 % of the optimum water limited yield in rainfed system (Table 3.4).

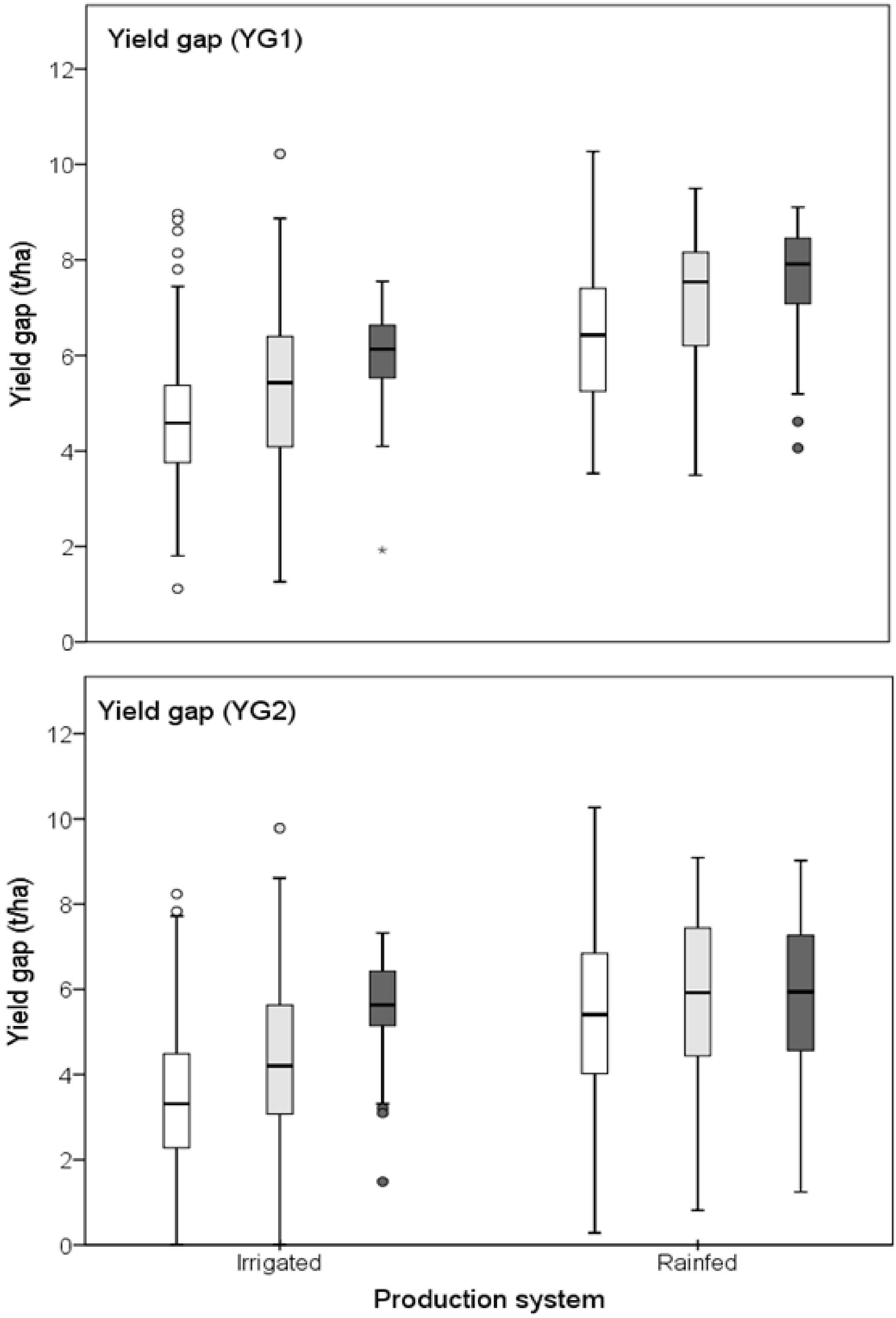


Figure 3.4: Range of the yield gaps in 2 production systems across 3 climatic zones (YG1 and YG2)

Table 3.4: Rice yields and yield gaps at each production system across agro-climatic zones

	Production systems					
	Irrigated			Rainfed		
	Semi-arid	Sub-humid	Humid	Semi-arid	Sub-humid	Humid
	Farmer's yield (% of potential yield)					
Farmers' sowing date	59	49	29	27	24	22
Optimum sowing date	51	44	27	22	20	17
	Yield gaps (t/ha)[a]					
YG_1	4.6a	5.3b	6.0c	6.6a	7.2b	7.6c
YG_2	3.4a	4.3b	5.5c	5.4a	5.8a	5.8a

[a] Yield gaps are compared horizontally between AEZ for the same production system. Yield gaps following with a different letter are significantly different at $p<0.05$

In irrigated systems, highest yield gaps were recorded in Navrongo in Ghana, Gagnoa in Côte d'Ivoire and Kouroumari in Mali between 5.7-6.4 t/ha for YG_1 and between 4-5.9 t/ha for YG_2. Similarly, highest values in rainfed system were between 6.7-7.9 t/ha for YG_1 and were observed in Kumasi in Ghana, Glazoué in Benin, Sikasso in Mali, Savelugu in Ghana and Man in Côte d'Ivoire. Highest YG_2 values were between 5.7-6.7 t/ha and were recorded in the same sites as YG_1 except for Kumasi which recorded lowest YG2 (Table 3.5). In irrigated system, the CV was between 18-34 % and between 21-50 % for YG_1 and YG_2 respectively and between 8-29 % and 22-48 % in rainfed system.

3.4. The role of management factors in the yield gap YG2

The most important yield predictors resulted from the RF classification were specific to each production system. The management factors explained 41 % and 32 % of the variance of YG_2 in irrigated and rainfed systems respectively.

In irrigated system, N application rate, weed score above and below rice canopy at maturity stage, weed score above rice canopy at tillering stage, N application splits and crop establishment method were classified as the most important variables explaining the yield gap (YG_2). In rainfed system these factors were variety choice, weed score above at maturity stage, weed below at flowering stage, straw management, field hydrology at flowering stage and N application splits (Table 3.6).

Table 3.5: Yield gaps and their variability at site level for each production system.

Sites	YG_1		YG_2	
	Mean (t/ha)	CV (%)	Mean (t/ha)	CV (%)
	Irrigated systems			
Central River	4.4	21	3.9	30
Gagnoa	6.0	16	5.5	21
Kouroumari	5.7	27	4.0	50
Malanville	4.0	34	2.9	46
Navrongo	6.4	22	5.9	22
Maritime	4.3	27	3.1	36
Tillabery	5.0	18	3.0	37
	Rainfed systems			
Glazoué	7.9	17	6.7	40
Kumasi	6.7	16	4.6	31
Man	8.1	8	6.7	25
Nasarawa	6.3	20	6.0	22
Plateaux	6.3	15	5.0	27
Savelugu	8.1	10	5.7	35
Sikasso	7.0	29	5.7	48
West Coast	6.0	16	5.2	31

In Table 3.7 we investigated the effects of these variables on the yield gap YG_2. In irrigated system transplanting as crop establishment method reduced yield gap by 0.6 t/ha compared to direct seeding. The percentage of weed invasion above canopy at tillering and maturity stages between 1 and 10% increased the yield gap by 0.8 and 0.5 t/ha while it was 1.2 and 2.3 t/ha increase when weed invasion at maturity stage was between 10 and 30% and more than 30% respectively. N application rate decreased yield gap by 5 kg/ha for each kg N applied. In rainfed system as it was in irrigated system weed above canopy at maturity have significant role on the increase of yield gap. It was 0.7, 0.9 and 1.9 t/ha decrease when weed invasion was between 1-10%, 10-30% and more than 30% respectively. In addition, the use of local variety increased the yield gap by 1.5 t/ha whereas an average field hydrology near dry condition increased the yield gap by 1.1 t/ha.

Table 3.6: Main management factors generated by the RF algorithm explaining rice yield gap (YG_2) variability

Rank based on %IncMSE[a]	Irrigated system	Rainfed system
1	N application rate	Variety
2	Weed score above canopy at maturity	Weed score above canopy at maturity
3	Weed score above canopy at tillering	Weed score below canopy at flowering
4	N application splits	straw management
5	Weed score below canopy at maturity	field hydrology at flowering stage
6	Crop establishment method	N application splits
Mean of squared residuals	1.6	2.7
% variance explained	41	32

[a] Rank 1 indicates higher % of increase in mean square error (%IncMSE) = high variable importance.

4. Discussion

Rice yield gaps were quantified in the two main production systems (irrigated and rainfed) and three agro-climatic zones (semi-arid, sub-humid and humid) in West Africa and the main causes were investigated. Farmers' yield gaps were variable in all systems with an average of 5.3 and 4.4 t/ha in irrigated system and 7.1 and 5.7 t/ha in rainfed system for YG_1 and YG_2 respectively. The results for irrigated systems are consistent with the range and average of yield gaps measured in the semi-arid and sub-humid zone (Wopereis *et al.*, 1999b) and in the humid zone (Becker *et al.*, 2003b). In rainfed system the significant difference in farmers' yield gap (YG_1) between zones was due to the difference in potential yield caused by the deviation from optimum crop establishment date. YG_2 showed no significant difference between climatic zones. On average, total yield gap represented 62% and 80% of the yield potential in the irrigated and rainfed systems respectively.

Table 3.7: Parameter coefficients estimates of the prediction of yield gap (YG2) in irrigated and rainfed system of West Africa

Variables	Irrigated system	Rainfed system
	Coefficients estimate	
Intercept	4.453***	4.236***
Crop establishment method: transplanting	-0.619*	
Weed score above canopy at tillering: 1	0.788**	
Weed score above canopy at maturity: 1	0.449*	0.718**
Weed score above canopy at maturity: 2	1.242**	0.935*
Weed score above canopy at maturity: 3	2.265***	1.873***
N application rate	-0.005*	
Field hydrology at flowering stage: 3		1.064*
Variety: local		1.447***
R^2	0.34	0.30

Coefficients are significant at *P≤0.05, **P≤0.01 and ***P≤0.001

The management factors that were important in explaining the yield gap YG_2 differed in some extent between production systems. This is an important and useful finding, because it tells us that recommendations to close the yield gap without a clear identification of the most important factors affecting the gap will be less effective.

In the rainfed systems the most effective ways to narrow the yield gap would be to encourage the dissemination of well improved varieties, promote bunding for water control, and to carry out more weeding frequency. These same interventions would probably be less useful in the irrigated zones, where priority should be given to promoting fertilizer application mainly nitrogen, weeding frequency and transplanting as crop establishment method. The results of this study showed the difference in potential yield due to deviating from the optimum crop establishment date. Farmers have generally less or no control on the crop establishment date mainly due to socio-economic factors eg: availability of inputs (seeds, fertilizers), labor and equipment for land preparation. However, this difference in potential yield was in many cases marginal compared to the yield gap YG_2 which represented the largest part of the total farmer's yield gap (YG_1) (>80%).

In both system weed infestation above rice canopy at maturity stage increased significantly rice yield gap. The separation of the effects of weed infestation at different stages of rice growth was rarely studied and deserve further investigation. From previous studies, weed infestation in rice fields was reported to negatively affect yield in West Africa (Johnson *et al.*, 2004; Rodenburg *et al.*, 2014a). In a recent study, Ihsan *et al.* (2014) has observed drastic reduction of the number of tillers, grain per panicle and 1000-grain weight attributed to weeds. Weeds compete with rice for light (above rice canopy), water and nutrients (above and below rice canopy), specially nitrogen (Becker and Johnson, 2001a). Singh *et al.* (2008) has observed no yield increase when nitrogen fertilizer was applied in the presence of weeds. Behera and Jena (1998) have observed increased yield by applying herbicide compared to other weed control. Herbicide use has been reported to be effective and labor saving in weed control but their relative high cost limit their use in low input systems by resource-poor farmer's (Kremer and Lock, 1993; Rodenburg *et al.*, 2015).

The importance of N rate in the irrigated system of this study has been reported in previous study (Becker *et al.*, 2003b) and is still important as before in explaining the variability of rice yield gap among farmers. In this study we observed a decrease in the yield gap in irrigated system attributed to transplanting compared to direct seeding. This finding agrees with Kim *et al.* (1992) who reported yield losses due to direct seeding which caused weed growth biomass and promote growth of a large diversity of weed species. However, in many cases, despite of the relative yield decrease in direct seeding method, it has shown to produce higher income to farmers than transplanting as the result of saving in labor (Guang *et al.*, 2005). According to Awan *et al.* (2015), farmers in the semi-arid zone of Pakistan prefer direct seeding to transplanting because of reduced labor, and less arduous work. In rainfed system, local variety was associated with increased yield gap compared to improved varieties. It has been reported a yield increase of 39.7 % in a similar study in Nigeria attributed to the use of improved varieties (Saka and Lawal, 2009). In addition, Rodenburg *et al.* (2009) has shown superior weed competitiveness attributed to improved varieties which is an advantage to achieve higher yield. In a recent study in the rainfed upland system in West

Africa, Saito (2016) has reported increased yield with improved varieties compared to farmers' local varieties as a result of greater biomass accumulation, highest harvest index and better nutrient use efficiency. Moreover it was also reported weed-suppressive traits for some interspecific improved varieties (Touré *et al.*, 2011; Saito and Futakuchi, 2014) which can help reduce weed biomass decreasing the yield gap. Average field water status was recorded during vegetative stage (tillering) and reproductive stage (flowering and maturity). In rainfed system, the regression model (Table 3.7) showed increasing yield gap by 1.1 t/ha when soil was dry at flowering. This result agrees with observed increasing yield with increasing water availability in an experiment in West Africa in a genotypic adaptation of varieties to field hydrology (Saito *et al.*, 2010). Many factors that are known to reduce yield gaps did not show significant importance in this study. For example, in irrigated system variety choice did not show importance in yield gap reduction probably due to the fact that 94% of the farmers used improved varieties.

The analysis of yield gaps at field level, allowed a comparative understanding of their magnitude and the factors affecting them in the different production systems across climatic zones. This study has identified the most important factors for each production system and their relative importance for intervention prioritization. From the results of this study, farmer participatory demonstration trials need to be implemented at each site with a combination of GAPs to check how much yield gap can be further reduced.

Chapter 4 : **Yield variation of rainfed rice as affected by field water availability and N fertilizer use in central Benin**[3]

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[3] Published in Nutrient Cycling in Agroecosystems as:

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Abstract

Rice is mainly grown under rainfed conditions in West Africa. Unpredictable and variable rainfall, poor soil quality, and sub-optimal crop management practices are the main determinants of low productivity. We assessed the effects of soil water availability and fertilizer application, and their interaction on the yield of rainfed rice in Glazoué, Department of Zou-Collines, central Benin between 2010 and 2013. On-farm fertilizer management trials and field surveys were conducted in 13 to 39 farmers' fields per year. Field water conditions were visually assessed three times per week during the rice-growing season and flood and drought indices were calculated on the basis of number of days with ponded water and dry surface soil relative to the total number of days for the vegetative, the reproductive and whole rice-growing period. Variations in flood and drought indices were related to the sand content of the soil. While nitrogen was the most limiting nutrient, average response to N fertilizer application was low with an agronomic N use efficiency of only 7–9 kg grain per kg of N applied. Year-to-year variation in rainfall and spatial variation in field water status affected both rice yield and response to N fertilizer. Some 47% of the observed yield variation was explained by field water status and the amounts of N fertilizer applied, with rice response to N fertilizer being less when water was limited. We conclude that the prevailing blanket fertilizer recommendations are unlikely to contribute to yield increases in rainfed systems of West Africa. There is a need for field-specific recommendations that consider soil texture and the spatial–temporal dynamics of water availability.

Keywords*:* Agronomic N use efficiency / Drought / *Oryza* spp. / West Africa

1. Introduction

Rice (*Oryza* spp.) is an important cereal in West Africa. Driven by increased per-capita consumption and population growth, the demand for rice has been rapidly increasing since the mid-1980s (Saito *et al.*, 2015b). Local production does not meet the growing demand, and about 40% of the consumption is met by rice imports (Seck *et al.*, 2013). The prevailing low production has been ascribed mainly to low yields in rainfed systems, which represent 70% of the total rice cultivation area (Diagne *et al.*, 2013b). Rainfed systems generally yield less than irrigated systems, and large gaps between simulated potential and actual farmers' yields (van Oort *et al.*, 2015b) indicate large scope for yield increases. However, successes of government and international development programs to raise production in rainfed systems have so far been limited (Oikeh *et al.*, 2009). Saito *et al.* (2015b) Indicated that greater proportions of rice-growing area under irrigation are related to accelerating rice yield growth rates at national level.

Major obstacles for enhancing rice productivity in rainfed systems include: (1) yield-limiting factors such as water availability (Becker and Johnson, 2001d; Saito and Futakuchi, 2009; Touré *et al.*, 2009), poor soil quality (Saito *et al.*, 2013b), including N deficiency (Becker *et al.*, 2002), poor soil texture (Abe *et al.*, 2010), iron toxicity (Worou *et al.*, 2013), and P deficiency (Oikeh *et al.*, 2008); (2) yield-reducing factors such as weeds (Becker and Johnson, 2001a) and birds (Diagne *et al.*, 2013c); (3) sub-optimal crop management practices, including low rates (Oikeh *et al.*, 2008; Kamara *et al.*, 2010) and untimely application of mineral N fertilizer (Becker and Johnson, 2001d), leading to low N fertilizer recovery (Wopereis *et al.*, 1999b); and (4) socio-economic factors such as subsistence orientation of the production, poor household wealth, and limited access to markets. Among the yield-limiting factors, unreliable supply of water and N deficiency have been identified as the dominant biophysical constraints (Becker *et al.*, 2002).

While yields can be increased by N fertilizer application (Becker and Johnson, 2001d), farmers' actual application rates are generally lower than recommended rates, as most smallholders have limited capital resources and access to external inputs, and are faced with high production risk due to unpredictable and variable rainfall (Haefele *et al.*, 2013b). Moreover, soil water conditions in inland valleys often vary within short distances (Touré *et al.*, 2009), differentially affecting the efficiency of applied N and rendering the prevailing blanket recommendation (no site-specific N application) unsuitable in most cases. We surmise that an improved understanding of the factors affecting variation in yield and rice response to applied N in relation to field water availability can guide the development of site-specific recommendations, and consequently increase the productivity of rainfed rice in West Africa.

Using on-farm fertilizer management trials and field surveys from the main rainfed rice-growing zone in Benin, we (i) assessed variations in on-farm rice yields, (ii) evaluated the effects of rainfall and soil attributes on field water status, and (iii) identified interacting effects of field water availability and N application on the yield of rainfed lowland rice.

2. Material and methods

2.1. Study area and farmers' practices

This study was conducted in the villages of Papazoumé (7°55´12˝N, 2°15´36˝E) and Sowé (7°59´59˝N 2°12´36˝E) in Glazoué commune, Zou-Collines department in central Benin. Central Benin is the major rainfed rice-producing area of the country, with rice being grown in inland valleys of diverse and highly variable hydrological conditions (Saito *et al.*, 2012). The area falls within the moist Savannah agro-ecological zone (FAO/IIASA, 2012). The average annual rainfall of about 1100 mm falls in a mono-modal pattern and the average temperature is 28°C with little variation over years (Table 4.1). Climate data were obtained from a weather station in Savé, about 40 km north of the study area. The soils are classified by the World Reference Base for Soil Resources as Ferralsol on the slopes and as Gleysol in the valley bottom lands (FAO, 2014).

Tillage is done either manually by hoe or using a cattle-drawn plow, and may include open plots or the building of field bunds. The rice cropping season starts in early June and ends in late December. Common varieties grown include both upland (NERICA 1, NERICA 2, NERICA 4) and lowland rice varieties (NERICA 5, WAB 32, IR 841) that are established mainly by direct broadcast or dibble seeding (Saito *et al.*, 2014). The distinction between upland and lowland production systems is not clear and depends on the position of field plots along the toposequence and the seasonally and annually highly variable field water conditions (Saka and Lawal, 2009). Weeds are mostly removed by hand, though a few farmers also use herbicides. While N fertilizer use is common, application rates are highly variable and mostly below the recommended rate of 60 kg/ha. Rice is harvested manually by sickle-cutting at ground level.

Table 4.1: Monthly rainfall and minimum and maximum temperatures in central Benin during rice-growing seasons (Savé weather station, 2010-2013).

Year	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Maximum temp (°C)							
2010	35	34	34	34	35	37	38
2011	36	33	33	34	35	37	38
2012	35	32	32	33	34	34	37
2013	33	34	31	32	34	36	36
Minimum temp (°C)							
2010	22	21	21	21	20	21	18
2011	21	21	20	21	21	21	16
2012	20	21	21	20	21	21	22
2013	20	20	20	20	20	20	18
Rainfall (mm)							
2010	80	99	273	228	153	43	0
2011	190	93	81	238	124	0	0
2012	152	248	82	237	119	0	0
2013	106	115	95	129	107	0	28

2.2. Experiments and field surveys

Six on-farm fertilizer management experiments were conducted in a total of 94 farmer fields during the wet seasons from 2010 to 2013 (Table 4.2). Each experiment had two to five treatments replicated once or twice in each of up to 27 farmers' fields per year. Individual treatment plots, ranging from 15 to 25 m^2, were randomized in each field. Farmers were selected on the basis of advice from local extension workers and village heads, and farmers' willingness to participate in experiments. Fertilizer application rates and timing are shown in Table 4.2. All crop management decisions and actions, except for fertilizer application, were taken by the individual farmers. In experiments 1, 2, 5, and 6, compound nitrogen, phosphorus, potassium (NPK) fertilizer (15–6–12) was applied basally and urea was applied as N top-dressing around panicle initiation (PI) stage. Experiments 3 and 4 aimed to identify the most limiting nutrient elements through omission plot studies (–N, –P, and –K) using urea, triple-superphosphate, and potassium chloride. Application rates differed by village. In experiment 6, the recommended fertilizer rate of 60 kg urea-N/ha (treatment 2, T2) was compared with individual farmers' practice (T1) with diverse application rates and timings of the top-dressing. In addition, field surveys were conducted in 2011 and 2012 to collect information on farmers' agricultural practices and yields. These surveys were conducted at the same farmers' fields as experiments 2–6, involving a total number of 72 fields or farm households.

2.3. Data collection

At rice seeding, soil samples (0–15 cm depth) were taken from each field; composites were made from eight core samples per field. The samples were air-dried and sieved for further analysis. As field surveys were conducted in the same fields as the on-farm experiments, same soil attributes were used for data analyses. Experiments and field surveys conducted over 2010–2013 in central Benin, fertilizer application rate and timing, and average rice yield. Fractions of particle size (clay, silt, and sand) were determined using pipette method. The soil pH (H_2O, 1:1), organic carbon, and total soil N contents, and available Bray-1 P were analyzed following methods described by Houba *et al.* (1995). Between 2011 and 2013, the field water status was recorded visually in each field two or three times per week and scored using a three-point scale (1: ponded water, 2: wet soil surface, 3: dry soil surface) following Haefele *et al.* (2006), and data were used for the analysis of both experiments and surveys. Flood and drought indices were calculated using the number of days with ponded water and dry soil surface (expressed as a percentage) and separated in (1) the total number of days of the rice-growing period (seeding to harvest), (2) the vegetative phase (seeding to PI), and (3) the reproductive phase (PI to flowering or maturity, or flowering to maturity). Thus, a field having standing ponded water in 10 out of a total of 100 field visits had a flood index of 10 (Table 4.2).

Table 4.2: Experiments and field surveys conducted over 2010–2013 in central Benin, fertilizer application rate and timing, and average rice yield.

Experiment/ survey	Year	No. farmers' fields	Treatments / Code[a]	Fertilizer application rate (kg/ha) and timing (DAP)[b]					Mean yield[c] (t/ha)
				Basal N	First N top-dressing	Second N top-dressing	P	K	
Survey	2011	33	Farmers' practice	0–69 (14–76)	0–86 (18–72)	0	0–23	0–38	2.3a
	2012	39	Farmers' practice	0–69 (18–94)	0–69 (42–91)	0	0–20	0–38	1.2b
Exp. 1	2010	13	No input	0	0	0	0	0	2.2c
		13	T2	15 (13–24)	23 (43–54)	0	7	13	2.8b
		13	T3	30 (13–24)	23 (43–54)	23 (63–74)	13	25	3.6a
Exp. 2	2011	8	No input	0	0	0	0	0	1.4b
		8	Low N, early TD	15 (15)	23 (45)	0	7	13	1.8b
		8	Low N, late TD	15 (15)	23 (65)	0	7	13	1.7b
		8	Med. N triple split	30 (15)	23 (45)	23 (65)	13	25	2.3a
		8	High N triple split	30 (15)	35 (45)	35 (65)	13	25	2.5a
Exp. 3	2011	12	No input	0	0	0	0	0	1.6b
		12	PK	0	0	0	30–50	50–83	2.0b
		12	NK	20–33 (15)	40–67 (45)	40–67 (65)	0	50–83	2.9a
		12	NP	20–33 (15)	40–67 (45)	40–67 (65)	30–50	0	3.0a
		12	NPK	20–33 (15)	40–67 (45)	40–67 (65)	30–50	50–83	3.3a
Exp. 4	2012	16	No input	0	0	0	0	0	0.7b
		16	PK	0	0	0	30	50	0.8b
		16	NK	20 (15)	40 (45)	40 (65)	0	50	1.3a
		16	NP	20 (15)	40 (45)	40 (65)	30	0	1.5a
		16	NPK	20 (15)	40 (45)	40 (65)	30	50	1.6a
Exp. 5	2012	18	No input	0	0	0	0	0	0.8b
		18	Recommandation	20 (15)	20 (45)	0	18	12	1.5a
Exp. 6	2013	27	Farmers' practices	0–94 (0–84)	0–41 (18–80)	0	0–37	0	1.0a
		27	Recommandation	40 (0–27)	28 (20–66)	0	9	17	1.2a

[c] *Yields of the same experiment followed by the same letter are not significantly different at 5% level based on least square mean difference.*

[a] *T indicates fertilizer treatments; TD: top-dressing of urea N; PK, NK, NP, and NPK are nutrient-omission treatments.*

[b] *DAP: days after planting.*

Genotypes were classified by growth duration as short (<100 days – NERICA varieties), medium (~120 days – WAB 32), or long duration (>140 days – IR 841, traditional types). PI and flowering dates were calculated as total crop growth duration minus 65 and 30 days, respectively. Rice management practices were recorded through interviews, comprising information on (1) land preparation, (2) seeds and crop establishment, (3) fertility management, and (4) pest and disease management. At maturity, rice yields were determined from 8-m^2 harvested areas in the center of each field plot and corrected to 14% moisture.

Table 4.3: Selected soil properties, flood and drought indices, and rice planting dates, and their variability.

	Average	Range	CV (%)[a]
Soil properties (n=126)			
Sand (%)	66	36–84	22
Silt (%)	22	7–45	57
Clay (%)	13	9–19	20
Organic C (g/kg)	6.7	3–12	27
Total N (g/kg)	0.5	0.2–1.0	33
pH (H_2O)	5.6	4.8–7.6	9
Bray-1 P (mg P/kg)	5.1	2–13	50
Flood index (cropping season)			
2011 (n=35)	14	0–76	144
2012 (n=40)	1	0–13	226
2013 (n=54)	0.4	0–13	482
Drought index (cropping season)			
2011 (n=35)	18	0–48	76
2012 (n=40)	21	0–55	83
2013 (n=54)	32	0–61	48
Planting date (Julian day)[b]			
2010 (n=39)	201	179–217	48
2011 (n=133)	211	166–250	30
2012 (n=155)	197	174–212	32
2013 (n=54)	195	175–221	64
Yield (t/ha) across all field plots			
2010 (n=39)	2.9	0.2–6.6	62
2011 (n=134)	2.3	0–6.0	74
2012 (n=156)	1.2	0–6.1	97
2013 (n=54)	1.1	0–5.5	103

[a] CV: coefficient of variation.

[b] Difference between each farmers' rice planting date and first farmers' planting date in each year was used to calculate CV.

2.4. Statistical analysis

For each experiment, ANOVA was conducted. Estimates of least square means of yield were followed by means comparison between treatments when treatment effects were significant (Table 4.2). Multiple linear regressions were applied on field surveys and fertilizer management trials, except for experiment 1 in 2010 for which no drought or flood indices were available. From the results of the analyses shown in Tables 4.2 and 4.3, total N fertilizer application rates, planting date, and flood and/or drought index were chosen as predictors of rice yield. The number of N splits was not included as it was correlated with total N rate (r =0.65, P <0.01). The effects of drought or flooding on yield and rice response to applied fertilizer was disaggregated by growth stages (vegetative, reproductive, total) as rice yields respond differentially to water conditions in different development stages (Bouman *et al.*, 2001)Eighteen models to predict rice yield and yield response to fertilizer were applied, fitted, and ranked based on lowest Akaike's information criterion (AIC) using R statistical software (R development Core Team, 2011). Factors affecting yield variation of were examined using the following models with yield as response variable:

- Model 1: N rate
- Model 2: N rate, planting date
- Model 3: flood and drought indices (planting date to maturity)
- Model 4: N rate, and flood and drought indices (planting date to maturity)
- Model 5: planting date, flood and drought indices (planting date to maturity)
- Model 6: N rate, planting date, flood and drought indices (planting date to maturity)
- Model 7: flood and drought indices (planting date to PI, PI to maturity)
- Model 8: N rate, drought index (planting date to PI, PI to maturity)
- Model 9: N rate, planting date, drought index (planting date to PI, PI to maturity)
- Model 10: drought index (planting date to PI, PI to flowering, flowering to maturity)
- Model 11: N rate, flood and drought indices (planting date to PI, PI to flowering, flowering to maturity)
- Model 12: N rate, planting date, flood and drought indices (planting date to PI, PI to flowering, flowering to maturity).

Multiple linear regression was applied to identify the main factors affecting yield response to N, P, and K fertilizers (calculated as the difference between the NPK plots and the omission plots (PK, NK, NP), following Cassman *et al.* (1998). As yield responses to P or K were very small (Table 4.2), only yield responses to applied mineral N were considered in subsequent analyses. Factors affecting the variation of yield response to N were examined using the following models with yield response to N as response variable:

- Model 13: drought index (planting date to maturity)
- Model 14: planting date, flood and drought indices (planting date to maturity)
- Model 15: drought index (planting date to PI, PI to maturity)
- Model 16: flood and drought indices (planting date to PI, PI to flowering, flowering to maturity).

As flood and drought indices were not normally distributed, a generalized linear model with binomial distribution was used to identify factors affecting variations in field water status (McCullagh and Nelder, 1989). The following models were used with flood or drought index as response variable and soil parameters as predictors. Only data of 2011 and 2012 that had complete soil data were used. As rainfall distribution and amount were similar during the most important part of the cropping season (August to November) in 2011 and 2012, rainfall was not included as a predictor:

- Model 17: sand content
- Model 18: sand and organic C content
- Model 19: clay content
- Model 20: clay and organic C content

3. Results

3.1. Rice-growing environments and crop management

Climatic conditions differed between study years and edaphic attributes differed between fields. Thus, total rainfall during the rice-growing season (June–December) was similar in 2010–2012 and 2014 (228–237 mm) but much lower in 2013 (129 mm) (Table 4.1). The rainfall distribution during the growing season also differed, differentially affecting field water availability during different rice development stages. Thus, rainfall-induced water limitations occurred during the vegetative growth stage in 2010, during the early reproductive stage in 2013, and during the maturity stage in 2011 and 2012. Maximum and minimum temperatures, on the other hand, showed little variation between years. Soil properties (except for soil pH) differed markedly between fields (Table 4.2). Texture classes comprised anything from sand to clay-loam, organic C content ranged from 3 to 12 g/kg, total N from 0.2 to 1.0 g/kg, and available P from 2 to 13 mg/kg soil. Related to rainfall and soil texture, the drought index varied from 0 (no day during the rice-growing period without ponded water) to 67 (up to 10 weeks of potential water deficit). In terms of crop management, the largest differences were observed in rice planting dates (Julian date 106 to 250) and mineral fertilizer application rates (0–155 kg N/ha, 0–38 kg P/ha, and 0–37 kg K/ha). Some 12% of the farmers did not apply any fertilizer, and 44% applied fertilizer only once. Less than 44% of the farmers followed the recommended split application of N fertilizer.

3.2. Yield variation and its determinants

These differences in growing conditions (years and soil attributes) and crop management practices resulted in large differences in rice grain yields, with mean yields of 1.0–3.6 t/ha across experiments and years and individual field yields ranging from complete crop failure to more than 6.6 t/ha (Table 4.2). Across experiments, sites, and fields, average yields tended to be highest in 2010 and lowest in 2013 (highest drought index). Both the fertilizer response and the nutrient-omission trials underlined the role of N as the main limiting nutrient. Responses to P and K application tended to be non-significant. The recommended fertilizer rates were apparently too low in wet years or in fields with high flood indices, and provided little yield advantage over the non-amended control in dry years or in fields with high drought indices.

Comparing the models, which differed in the site and management attributes used to explain rice yields, model 5 provided the best fit for the survey data with an AIC of 310. This model considered only the rice planting date and water status throughout the growing period (drought and flood indices) for explaining yields and yield variability. In the case of the experimental data and the combined experiment plus survey data, model 12 provided the best fit with AICs of 718 and 1040, respectively. The model considered the planting date, the applied N rate, and the water status (drought and flood indices) during the vegetative and reproductive stages, explaining up to 56% of the observed variance. In all cases, the field water status (be it expressed as water availability in relation to planting date and rainfall, or as the observed drought/flood indices) affected yields. Most critical was the occurrence of drought in the reproductive growth stage between PI and flowering. During this period, a 10% increase in the flood index was associated with a 0.2 t/ha yield increase.

Table 4.4: Model parameters explaining variations in yield and N fertilizer response, regression coefficients, and 95% lower / upper confidence interval estimates.

Variable	Estimate	95% confidence interval		P-value[a]
		Lower	Upper	
Case 1: Farmer-managed plots (n=100) – model 5				
Flood index (P–M)[b]	0.022	0.003	0.041	0.02
Drought index (P–M)	–0.034	–0.049	–0.018	<0.01
Planting date	–0.005	–0.011	0.022	ns
Intercept	1.112	–2.192	4.416	ns
Case 2: Farmer-managed on-farm experimental plots (n=244) – model 12				
Flood index (P–PI)	0.101	0.074	0.127	<0.01
Flood index (PI–F)	–0.019	–0.050	0.012	ns
Flood index (F–M)	–0.486	–0.893	–0.079	0.02
Drought index (P–PI)	–0.017	–0.047	0.014	ns
Drought index (PI–F)	–0.065	–0.088	–0.043	<0.01
Drought index (F–M)	–0.040	–0.058	–0.022	<0.01
Planting date	0.011	–0.001	0.023	ns
Total N fertilizer applied	0.009	0.006	0.011	<0.01
Intercept	–0.500	–2.936	1.935	ns
Case 3: All plots (n=344) – model 12				
Flood index (P–PI)	0.069	0.049	0.089	<0.01
Flood index (PI–F)	0.007	–0.019	0.033	ns
Flood index (F–M)	–0.131	–0.346	0.084	ns
Drought index (P–PI)	–0.011	–0.036	0.014	ns
Drought index (PI–F)	–0.065	–0.086	–0.045	<0.01
Drought index (F–M)	–0.030	–0.045	–0.015	<0.01
Planting date	0.009	–0.001	0.018	ns
Total N fertilizer applied	0.007	0.005	0.010	<0.01
Intercept	0.068	–1.882	2.018	ns
Yield response to N fertilizer in experiments 3 and 4 (n=28) – model 13				
Flood index (P–M)	0.015	–0.008	0.037	ns
Drought index (P–M)	–0.035	–0.055	–0.015	<0.01
Intercept	1.703	1.126	2.280	<0.01

[a] ns = not significant.

[b] Letters in parentheses indicate period index measured for: P: planting, M: maturity, PI: panicle initiation, F: flowering.

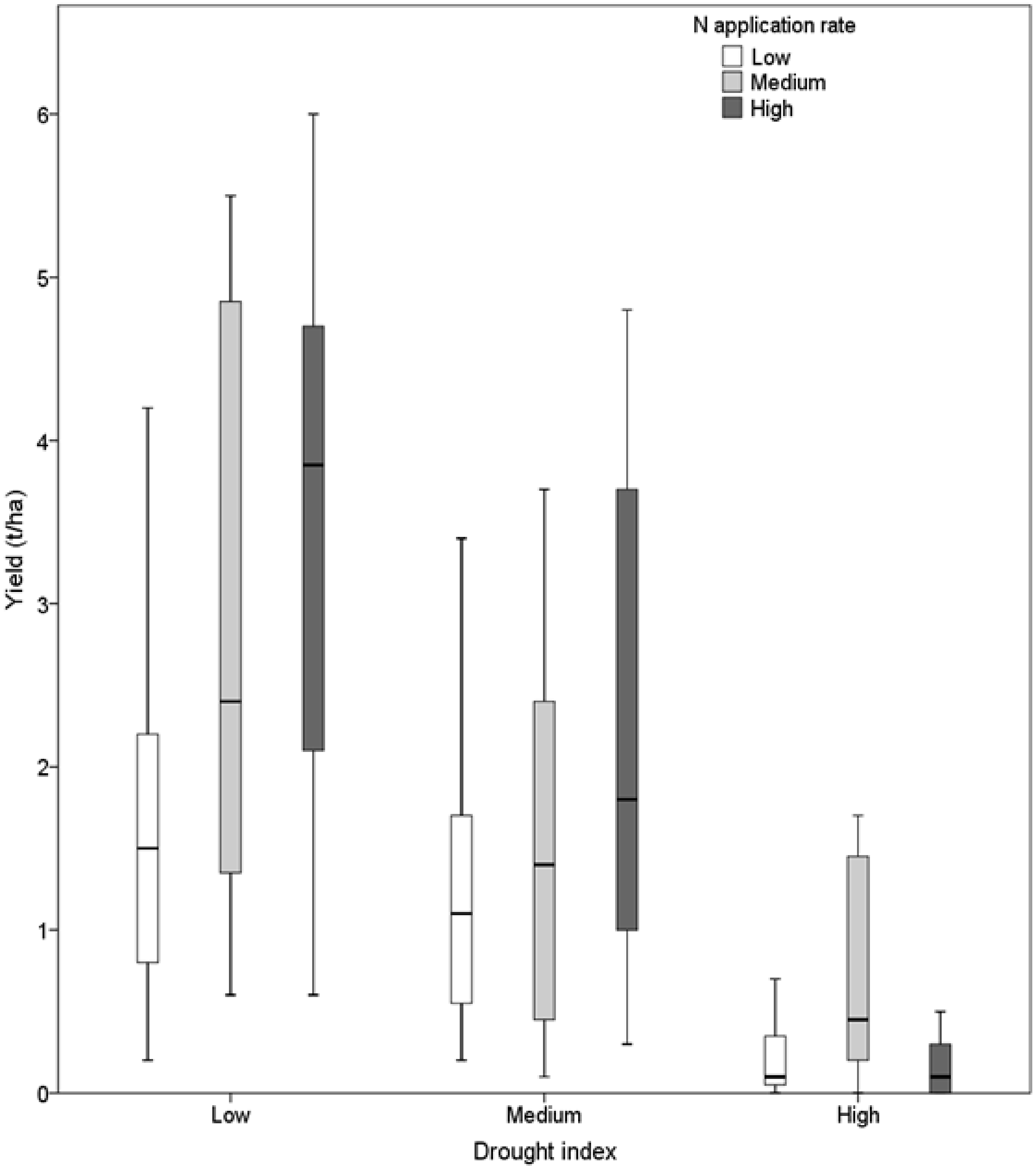

Figure 4.1: Yield response to N fertilizer application in three categories of drought index (N fertilizer: low: ≤50, medium: >50, ≤80, and high: >80; drought index: low: ≤15, medium: >15, ≤30, and high: >30)

Mineral N fertilizer rates were significantly related to yield in 66% of the cases and strongly interacted with the field water status. Thus, the drought index significantly affected yield response to N fertilizer, and yields declined by 0.35 t/ha for each 10% increase in drought index (model 13, Table 4.3). Largest yield differences between low, medium, and high N fertilizer application rates were observed for the lowest drought indices (Figure 4.1). N-induced yield increases were highest with low drought indices during the reproductive growth stage. N application rate resulted in a 7–9 kg grain increase per kg N applied (cases 2 and 3, Table 4.3).

3.3. Factors affecting field water status

Model 18, which considered soil texture and C content, proved best suited to describe the determinants of flood and drought indices with AICs of 6128 and 4336, respectively. High sand content consistently lowered the flood index while increasing the drought index, while high organic C content increased the flood index (Table 4.4)

Table 4.5: Model parameters explaining variation of flood and drought indices

Variable	Estimate	Std Error	P value
Flood index – model 18			
Sand (%)	–0.043	0.002	<0.01
Organic C (%)	1.388	0.139	<0.01
Intercept	–1.075	0.186	<0.01
Drought – model 18			
Sand (%)	0.039	0.001	<0.01
Organic C (%)	–0.261	0.092	<0.01
Intercept	–4.173	0.129	<0.01

4. Discussion

This study assessed variation in on-farm rice yields in central Benin in relation to rainfall, water status, and crop management practices, including fertilizer management. Large variation in yield in this study confirmed findings of previous studies in rainfed lowland rice systems in West Africa (Becker and Johnson, 2001d; Touré *et al.*, 2009; Worou *et al.*, 2013). Year-to-year variation in rainfall and spatial variation in field water status strongly affected rice yield in this study. The relationship between rainfall and yield in this study is consistent to some extent with previous studies in Asia (Malabuyoc *et al.*, 1993; Saito *et al.*, 2006a). Furthermore, our finding of association of water status with yield agree with previous reports from Asia (Haefele *et al.*, 2006; 2013a). While (Haefele *et al.*, 2006) used average scores over the rice-growing season (higher score indicating greater water stress), our approach gave more detailed information on the proportion of days with water deficit and flooding during the rice-growing stages. Therefore, together with this study, results from previous studies suggest that visual assessment of water status can be a simple and useful means for assessing spatial and temporal variation in water conditions, as well as its influence on rice productivity.

Our findings of soil N deficiency and effect of N fertilizer application on yield confirmed previous studies in rainfed systems in West Africa (Kamara *et al.*, 2010). However, for farmer-managed plots (case 1, Table 4.3) the model with total N application rate did not provide the best fit. This could be due to limited variation in N fertilizer application among farmers in comparison with field experiments. In farmers' practices, fertilizer timing was variable, and this could also have affected the results. Delayed fertilizer application results in low fertilizer recovery (Haefele *et al.*, 2013b). The blanket fertilizer recommendation did not show higher yield than farmers' practices in experiment 6. This confirms previous studies (Segda *et al.*, 2005; Tittonell and Giller, 2013), and suggests that field-specific recommendations are needed.

High drought indices were associated with high sand content of the soil, low yield, and low yield response to N fertilizer application as sandy soils tend to have reportedly low moisture-holding capacities (Homma *et al.*, 2003; Odunze *et al.*, 2010). It is well understood that N fertilizer should be applied when the soil surface is wet or slightly flooded, to avoid N loss through volatilization and increase N fertilizer recovery (Raun and Johnson, 1999). We also found that yield response to fertilizers was smaller with greater water deficit levels. It should be pointed out that our drought and flood indices include the indirect effect of sowing timing and crop duration on yield, as we calculated drought and flood indices for actual sowing date and crop duration. For example, if short and long duration varieties are sown on the same date and there is terminal drought, drought index may be higher or flood index lower for the long duration variety than the short-duration variety. Thus, use of short-duration varieties could be an option for reducing the drought index, and consequently could result in higher yield under drought conditions. Reasons for the positive relationship between drought index and soil carbon in this study are not known. But, it must also be recognized that drought and flood indices can be affected by soil percolation rates and water runoff from surrounding areas (Bouman *et al.*, 1994), and these factors were not quantified in this study

Field water status and total N application explained 28–56% of yield variation in this study. Thus, we did not capture a large part of the yield variation. Other factors such as weeds, pests, and diseases were not consider in this study and may also have contributed to yield variation (Rodenburg and Johnson, 2009; de Mey *et al.*, 2012; Nwilene *et al.*, 2013; Saito *et al.*, 2013b; Séré *et al.*, 2013).

Our assessment of the field water status was quite easy and simple, and results indicate that sandy soils have generally higher drought index, and fertilizer should be applied on wet soils with higher flood index rather than dry soils with higher drought index (i.e. index >30%). Where the drought index is expected to be high, N fertilizer should not be applied. It remains to be seen, how useful such recommendations will be for farmers and their decision-making. Further studies to examine the linkage between farmers' knowledge (of water status and soil texture), and our water status assessment, laboratory analysis (including soil sand content), and rice productivity, could help in developing a comprehensive field-specific decision support system (Saito *et al.*, 2006b). Furthermore, as drought index in a given field is affected by seasonal rainfall pattern and amount, forecasting is needed to help farmers decide whether or not to apply fertilizer. Thus, the challenge would be to examine if weather forecasting can be reliable for recommending fertilizer application. In addition to bunding, used in some farmers' fields in the area, other water conservation measures, such as mulching, land leveling, or no-tillage, should also be tested for enhancing soil moisture. Also, in drier soils, short-duration rice varieties or upland crops may be recommended if terminal drought risk is high.

We conclude that year-to-year variation in rainfall and spatial variation in field water status strongly affect variations in rice yield and yield response to N fertilizer application. Yield response to applied N tends to be less when water deficits are severe and spatial variations in field water status are related to the sand content of soils. Thus, the prevailing blanket fertilizer recommendations are unlikely to contribute to yield increase in rainfed systems, and there is a need to develop field-specific recommendations that take into account soil texture and the spatial–temporal dynamics of water availability.

Chapter 5 : **Implementation of GAPs in West Africa**

Abstract

The rice production in West Africa has not yet satisfied the population's growing demand partly due to the low farmers' productivity. If potential production is high in the region, actual production has never followed the potential trends because of numerous constraints ranging from climate factors, soil problems and crop management practices. The improvement of farmers' management practices has the potential to increase yield per unit of area increasing total rice production. Thus, the objective of this study was to evaluate the effect of introduced practices in on farmers' yields and to assess factors affecting yield variations. For each site, a combination of GAP were selected using knowledge expertise from local researchers for two years and implemented in selected farmers' fields. From the farmers who have previously participated in the yield gap survey, 503 fields were randomly selected. A 200 m^2 plot was demarcated at each selected farmer's field where GAP was implemented. Farmer's management practices and crop were monitored during the cropping season and yield measured at harvest. Average yield gain was higher in rainfed lowland and ranged between 1.3 and 3.3 t/ha in rainfed lowland whereas in in irrigated lowland it was from -0.9 and 1.1 t/ha. The yield gain can be further enhanced with optimized sowing date in irrigated lowland, with improved varieties and timely application of mineral fertilizers with better water control in rainfed lowland system.

Keywords*:* Bunding / GAP / Leveling / Nitrogen / *Oryza* spp. / West Africa

1. Introduction

Rice is a staple food crop for many countries in West Africa and its importance has increased over the past decades (Seck *et al.*, 2010). Rice is a source of income for many rural households and play a key role in regional food security and in national economies (Diagne *et al.*, 2013a). While rice production has increased since the 1970s due to area expansion, it has never satisfied consumption demand (Seck *et al.*, 2013). Although area expansion is still possible in many parts of Africa, more efforts are needed to increase rice productivity as farmers' yield level is quite low (Becker and Johnson, 1999b). Most of the constraints to rice production are due to farmers' management practices due to the low adoption rate of the modern cropping system technologies (Balasubramanian *et al.*, 2007b). In previous studies in West Africa, it was reported large yield gaps of 3.2-5.9 t/ha across AEZ in the irrigated system in Côte d'Ivoire (Becker *et al.*, 2003b) and between 0.6-4.1 t/hain the sub-humid zone of Burkina Faso (Wopereis *et al.*, 1999b). From these studies poor water control, low fertilizer rate, inefficient weeding practices were reported as the main factors affecting yield in irrigated system in Côte d'Ivoire while timing of N, seedling age, inadequate water control, K and P deficiency were the main factors in the Guinea Savannah in Burkina Faso.

From the current study, the crop management practices susceptible to increase rice production are identified and specific to each production system. In irrigated systems, timing of nitrogen fertilizer and strategies to timely control weeds are measures to improve productivity. In rainfed system the low level of farmers' instruction, the nonexistence of infrastructure (irrigation and drainage schemes), the low level of farmers' organization and the quasi-absence of incentive policies are constraints that need to be addressed. The measures towards increasing farmers' yields include: the construction of bunds around fields, the dissemination of improved varieties from certified seeds to target farmers, the application and the timing of recommended rate of N fertilizer and efficient bird control measures.

The objectives of this study were to evaluate the effect of introduced GAP on farmers' yields and to examine factors that affected the variation of yield gains after the introduction of GAP.

2. Materials and methods

2.1. GAP components

At each site, 6 farmers out of 10 from each village who earlier participated in the previous farmer's yield gap survey (YGS) were randomly selected to participate in the current GAP test. The GAP component technologies were selected by local experts from National Research System and their partners and were considered as being the most important yield-reducing factors and that can be easily adopted by farmers. Once the combination of improved practices was selected, farmers were provided with training on new introduced technologies (eg. how to use mechanical weeders or updated training on how to timely apply fertilizer or herbicide, supply of new equipment, seeds or fertilizers as required by the GAP component). Farmers were asked to apply the technologies in the plot demarcated in fields under supervision during the GAP test periods. The practices were subdivided into six groups: land preparation methods, variety and seeds, sowing method, fertilizer input, weed control and harvest. The GAP components per group at each site per production system are shown in Annexes 1 and 2. For a proper yield gain comparison, sites with at least two years data on YGS and two years on GAP were considered.

2.2. GAP implementation

Each selected farmer applied the GAP components technologies in a 200 m^2 plot demarcated and separated from his/her own field using bunds. Control plots were not implemented during the period of GAP tests to avoid bias induced by farmers copying introduced technologies in their own plots. The previous 2 years' data of the YGS were used as control. All planned activities in the GAP plots were supervised by field observers to make sure operations were done as planned. Each selected field was monitored during the cropping seasons GAP tests were implemented. Three subplots of 12 m^2 were randomly delimited inside the GAP plot at the beginning of the season for yield determination. At harvest, all plants in each of the three 12 m^2 harvested areas were cut and grains were manually threshed, air-dried and weighed. Grain moisture content was determined and yields adjusted to 14% humidity. For each field, grain yield was the average yield from the three harvest areas.

2.3. Yield gain estimation

To determine the effects of improved practices on yield, yield gain was estimated from the following equation:

$$Yg\ (t/ha) = Y_{GAP} - Y_{YGS}$$

Where Yg is yield gain, Y_{GAP} is the yield obtained in the GAP test plot at each farmer's field and Y_{YGS} the average yield per site during previous YGS (control).

2.4. Statistical analysis

Descriptive statistics were used to estimate mean yield and yield gains at each site.

3. Results and discussion

Average yields in GAP fields were variable across sites and were higher than average yields obtained in survey fields (Table 5.1).

Table 5.1. Yields in survey and in GAP plots at different sites and production systems

		Average farmers' yield in t/ha (sample number)				
Country	Site	Survey year 1	Survey year 2	GAP year 1	GAP year 2	GAP component[1]
Irrigated lowland						
Benin	Malanville	4.8 (49)	5.6 (30)	6.1 (29)	4.9 (24)	3, 4, 5, 6
Mali	Kouroumari	5.3 (24)	5.0 (19)	3.7 (8)	4.6 (10)	1, 2, 3, 4
The Gambia	Central river	3.6 (50)	3.7 (20)	5.2 (25)	4.1 (25)	2, 3, 4, 6
Rainfed lowland						
Benin	Glazoué	0.8 (25)	1.9 (9)	1.4 (15)	7.0 (17)	2, 4, 5, 6
Mali	Sikasso	1.8 (43)	2.3 (45)	2.8 (16)	3.9 (20)	3, 4
Nigeria	Nasarawa	2.1 (24)	2.0 (10)	3.2 (16)	4.9 (11)	3,4,5
Sierra Leone	Bo & Kenema	1.8 (50)	2.8 (9)	4.7 (16)	2.8 (20)	1, 2, 3

[1] 1=Land preparation, 2=variety and seed, 3=Sowing method, 4=Fertilizer input, 5=Weed control, 6=Harvest

Mean yield gains ranged between -0.9 t/ha (Kouroumari) and 3.3 t/ha (Glazoué) (Table 5.2). N application rates were higher in GAP plots than in YGS fields and can explain the positive yield gain obtained in all sites except for Kouroumari, Mali. The negative yield gain obtained in Kouroumari can be ascribed to delay sowing date due to the late implementation of the GAP plot test during the first year (Table 5.3). Yield gains obtained in rainfed lowland were not only from fertilizer but are not only from fertilizer application, but also from other technologies components. For example, bunding and leveling, and transplanting (Table 5.2, Annex 2) in Nasrawa, Nigeria have contributed to increased yield. In Sierra Leone lowland, yield gain obtained was due to the combination of bunding, the use of iron tolerant variety and the application of organic fertilizer. In Glazoué, yield in GAP plots increased from 1.4 to 7 t/ha. In the second year the variety was changed to a drought tolerant variety (Table 5.1, Annex 2).

Table 5.2: Yield gaps, yield gains and percentage of yield gap closed after GAP test at site level

Country	Site	Average of yield gap (t/ha)	Average of yield gain (t/ha)	Percentage of yield gap closed (%)
Irrigated lowland				
Benin	Malanville	4.0	0.5	13
Mali	Kouroumari	5.7	-0.9	0
The Gambia	Central River	4.4	1.1	25
Rainfed lowland				
Benin	Glazoué	7.9	3.3	42
Mali	Sikasso	7.0	1.4	20
Nigeria	Nasarawa	6.3	2.4	38
Sierra Leone[1]	Bo & Kenema	-	1.7	-

[1] Yield gap was not estimated in Sierra Leone due to unavailability of climate data

In irrigated lowland sites 13% and 25% of the average yield gap estimated during previous survey years was reduced in Malanville, Benin and in Central River, The Gambia respectively. In rainfed lowland, yield gap reduction was higher than in irrigated lowland. It was 20% in Sikasso, Mali, 38% in Nasrawa, Nigeria and 42% in Glazoué, Benin (Table 5.2). In Nasrawa and Glazoué, N fertilizer rate was very low during survey (6 kg/ha) compared to average N fertilizer rate during GAP test (79 kg/ha) which have contributed to higher yield gap reduction in these sites. The higher yield gap obtained in rainfed lowland compared to irrigated lowland can also explained the higher yield gap reduction in this system.

Table 5.3: Average N rates and crop establishment dates recorded during YGS and GAP test

Country	Site	Survey year 1		Survey year 2		GAP year 1		GAP year 2	
		Average N application rate and number of splits over farmers' fields							
		Rate	Splits	Rate	Splits	Rate	Splits	Rate	Splits
Irrigated lowland									
Benin	Malanville	105	2	86	2	168	3	76	3
Mali	Kouroumari	100	2	84	2	138	3	138	3
The Gambia	Central River	19	2	68	2	76	4	168	4
		Rainfed lowland							
Benin	Glazoué	6	1	9	2	85	3	85	3
Mali	Sikasso	73	2	53	2	76	3	76	3
Nigeria	Nasarawa	6	1	0	0	72	1	72	1
Sierra Leone	Bo & Kenema	32	1	3	1	0	-	0	-
		Average crop establishment date (Julian date)							
		Irrigated lowland							
Benin	Malanville	187		183		198		217	
Mali	Kouroumari	162		192		235		150	
The Gambia	Central River	201		202		225		223	
		Rainfed lowland							
Benin	Glazoué	181		176		194		199	
Mali	Sikasso	179		188		184		186	
Nigeria	Nasarawa	182		173		205		196	
Sierra Leone	Bo & Kenema	200		237		232		226	

4. Conclusion

The implementation of GAPs plots in different sites in West Africa has resulted in increasing yield. There is still a large scope to obtain higher yield gains if other good practices including the use of optimum sowing date are integrated in the GAP component 3 especially in irrigated system in the arid to semi-arid zone. There is a need for a development of a site-specific decision support guide including variety choice and source of seeds, weeding timing and method and fertilizer management for an efficient use of the available farmers' resources.

Chapter 6 : **General discussion and conclusion**

Similar yield ranges recorded in this study were reported twenty years ago from rainfed upland (Becker and Johnson, 1999a), rainfed lowland (Becker and Johnson, 2001d), and irrigated lowland systems (Dingkuhn, 1993; Becker *et al.*, 2003b), indicating stagnant yield ranges as reported recently from Senegal river valley (Tanaka *et al.*, 2015). The yield difference between climatic zones can be explained by both climatic and edaphic conditions (higher solar radiation and lower relative air humidity in arid and semi-arid regions, more fragile soils and more exposure to pests and diseases in sub-humid and humid zones). However, in this study no relationship was found between yield and Bray P and between yield and total N and total C. Although soil organic matter and total N are important indicator for soil quality, they are not suitable parameters to predict rice yields as supported by Ilstedt *et al.* (2003) in Malaysia and further by Liu *et al.* (2014) in South China. The relative low effect of higher seasonal rainfall on yield in rainfed systems suggests that rainfall alone is not a good indicator for available water in rainfed systems. The water control measures such as bunding, the ground water table depth and water infiltration rate are additional parameters to take into account to predict actual farmers' yield than only seasonal rainfall. The present work presents the first comprehensive information on rice yields and crop management methods across climatic zones and production systems since the 1990s. In contrast to these initial surveys with 228 observations from upland fields (Becker and Johnson, 2001a), 204 from rainfed lowlands (Becker and Johnson, 2001d) and 164 from irrigated lowlands (Becker *et al.*, 2003b) in four countries, the present survey covers more than 1300 farmers' fields in 11 countries. Overall trends are similar to previous reports with highest mean yields obtained in the semi-arid zones and from irrigated systems (Figure 6.1). However, the yield gains over two decades were marginal. While upland rice yields increased by 30% over 20 years (from 1.15 in 1995 to 1.52 t/ha in 2014), comparable increases in the rainfed lowlands were observed in the order of 25% (from 1.62 to 2.02 t/ha). In irrigated systems, yield increases of 18 and 12 % were observed in semi-arid and sub-humid zones respectively and a yield decline by 40% was observed in the humid zone resulting in an overall yield stagnation in the irrigated systems (3.6 vs 3.5 t/ha). However, these comparisons should be taken with cautious since surveys for the two periods were not carried out in the same locations.

The FAO (1999) has reported average yield of 2.1 t/ha in Africa, corresponding to previous reports in the same period. (Population, 2015). This increase in production is most likely due to area expansion with an annual growth rate of 4.6 % in the same period (FAOSTAT, 2015). The average yield of 2.4 t/ha reported in this study represents only a slight increase compared to the 1990s. However, overall rice production increased by 5.8 % between 1993 and 2013 (FAOSTAT, 2015). This growth rate is

higher than the rate of average demographic growth of 2.8 % In contrast to the mean yields, both production and cultivated area increased at comparable rates, indicating that recent rice production increases in West Africa can primarily be ascribed to an expansion of cultivated area rather than productivity gains (Figure 6.2). However, this increase in production has not been able to satisfy the increased

consumption demand as a result of increasing rice imports in most of the surveyed countries during the same period (Seck *et al.*, 2013).

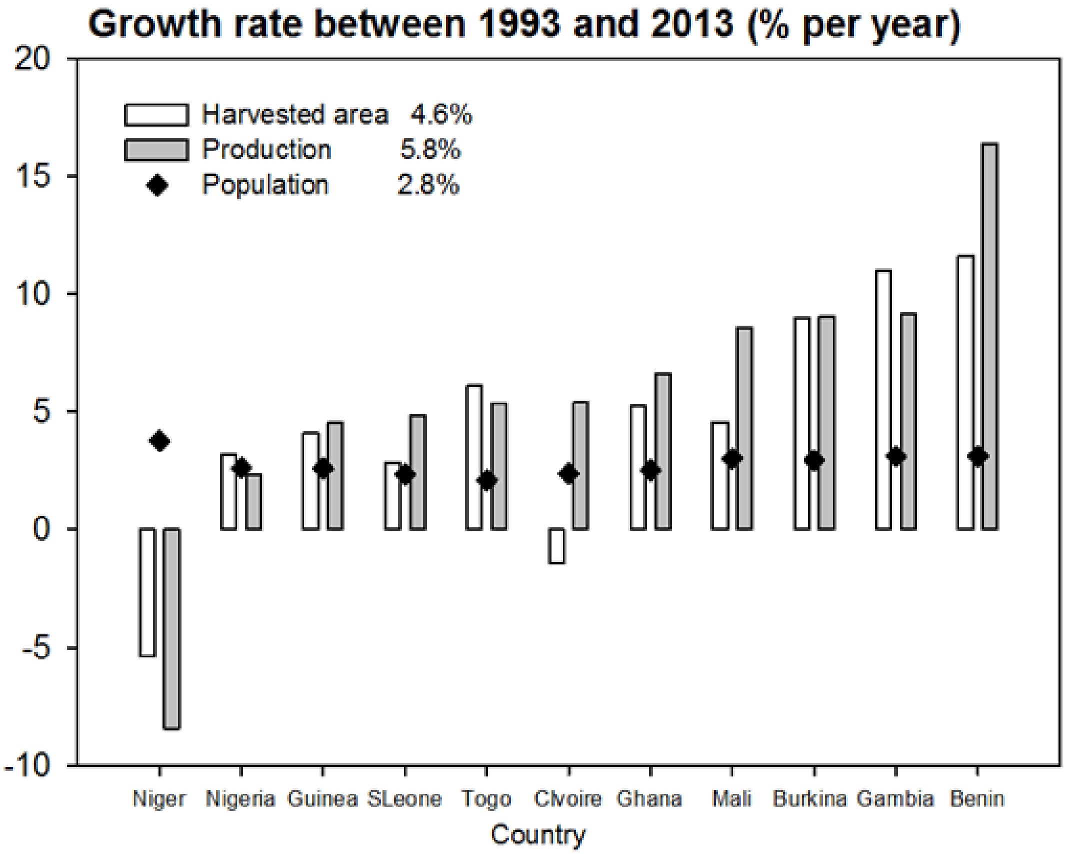

Figure 6.1: Production, population and harvest area growth rates of surveyed countries between 1993 and 2013. Source: (FAOSTAT, 2015) for production and harvest area data, (Population, 2015) for population data

In addition, expansion of area is not unlimited, because of growing demand for other land use needs. Therefore, the only sustainable way to increase production is the increase of yield per unit of area.

In this study, the relatively high rate of farmers that applied improved cropping practices may explain the reported grain yield increases in the production systems compared to the previous survey. Today, 92% of farmers in the irrigated systems construct bunds around their fields, use machines for tillage, and sow improved varieties and certified seeds. In this study, bunding in rainfed lowland was associated with 64% yield increase. This result confirms the previously reported 60 % increase of grain yield due to bunding in the moist Savannah zone (Becker and Johnson, 2001d). The resulting improved water control contributes also to reduce weed biomass (Becker and Johnson, 1999c). Mechanical tillage by deep plowing is particularly beneficial in compacted lowland soils reducing bulk soil density and improving nutrient and water use efficiency

(Babalola and Opara-Nadi, 1993). The use of certified seeds was associated with 30% increase of yields in irrigated and rainfed lowlands. Similar yield increases of up to 19 % was ascribed to the use of good quality seeds in a farmer participatory experiments in the Philippines (Diaz *et al.*, 1998).

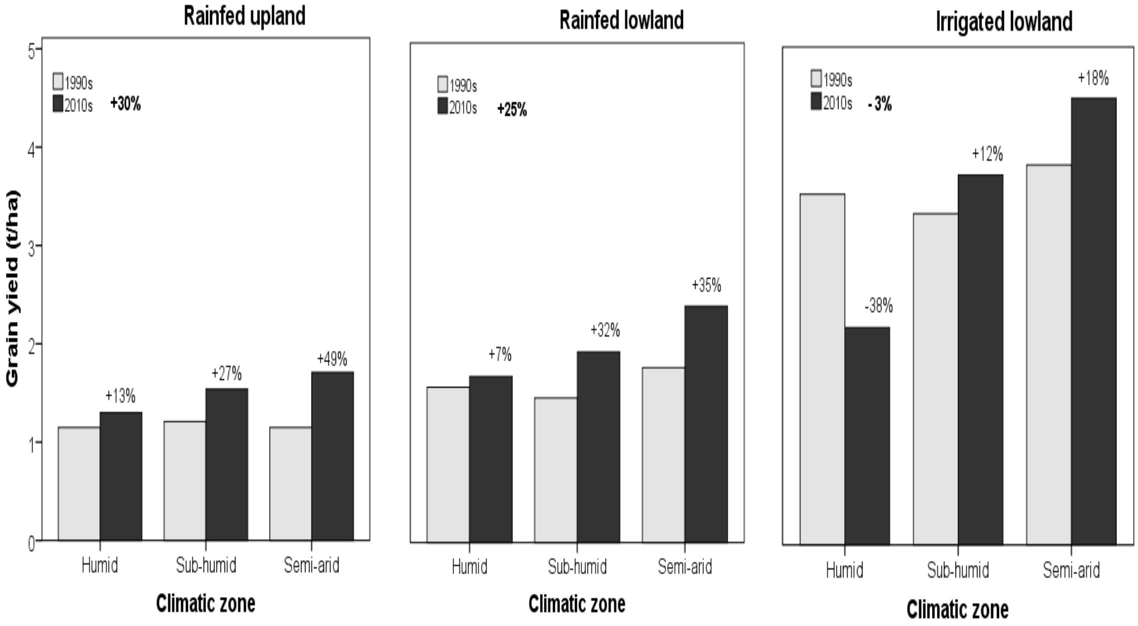

Figure 6.2: Comparative rice yields between the 1990s and the 2010s in different production systems at each climatic zone

Transplanting has been adopted by more than two third of the farmers in irrigated systems and has been linked to the observed 16% yield increase. However, despite this yield improvement, there is a shift from transplanting towards direct seeding due to lack of labor in some rainfed and irrigated lowlands (Nantasomsaran and Moody, 1995). Direct seeding reportedly increases weed biomass and results in a reduced crop response to fertilizer (Nantasomsaran and Moody, 1995; Singh *et al.*, 2001). A higher weeding frequency, more split applications of mineral fertilizers and the incorporation of rice straw are gaining popularity in irrigated systems and are also associated with yield increases. Similar improvements in management practices have been observed in rainfed lowland and rainfed upland systems but at lower rates of adoption. Increased productivity to meet growing demand requires exploiting much more than presently the existing yield variability by up leveling yields to enhance regional production. This may be achieved by site and specific targeting of incentive measures for the dissemination of current technologies. The following conclusions are derived from the analysis of rice yield and yield gaps variability in West Africa described in previous chapters:

- Rice yields and yield gaps variations were large in the different production across the main climatic zones in West Africa.
- Boundary function estimated attainable yields with increasing total solar radiation in all systems and increasing total rainfall in rainfed systems.
- RF algorithm evaluated the importance of the yield and yield gap determinants at different production systems.
- Yield determinants were specific to each production system.
- Nitrogen application rate was the most important factor explaining yield variability in irrigated system whereas water control, variety choice and bird control explained most of the variability in rainfed systems.
- Weeding frequency was selected as an important factor explaining yield variability regardless the production system.
- Nitrogen use efficiency was dependent on field water status in rainfed system of central Benin.
- The implementation of GAP plots helped increase average farmers’ yield with higher yield gain in rainfed lowland system.

- Site-specific GAP components implementation need to be further developed with continuous fine tuning in order to find for each site the most important factors that will yield higher production that is profitable to the farmers.

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ANNEX

Annex 1: Components of GAPs in irrigated lowland sites

Sites	GAP components					
	Land preparation	Variety and seed	Sowing method	Fertilizer input	Weed control	Harvest
Central river (Gambia)		introduction of improved varieties: Seed priming and soaking to increase seedling vigor	use of rope and line markers Transplanting at 20 x 20 cm density at 14 DAS[2], 3 seedlings/hill	Basal: 200 kg/ha NPK[1] (15-15-15) Top dress: 100 kg/ha urea at active tillering, PI and booting stages		Timely Harvesting at 80% maturity
Kouroumari (Mali)	Land leveling with 5 cm water height till 20 DAS then drain at 21 DAS	Pre-germinated seeds	Direct seeding: broadcasting Transplanting: row sowing at 20 x 20 cm density	Basal: 100 kg/ha Days after planting at 24 DAS Top dress 1: 100 kg/ha urea at 20 days after basal application, Top dress2: 100 kg/ha urea at 20 days after top dress 1		
Malanville (Benin)			Transplanting at 15 DAS Plant density: 20 x 20 cm	Basal: 200 kg/ha NPK at transplanting Top dress 1: 50 kg/ha urea at PI Top dress 2: 50 kg/ha urea at grain filling stage	Post emergence herbicide at 15 DAS Hand weeding when needed	Drainage before harvest
Tillabery (Niger)			optimal density for transplanting	Deep placement of urea super granule	Use of herbicide to control weeds	

Annex 2: Components of GAPs in rainfed lowland sites

Sites	GAP components					
	Land preparation	Variety and seed	Sowing method	Fertilizer input	Weed control	Harvest
Bo & Kenema (Sierra Leone)	Construction of bunds around plot	Variety ROK24 tolerant to iron toxicity. 1 kg seed soaked before nursery in 1g/L Zn solution		Incorporating 2.5 t/ha rice husk 7 days before transplanting		
Glazoué (Benin)		Improved variety IR 841 changed to early maturing drought tolerant NERICA L56 in the 2nd year		Basal: 200 kg/ha NPK (14 23 14) latest 21 DAS, Top dress 1: 75 kg/ha urea at PI Top dress 2: 50 kg/ha urea at grain filling stage	Post emergence herbicide (Garil) at 4 leaves age of plants or latest 21 DAS, 2 manual weeding when needed	Drainage before harvest
Nasarawa (Nigeria)			Transplant in rows at 17-21 DAS, 2 seedlings per hill. Plant density: 20 x 20 cm	Basal: 18 kg/ha P, 33 kg K/ha and Top dress: 156 kg/ha pelleted urea	Post emergence herbicide: Propanil and 2, 4 D at 4 L/ha (post emergence) On-time herbicide application	
Sikasso (Mali)			Dibbling sowing on line with 20cm x 20cm with 3 grains per hill changed in the 2nd year to drilling sowing with a seeder on line with 20cm x 20cm by using 50 kg of seeds per ha	Basal: 200 kg/ha NPK (15-15-15) at 14 DAS Top dress 1: 50kg/ha urea at 18-22 DAS, Top dress 2: 50kg/ha urea at 35-40 DAS		