Adaptive management of irrigated rice in the changing environments of the Sahel

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This research was conducted under the auspices of the C.T. de Wit Graduate School of Production Ecology and Resource Conservation.

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Thesis
submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. dr. M.J. Kropff,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Wednesday 14 September 2011
at 4 p.m. in the Aula.

Michiel E. de Vries

Adaptive management of irrigated rice in the changing environments of the Sahel,

168 pages.

Thesis, Wageningen University, Wageningen, NL (2011)

With references, with summaries in English, French and Dutch

ISBN: 978-90-8585-991-8

Abstract

In the vulnerable environment of the Sahel with its erratic rainfall pattern, irrigated rice production is of major importance. To aid Sahelian rice farmers to sustain irrigated rice production, this study explores management options. It includes field experiments performed at two typical Sahelian sites and simulation studies using crop growth simulation models. This thesis provides evidence that it is possible to use less irrigation water while maintaining rice production, thus increasing water productivity. The effects of a temperature increase on the growing cycle and spikelet sterility of new rice varieties in interaction with different sowing dates is quantified. The simulation results show that the sowing window will be restricted and that the cultivar choice may alter; together they will remain the most important determinants of rice production in the coming decades.

In Chapter 2, field experiments involving three water saving regimes using combinations of alternate wetting and drying (AWD) and flooding and a fully flooded control show that between 480 and 1060 mm of irrigation water was used in the water saving treatments compared with 800 to 1490 mm in the flooded rice treatment. Water productivity of the water-saving treatments was higher than of the flooded control, and yields ranged between 141 and 56% of the control. When weeds were controlled, crop yields obtained with a combination of AWD and flooding were comparable with those obtained in fully flooded plots receiving the same weed management. In Ndiaye, agronomic N use efficiency was smaller in the AWD treatments compared with fully flooded conditions. An irrigation regime for rice that starts as conventional (flooded), and then changes to AWD can save water with little or no yield loss, while maintaining low weed pressure and efficient use of N. To assess genotype adaptability, in Chapter 3 the results of experiments involving five genotypes, sown on 15 consecutive dates are presented. Yield (0-12 t ha^{-1}) and crop cycle duration (117-190 days) varied with sowing date, genotype and site. Rice yield was very sensitive to sowing date and the associated temperature regimes. Spikelet sterility due to cold stress ($T < 20^{o}C$) was observed when the crops were sown between August and October, and heat stress ($T > 35^{o}C$) resulted in spikelet sterility for sowing in April and May. For the simulation studies of Chapter 4, experimental data were used to calibrate both the DSSAT and

ORYZA2000 models. Original genetic coefficients of DSSAT did not simulate phenology well, while genetic coefficients that did, resulted in lower than observed yields. Simulations by ORYZA_S and ORYZA2000 resulted in an increase in simulation error at sowing dates in the last three months of the year. The results show that local calibration at the same sowing date is needed. In the African Sahel, a temperature increase of between 1.8 and 4.7°C is predicted by 2080. Simulations by an improved and validated version of ORYZA2000 presented in Chapter 5 show that rice crop cycle length will decrease by 10–30 days. The results suggest that with projected temperature changes, timing of sowing and consequently of the risk for crop loss due to sterility will remain the major determinant of rice yield. There is an urgent need for heat tolerant rice varieties. Without adaptation, cropping calendars will change, in the worst case scenario only a single crop will be possible. I conclude by suggesting viable options for adaptive management of irrigated rice in the changing environments of the Sahel to sustain production in the 21st century.

Key words: Alternate wetting and drying, Climate change adaptation, Crop growth simulation models, Genotype × environment interaction, N use efficiency, *Oryza sativa* L., Phenology, Sahelian irrigation schemes, Sowing date, Spikelet sterility, Temperature increase, Water productivity, Weed control.

“Want niet in het snyden der padie is de vreugde: de vreugde is in het snyden der padie die men geplant heeft.”

(“*After all, there is no joy in cutting paddy: joy is in cutting paddy that one has planted.*”)

Multatuli - Toespraak tot de hoofden van Lebak, in: *Max Havelaar of de koffieveilingen der Nederlandsche Handelmaatschappy*. Amsterdam, 1860

Contents

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Chapter 1

General introduction

1 Setting the stage

Food shortage continues to be a major problem in sub-Saharan Africa, and the semi-arid countries of the Sahel are no exception with 5-34% of the population being undernourished today (FAOSTAT, 2011). It is in these highly vulnerable environments with an erratic rainfall pattern that irrigated agriculture is of major importance for the local population. The continuous irrigation water supply provided by large rivers such as the Senegal, Niger and Voltas increases food security enormously (Connor *et al.*, 2008). In the Sahel (Figure 1.1), rice is one of the staple foods with a consumption of on average 49 kg capita^{-1} yr^{-1} in 2007 (FAOSTAT, 2011). Presently, West-Africa is not self-sufficient in rice and imports more than 5 million tonnes annually. It is therefore vital that irrigated rice production continues and even increases, to sustain local food production and to decrease the reliance on foreign imports. To harness Sahelian rice farmers against variability of their perpetually changing environments, this study experiments with rice management to explore different options to sustain production in the 21st century.

2 Rice in West-Africa

Rice cultivation in West-Africa dates back to ancient times (Nayar, 2010; Porteres, 1962), and was remarked by the first Europeans who visited the West-African coast (Dapper, 1668 in Carney, 1996). The area of domestication of the African rice (*Oryza glaberrima* Steud.) was traced to the sources of the Senegal and Niger rivers: the Fouta Djalon plateau in Guinea (Li *et al.*, 2011; Linares, 2002). Today the majority of both the lowland and upland rice surface area is cultivated with modern Asian rice varieties (*Oryza sativa* L.), valued for its high yielding capacity. Although *O. glaberrima* genotypes with drought-resistance (Sarla and Swamy, 2005), resistance to rice yellow mottle virus, a major disease in African lowland rice (Ndjiondjop *et al.*, 1999), bacterial leaf blight (Djedatin *et al.*, 2011), nematodes (Plowright *et al.*, 1999) and African rice gall midge (Balasubramanian *et al.*, 2007) have been found, they also possess undesirable agronomic characteristics, such as lodging, grain shattering, long growing cycle and low yield potential (Nayar, 2010).

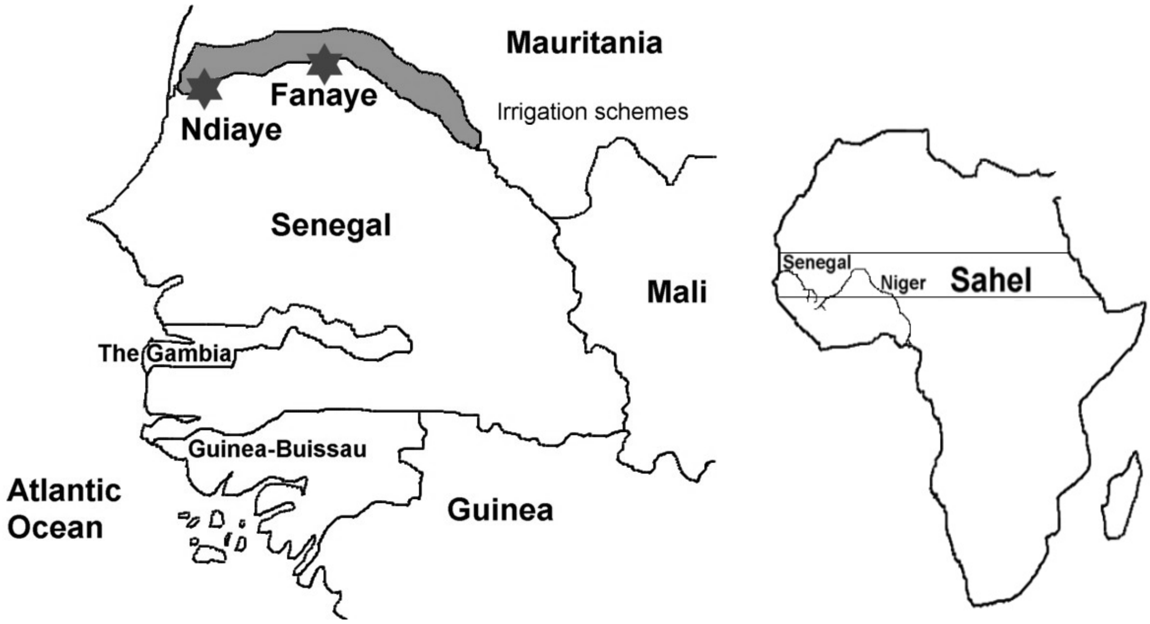

Figure 1.1: Maps of the research sites Ndiaye and Fanaye in irrigation schemes along the Senegal river (left) and of the Sahelian rivers Senegal and Niger (right).

There is evidence of spontaneous interspecific crosses of *O. sativa* and *O. glaberrima* and selection of these hybrids by farmers (Barry *et al.*, 2007; Nuijten *et al.*, 2009). However, the Africa Rice Center released interspecific varieties, named NERICA (NEw RICe for Africa), as a result of a deliberate breeding program (Jones *et al.*, 1997). Upland as well as lowland NERICA varieties have been released in the majority of countries in sub-Saharan Africa (Somado *et al.*, 2008), with high rates of adoption in for example, Côte d'Ivoire (Diagne, 2006a) and Uganda (Kijima *et al.*, 2008).

The irrigated rice schemes in the Sahel have high potential yields (8-10 t ha^{-1}), but are dependent on external inputs (Dingkuhn and Sow, 1997b; Poussin *et al.*, 2003; Segda *et al.*, 2004). Inorganic fertilizer and herbicides are widely used along the Senegal river (Kebbeh and Miezan, 2003), Office du Niger in Mali (Wopereis *et al.*, 1999) and in the Kou valley in Burkina Faso (Segda *et al.*, 2004). Soil fertility management has been identified as a major constraint (Haefele *et al.*, 2001; Haefele and Wopereis, 2005; Wopereis *et al.*, 1999). The sustainability of long-term rice mono-cropping with appreciable yield has been shown in the Sahel (Bado *et al.*, 2010; Haefele *et al.*, 2002b; 2004). Furthermore, improvement of weed management was found profitable for Sahelian farmers (Haefele et al., 2000; Johnson et al., 2004). By adequately managing water and addition of sufficient amounts of fertilizer, irrigated cropping can be conducted without jeopardizing soil quality (Boivin *et al.*, 2002; Ceuppens *et al.*, 1997; Van Asten *et al.*, 2002; 2003; 2004; Wopereis *et al.*, 1998).

Water management is a key factor in irrigated rice. In irrigation schemes in the Sahel, water use is high due to a large evaporative demand and inefficient water management (Raes *et al.*, 1995; Vandersypen *et al.*, 2006a). Due to foreseen changes in availability of irrigation water, using less water will be necessary (Ceuppens, 2000; Venema *et al.*, 1997). In tropical and subtropical Asia, water saving in lowland rice has been tested extensively, as reviewed by Bouman *et al.* (2007b). Annual and diurnal temperature fluctuations in the Sahel are large. For example, Dingkuhn and Sow (1997b) show that almost every day the temperature in the Sahel is both higher and lower than in Los Baños, The Philippines. The risks of either heat or cold induced sterility are large and therefore are the main determinants of the planting season (Dingkuhn, 1995; Dingkuhn *et al.*, 1995b; Poussin *et al.*, 2003). The length of the growing season of rice is determined by temperature and photoperiod requirements (Vergara and Chang, 1985). Even small changes in temperature can have large effects, notably around the thresholds for both heat and cold sterility. The difference in environmental conditions between a successful yield and crop failure is small. Therefore, farmers need to be aware of the magnitude of these risks, and need have varieties that yield well at different planting dates at their disposal.

3 Research objectives and methodology

This thesis explored options for future management of irrigated rice in the Sahel. The exploration of management options by detailed experiments and modelling lead to an improved understanding of the system, proposals for improved rice management in the Sahel, and set the agenda for future research. The results of this thesis should assist researchers to set priorities, breeders to direct their breeding programmes, and policy makers to adapt agricultural policies to global change. Agricultural extensionists and development workers could draw practical lessons from the experimental work presented in the first chapters.

The specific objectives of the study were:

- To determine whether it is possible to use less irrigation water for rice cultivation;
- To quantify the effect of sowing date on yield of new irrigated rice varieties and their adaptability to Sahelian conditions;
- To investigate whether globally used rice growth simulation models can be applied under Sahelian conditions;
- To explore the effects of temperature increase on the rice cropping system in connection with projected climate change scenarios;
- To develop management options to sustain rice production that can cope with the most prominent changes in climate and irrigation water availability.

For this research a combination of two methods was used: field experiments and crop growth simulation models. This combination of methods has been used satisfactorily in explorative studies on rice management before (Belder *et al.*, 2007; Haefele *et al.*, 2003b; Jing *et al.*, 2008). The field experiments provided realistic and sound data which were used to calibrate existing models. Rice growth simulation models ORYZA1 (Kropff *et al.*, 1994), its successor ORYZA2000 (Bouman *et al.*, 2001) and DSSAT4 (Jones *et al.*, 2003) were evaluated for their capability to simulate phenology and potential yield under Sahelian conditions. To better capture the effects of temperature on phenology, Van Oort *et al.* (2011) proposed adaptations to the ORYZA2000 model that were used in this study. The field experiments were performed at research stations of the Africa Rice Centre, Ndiaye and Fanaye (Figure 1.1). Both research stations were representative for large irrigated rice ecologies: Ndiaye for the Delta of the Senegal river valley, in which 70% of the irrigated rice is grown, and Fanaye for the middle valley, with a continental climate, representative for irrigation systems in the middle and upper valley of the Senegal river. Both sites had a typically Sahelian climate: a short wet season (three months), followed by a cooler dry season (four months) and hot dry season (five months). The use of two sites and multiple cropping seasons made the outcomes robust. The results could therefore be extrapolated to other Sahelian irrigation schemes, as shown by Dinkuhn (1995) on the presumption that crop cycle duration and spikelet sterility are determined by temperature and in some cases photoperiod.

This study was limited to the biophysical aspects of rice production, although farmers' day-to-day decisions are made on the basis of a mix of socio-economic and biophysical information. Newly developed management options should fit within their socio-ecological niche (Ojiem *et al.*, 2006). In this study, we explored future options, based on predictions in changes of the biophysical environment. Such predictions were not available for the socio-economic environment, and were thus not taken into account.

4 Outline of the thesis

This thesis consists of a general introduction, four chapters in which original research is presented (Chapters 2-5) and a general discussion (Chapter 6). In the next chapter alternative water-saving irrigation regimes are tested in combination with different weed and nitrogen management regimes to investigate whether it is possible to use less irrigation water while keeping the same yield. In Chapter 3, Genotype × Environment interactions are analysed of an extensive planting date experiment to test yield stability of newly developed cultivars. Chapter 4 discusses the performance of currently used rice growth simulation models and the sensitivity of their parameters. Chapter 5 explores the impacts of temperature changes on the rice cropping system using an improved simulation model. Chapter 6 presents the results of a combination of water-saving and temperature increase, the implications of the findings of this thesis for other disciplines and relevance in other cropping systems.

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Chapter 2

Rice production with less irrigation water is possible in a Sahelian environment*

* This chapter is published as:

De Vries, M. E., J. Rodenburg, B. V. Bado, A. Sow, P. A. Leffelaar & K. E. Giller. 2010. Rice production with less irrigation water is possible in a Sahelian environment. Field Crops Research 116: 154-164.

Abstract

We investigated the possibility of saving irrigation water in rice production in a Sahelian environment with different nitrogen rates and weed control treatments. A series of field experiments was conducted at Ndiaye (shallow water table, dry and wet season) and at Fanaye (deep water table, wet season) in Senegal with four irrigation treatments, involving three water saving regimes using alternate wetting and drying (AWD) and a flooded control, and three weed management treatments. This was followed by two experiments with the same four irrigation treatments in combination with three nitrogen (N) application rates, at the same locations. Hence four irrigation regimes were tested over three seasons. Between 480 and 1060 mm of irrigation water was used in the water saving treatments compared with 800 to 1490 mm in the flooded rice treatment. Rice yields ranged from 2.3 to 11.8 t ha^{-1} in the water saving treatments, whereas in the flooded control the yields ranged from 3.7 to 11.7 t ha^{-1}. In the wet season (WS), the treatments in which AWD was applied during part of the season resulted in the highest yields at both sites. In the dry season (DS), the continuously flooded treatment out-yielded other treatments, with the exception of AWD in Fanaye. At the Ndiaye site, the control of weeds increased yields from on average 2.0 to 7.4 t ha^{-1} in the DS and from 1.4 to 4.9 t ha^{-1} in the WS. No weed control in combination with AWD during the vegetative stage reduced yields to below 1.0 t ha^{-1}. However, when weeds were controlled, crop yields obtained with a combination of AWD and flooding were comparable with those obtained in fully flooded plots receiving the same weed management at both sites in the 2005 WS. Increasing rates of N significantly increased grain yield. Internal N efficiency was poorer at Ndiaye than at Fanaye suggesting that yields in Ndiaye are constrained by other factors than N. In Ndiaye, agronomic N use efficiency was smaller in the AWD treatments compared with fully flooded conditions. This study demonstrates that it is possible to save irrigation water and improve water productivity in rice grown in a Sahelian environment. An irrigation regime for rice that starts as conventional (flooded), and then changes to AWD can save water with little or no yield loss, while maintaining low weed pressure and efficient use of N.

Key words: Alternate wetting and drying, Fertilizer N supply, Herbicides, N use efficiency, Water productivity, Weed control.

1 Introduction

Food insecurity is a day-to-day reality for many people in sub-Saharan Africa. In Sahelian countries, 48 kg rice was consumed per capita in 2003 (FAOSTAT, 2011). Despite a long tradition of local production, 50% of the rice (*Oryza sativa* L.) is imported in Sahelian countries, at a cost of US$ 1.1 billion in 2005 (FAOSTAT, 2011). Although the climate enables high potential rice yields (8-10 t ha^{-1}) in irrigated systems in the Sahel (Dingkuhn and Sow, 1997b), irrigation water is becoming increasingly scarce (Rijsberman, 2006) and costly. In the Senegal River Valley (SRV), irrigation accounts for 25% of the total costs of rice production (Raes *et al.*, 1995), and 29% in Mauritania (Poussin *et al.*, 2006). On the left bank of the Senegal river, irrigation water for 50,000 ha of land is pumped from the river and its tributaries by either small diesel pumps or large electric pumping systems (SAED, 1997). Competition among user groups for water from the Senegal river will become more severe in the future, as demands for domestic use from the Dakar metropolitan area will increase, whereas water availability is expected to decrease (Ceuppens, 2000; Venema *et al.*, 1997). Hence, improvement of irrigation water productivity is highly relevant for rice production in the SRV, and other Sahelian schemes such as the Office du Niger in Mali (e.g. Vandersypen *et al.* 2006a).

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In tropical and sub-tropical rice production systems in Asia, alternative irrigation methods have been shown to save up to 50% of the water while maintaining yields at 70-80% of non-water saving conditions (Belder *et al.*, 2005b). In the alternate wetting and drying (AWD) system, rice is grown without a permanent layer of standing water on the field, and irrigation water is applied to obtain flooded conditions after a certain number of days have passed after the disappearance of ponded water (Bouman *et al.*, 2007b). Another newly-developed method is aerobic rice, where adapted rice varieties are grown as a normal field crop with or without supplementary irrigation. This was reported to be successful under sub-tropical conditions in China (Bouman *et al.*, 2006) and, to some extent, under tropical conditions in the Philippines (Bouman *et al.*, 2005). Water productivity of rice with respect to total water input (irrigation plus rainfall) is on average 0.4 kg grain m^{-3} water (Tuong *et al.*, 2004). Under water saving regimes, an increase in water productivity to 0.8-1.0 kg grain m^{-3} water has been reported (Belder *et al.*, 2005b; Kato *et al.*, 2009).

Depth of flood water affects the performance of the rice crop. The level of water and plant height are positively correlated (Anbumozhi *et al*., 1998), but tillering is negatively affected by excess flooding in the early growth stages (Ito *et al*., 1999). On the other hand, moderate water deficits are directly linked to a decrease in carbon fixation by the photosynthetic apparatus, primarily due to stomatal closure (Chaves and Oliveira, 2004) and a decrease in leaf elongation (Nguyen *et al*., 2009).

Soil fertility and weeds are the most prominent problems that can be addressed through improvement of crop management in irrigated systems of the Sahel (Haefele *et al*., 2000). Standing water is used to control weeds in irrigated systems. In aerobic rice, weeds may cause yield losses of 30-100%, hence weed management needs to be taken into account when irrigation water saving is introduced (Rao *et al*., 2007). Nitrogen is the most determining nutrient for rice yield, because of its importance in the photosynthesis process, determining biomass accumulation and crop yield and in the formation of spikelets (Hasegawa *et al*., 1994; Yoshida *et al*., 2006). Water saving has been shown to be possible in Asia, but it has not yet been tested in the Sahel. This research aimed to improve irrigation water management, while dealing with weed and soil fertility problems, which are key constraints in irrigated rice in West-Africa. The specific objectives of this study were to test the possibility to save water in rice production in a Sahelian environment by quantifying the effects of different water regimes on rice yield and irrigation water productivity under weed-free conditions with ample nitrogen. In addition, the interactions between water-saving irrigation regimes and nitrogen and weed management were studied. To test the possibilities for saving irrigation water, we chose two sites that differed in climate, ground water and salinity and conducted the experiments in wet and dry seasons with different yield potentials and growth durations. For this study we tested AWD, rather than a fully aerobic regime, as a potential water-saving treatment. Whereas a fully aerobic regime would potentially save more water, the threats of salinization and drought stress, due to high evaporative demands, probably are too great a risk in a Sahelian environment.

2 Materials and Methods

2.1 Experimental site

Field experiments were conducted in the dry and wet seasons of 2005 and dry season (DS) of 2006 at Ndiaye (16°11'N, 16°15'W), and in the wet season (WS) of 2005 and dry season of 2006 at Fanaye (16°32'N, 15°11'W) in Senegal. Both are experimental research stations of the Africa Rice Center (AfricaRice). The sites were located in the delta (Ndiaye), 35 km inland, and middle part (Fanaye), 150 km inland, of the Senegal river valley.

2.1.1 Climate

Climate at both sites is typically Sahelian: a nine month dry period followed by a short wet season, and large annual amplitudes in temperature, as shown in Figure 2.1. Between March and July, solar radiation and maximum temperatures are higher at Fanaye than in Ndiaye. Rice production takes place twice a year, from February to June in the hot dry season, and from August to November in the wet season. Table 2.2 shows the planting and maturity dates of the different experimental sites and seasons.

2.1.2 Soil

The experimental station at Ndiaye is located in a depression along one of the branches of the Senegal river (Haefele, 2001). Deposits of marine origin in the sub-soil result in a saline ground water table of 20 dS m^{-1} or more (Ceuppens, 2000), which is 0.9 to 0.4 m below the soil surface. Following the FAO soil classification (FAO, 2006), the soil is characterized as an orthothionic Gleysol, with a clayey structure that contains 40 to 54% clay, composed of smectite and kaolinite (Haefele, 2001). Average percolation rate of this soil was estimated at 2.8 mm d^{-1} by Haefele (2001). Clay content of the Fanaye soil was higher with less porosity and bulk density than in the Ndiaye soil. Total N and organic C were larger in the Ndiaye soil, but C:N ratios were similar (10:1). The Fanaye station has a deep ground water table, constantly below 3.0 m. No inherent salinity was found at this site. The soil type is characterized as an eutric Vertisol (FAO soil classification), where clay content varies between 45 and 65%, composed of kaolinite and smectite minerals (Haefele, 2001; Samba Diène, 1998). The percolation rate was estimated at 2.0 mm d^{-1} at the same site (Haefele, 2001).

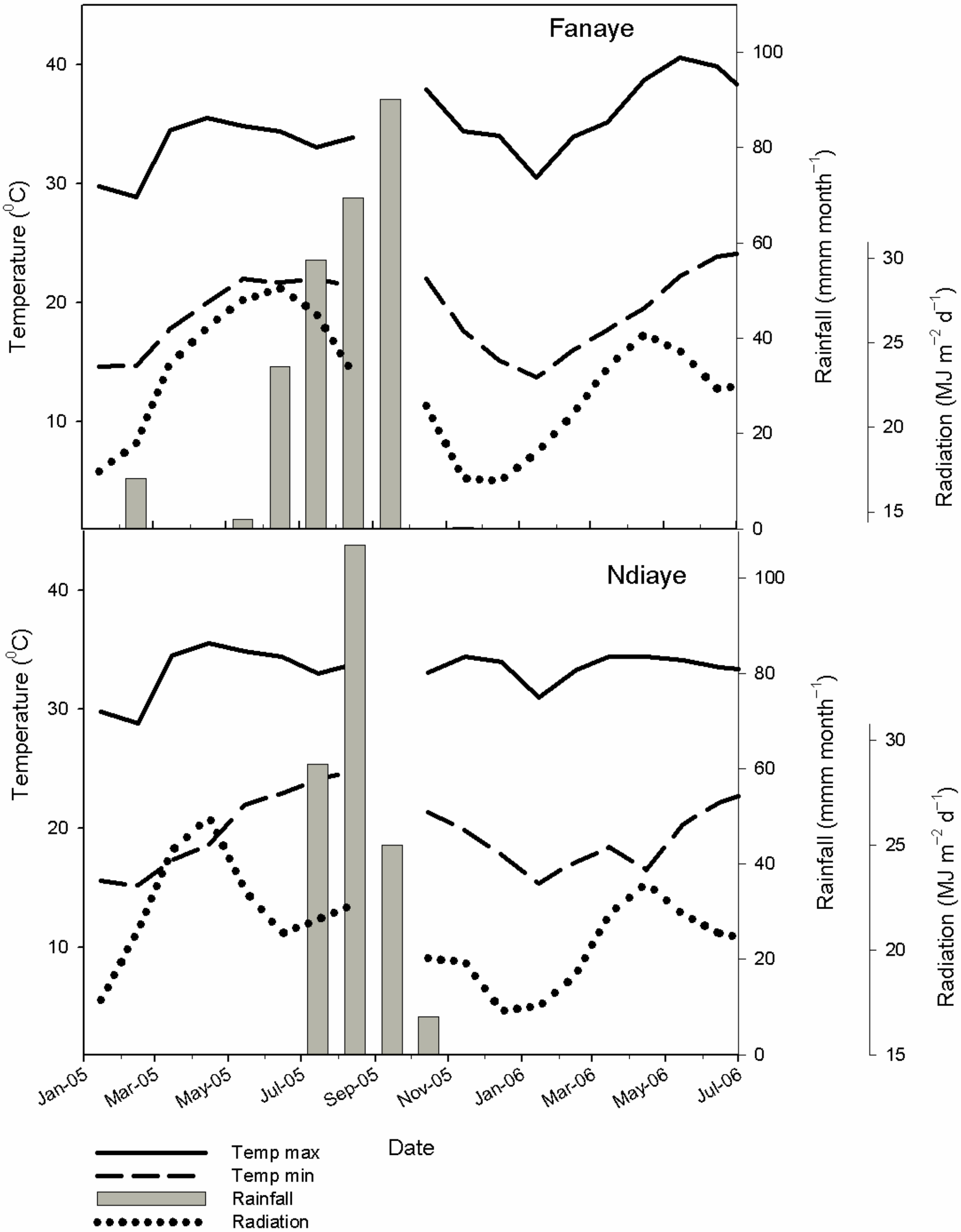

Figure 2.1: Climate in Fanaye and Ndiaye (Senegal), with monthly mean maximum (full lines) and minimum temperatures (dashed lines), monthly mean daily radiation (dotted lines) and rainfall (bars) between January 2005 and July 2006. Due to storms, data on temperature and radiation are missing in September 2005.

Samba Diène (1998) indicated that infiltration rates at both sites can vary by an order of magnitude due to cracks. At both sites, the experiments were established on fields that had been under continuous flooded rice cultivation for at least three seasons. Prior to the field experiments, soil samples were taken from individual plots and chemical and physical properties were measured (Table 2.1). Total N was determined using the micro-Kjeldahl method for N analysis (Bremner, 1965). Organic C was determined using the Walkley Black method (Nelson and Sommers, 1996). pH was determined in a 1:1.25 H_2O solution and EC in a 1:5 paste. Volumetric water content at wilting point (pF 4.2) was determined using a pressure membrane apparatus and at field capacity (pF 2.0) using a sand box.

Table 2.1 Characteristics of the top soil (0-15 cm) of the two experimental sites (Ndiaye and Fanaye). Acidity (pH in water), organic carbon, total N, cation exchange capacity, volumetric water content, porosity and bulk density.

Characteristic		**Site**	
		Ndiaye	Fanaye
$pH(H_2O)$	-	5.1	5.6
EC(1:5)	dSm^{-1}	0.3	0.1
organic C[a]	$g\ kg^{-1}$	10.3	7.5
N total[b]	$g\ kg^{-1}$	1.0	0.8
CEC[c]	$cmol_c\ kg^{-1}$	13.0	26.2
Volumetric water content	pF 2.0 %	39	40
	pF 4.2 %	25	25
Porosity	%	52	49
Bulk density	$g\ cm^{-3}$	1.42	1.3

[a] Determined using Walkley–Black method.

[b] Determined by micro-Kjeldahl method .

[c] According to Haefele (2001).

2.2 Experimental design and treatments

A total of five experiments were conducted to study the performance of different water regimes over two sites and three seasons (Table 2.2). A split-plot design was used with water management as main treatment (main-plot) and weed management (2005) or nitrogen application (2006) as sub-treatments (sub-plot) in three replicates (Table 2.3). The main-plots were not randomly assigned but laid out at fixed positions. This was necessary to ensure strict and distinct water regimes in an economically and logistically feasible way. This resulted in three experiments where water × weed interactions and two experiments where water × nitrogen interactions were explored. The experiments were designed in such a way that within each irrigation treatment, a combination of the recommended nitrogen fertilizer dose and weed control was always present. This allowed a comparison of irrigation regimes across sites and seasons.

Two bunded canals were installed between main-plots, separating these by at least 3 m. This way, water seeping out of blocks could be drained away and the water levels in plots could be managed independently. The bunds were 0.4 m above the soil surface to prevent overflow. The main irrigation blocks measured 9 × 12 m, resulting in a bund: area ratio of 0.39 m m^{-2}, similar to the ratio in experiments reported by Humphreys *et al.* (2008).

Table 2.2 : Sowing and maturity dates, length of the growing cycle (days and degree days), for different years and sites.

Year	Season	Site	Sowing date	Maturity date	Duration [days	°Cdays]
2005	Dry	Ndiaye	18 March '05	16 July '05	120	2300[a]
	Wet	Ndiaye	17 August '05	1 December '05	106	nd[b]
		Fanaye	1 September '05	13 December '05	103	nd
2006	Dry	Ndiaye	23 February '06	23 June '06	120	2120
		Fanaye	23 February '06	20 June '06	117	2510

[a] Degree days were calculated using daily mean temperatures and 9°C as base temperature.

[b] No data; due to a gap in the meteorological data, the temperature sum could not be calculated.

In farmers' fields in the SRV a bund: area ratio of 0.1 m m^{-2} is common. The outer bunds were lined on the inside of the blocks with plastic from a depth of 0.2 m below the soil surface over the top of the bund to the soil surface on the other side. The sub-plots (3 × 12 m) had small bunds between the herbicide treatments. For all experiments the medium-duration rice variety Sahel108 (IR 13240-108-2-2-3) was used, which is most popular in the region.

2.2.1 Crop establishment

The crop was directly sown at a rate of 100 kg seed ha^{-1} after 48 hours of soaking in water. The soil was wet at the time of sowing, and a layer of 2 cm of water was maintained. In 2005, all plots were fertilized uniformly with N and P in the form of urea and diammonium phosphate (DAP). DAP was broadcast at sowing (21 kg P ha^{-1} and 18 kg N ha^{-1}), and urea was broadcast in three splits: 42 kg N ha^{-1} at the beginning of tillering, 60 kg N ha^{-1} at panicle initiation and

30 kg N ha^{-1} at heading stage. Resulting in 150 kg N ha^{-1} and 21 kg P ha^{-1}. Urea was broadcast into a 5 cm layer of water. No major pests or diseases were observed. In the 2006 experiments, the same rate of P was applied as in 2005, but this time in the form of triple super phosphate, while the complete N-rate was applied as urea.

Table 2.3: Structure of the sub-plot factors of five water saving experiments. Each column represents three weed control (days after sowing [DAS]) × nitrogen (kg N ha^{-1}) combinations in an experiment. In bold the recommended weed control and nitrogen management combination.

Season	**2005 Dry**	**2005 Wet**		**2006 Dry**	
site	Ndiaye	Ndiaye	Fanaye	Ndiaye	Fanaye
Weed control	No	No	No	21 DAS	21 DAS
Nitrogen	150	150	150	0	0
Weed control	**21 DAS**	**21 DAS**	**21 DAS**	21 DAS	21 DAS
Nitrogen	**150**	**150**	**150**	90	90
Weed control	35 DAS	35 DAS	35 DAS	**21 DAS**	**21 DAS**
Nitrogen	150	150	150	**150**	**150**

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2.2.2 Water management

To evaluate the effect of water management on rice production four different irrigation regimes were compared:

- **I1**: continuously AWD;
- **I2**: AWD until PI, then Flooded;
- **I3**: Flooded until PI, then AWD and
- **I4**: continuously flooded.

Irrigation was applied when necessary to maintain the desired water level, but not more often than three times a week, see Figure 2.2. The same amount of irrigation water was applied to all replicates. Due to the hot and dry climate, the evaporative demand in the Sahel is high. Hence season-long AWD increases the risk of salt and moisture stress for the rice crop. AWD was chosen as the water saving irrigation technique in one of the treatments (I1). In two other treatments, water saving regimes with AWD for part of the growing season were applied. One treatment followed AWD during the vegetative part of the growing cycle only (I2), with permanent flooded fields at a depth of 10-15 cm thereafter, while another treatment started with permanently flooding (10-15 cm) during the vegetative stage, followed by AWD during the generative stage (I3). The fourth treatment was continuous flooding (I4), applying the recommended water depth (10-15 cm). All treatments started 15 days after sowing (DAS), when the crop had emerged, and all plots were drained 10 days before harvesting, to ensure uniform ripening and facilitate harvesting. The amount of irrigation water applied to all treatments is presented in Table 2.5. Between sowing and the start of the water treatments, the water level was kept the same in all plots, starting with a thin layer of 3-5 cm, and gradually increasing to 10 cm. as the crop established. PI was determined as the moment when the panicles were visible with the naked eye.

2.2.3 Weed management

In the 2005 DS and WS experiments, there were three different weed control treatments (Table 2.3). The aim of the three treatments was to determine whether there would be an interaction of late or no weed control with water management. Delayed application of herbicides is a common practice among farmers in the SRV. In two treatments herbicides were applied at the recommended rates but at different times, whereas in the check treatment no herbicides were applied:

- **W1**: 21 DAS Herbicides. A 1:5 mix of weed-one (2,4-dichlorophenoxyacetic acid) and propanil, selective herbicides, applied at 6 l ha^{-1} at 21 DAS, followed by one manual weeding two weeks later. This represents the weed control strategy that is recommended by the local extension services.
- **W2**: 35 DAS Herbicides. A 1:5 mix of weed-one and propanil applied at 6 l ha^{-1} at 35 DAS, followed by one manual weeding two weeks later. This represents delayed herbicide application. The herbicides were applied in the recommended mix and concentration.
- **W3**: No weed management. Neither herbicide application nor manual weeding was applied.

For 2006, the experimental plots were sprayed with herbicides at 21 DAS, a 1:5 mix of weed-one and propanil applied at 6 l ha^{-1}. This was followed by two manual weedings, at two and four weeks after application of the herbicides, to avoid any residual effect of the 2005 weed management treatments.

2.2.4 Nitrogen management

In 2006 DS only, the same water treatments were applied at both sites, but instead of herbicide, nitrogen treatments were tested (Table 2.3). These treatments included three nitrogen fertilizer rates: 0, 90 and 150 kg N ha^{-1}. Nitrogen was applied in three split doses, first 40% two weeks after sowing, second 30% top dressed at panicle initiation, and finally 30% at heading. Urea was applied in a shallow layer of ponded water (5 cm).

2.3 Measurements

At maturity a 2 × 2 m surface was harvested and weighed to calculate the grain yield at 14% moisture content, and straw and weed biomass. A surface area of 0.4 × 0.4 m was harvested to measure the number of filled and unfilled grains. The water level was monitored daily in each main-plot through 0.4 m diameter perforated PVC tubes that were inserted into the soil to a depth of 0.3 m. At Ndiaye, flood water salinity was measured twice a week using a portable conductivity meter. Irrigation volume was measured by a V-notched weir that was calibrated in the field and installed at the inlet of each block. Irrigation volume was assessed by measuring the height of the water, flowing through the V-notched weir, with a measuring stick at an interval of 5 minutes at the beginning of an irrigation event; the interval was increased to 15 minutes, when the inflow had stabilized. The relationship between water volume and water height in the weir was $Q=8.7 \tan(\theta/2) H^{2.5}$, where Q is the discharge (l min^{-1}), θ the angle of V-notch, and H the height of water flowing through the weir (cm) (USBR, 2001).

2.4 Computations and statistical analysis

The lay-out of the experimental plots was such that repetitions accounted for heterogeneity in one direction, but not in the perpendicular direction. Homogeneity of the experimental fields in the perpendicular direction was tested using analysis of covariance. A covariate was created by assigning a number to plots in the perpendicular direction, and it was tested whether there was a relation between the grain yield and the assigned number of a plot. This analysis was carried out for each experiment separately and effects of plot number were not significant. As a further analysis, residuals of grain yields of all individual plots were calculated according to procedures described by Dyke (1988) to determine whether the residuals of the blocks in the perpendicular direction were above 1.0 or below -1.0, which was not the case. The calculation was carried out for each experiment individually, and no significant block effects were found. This confirms that the assumptions underlying the analysis of variance (ANOVA) were not violated by fixing the main plot locations. Therefore, ANOVA was used to analyse main effects of water, nitrogen and weed management and their interactions using the statistical software package Genstat version 10 (VSN international, 2007). Grain N concentration was determined by Kjeldahl digestion. Total N uptake was estimated by using grain N concentration measured and by applying the ratio between grain N and straw N content of 1.0 : 0.6, as found by Witt *et al.* (1999) from a large number of samples, which was multiplied by the weight of grain and straw harvested.

Table 2.4: Results of the analysis of variance: the degrees of freedom, variance ratios and associated probabilities of main effects and their interactions on grain yield of five experiments.

Experiment	Source	d.f.	Variance ratio	*P* value
Ndiaye Dry '05	Irrigation (I)	3	10.2	0.009**
	Weed control (W)	2	84.8	0.001**
	I × W	6	7.4	0.002**
Ndiaye Wet '05	I	3	6.4	0.027*
	W	2	21.8	0.007**
	I × W	6	0.4	0.84
Fanaye Wet '05	I	3	3.8	0.075
	W	2	0.2	0.79
	I × W	6	1.9	0.16
Ndiaye Dry '06	I	3	1.9	0.233
	Nitrogen (N)	2	144.9	<.001**
	I × N	6	1.5	0.248
Fanaye Dry '06	I	3	0.2	0.911
	N	2	139.2	<.001**
	I × N	6	1.4	0.294

* P <0.05, ** P <0.01

The internal efficiency of nitrogen (IEN) was determined by dividing the grain yield by the total amount of nitrogen taken up by the plant. The fertilizer recovery fraction was determined as the total above ground plant N in the fertilized pots minus the total plant N in the unfertilized plots divided by the N application rate. Agronomic nitrogen use efficiency was calculated as the grain yields of the fertilized plots minus the grain yields of the unfertilized plots divided by the N application rate (Belder *et al.*, 2005b). Input water productivity was determined by dividing grain yield over the sum of irrigated volume and rainfall received.

3 Results

The results of the analyses of variance on grain yield for all experiments are shown in Table 2.4. Main effects of the irrigation regime were significant in 2005 in the DS and WS, but not in the 2006 DS. In the DS of 2006 in Fanaye, the volume irrigated did not differ between treatments. Main effects of herbicides and nitrogen treatments were always significant. Significant interaction effects were only found between the irrigation regime and the herbicide application in the DS of 2005.

3.1 Water management

3.1.1 Field water level and irrigation

Daily water levels in the fields of the four water treatments are shown in Figure 2.2. In Ndiaye, the treatments were successfully applied, with AWD regimes that had field water levels between 2 and -3 cm, while water levels of the flooded treatments were between 5 and 10 cm. Due to filling up of the soil profile the water level varied at the beginning of the season. Irrigation was applied twice a week. In Fanaye, the field water levels showed large fluctuations, with rapid decreases in water level. The differences between water treatments are less pronounced than in Ndiaye, but the AWD water treatments had significantly lower field water tables than the flooded treatments. Large cracks were observed in the fields of Fanaye, which were probably the reason for the high percolation rates (up to 20 cm d^{-1}). The volume of irrigation water used ranged between 480 (AWD WS 2005 Ndiaye) and 1490 mm (flooded DS 2005 Ndiaye) (Table 2.5). At both Fanaye and Ndiaye, the amount of irrigation water was larger in the dry seasons than in the wet seasons.

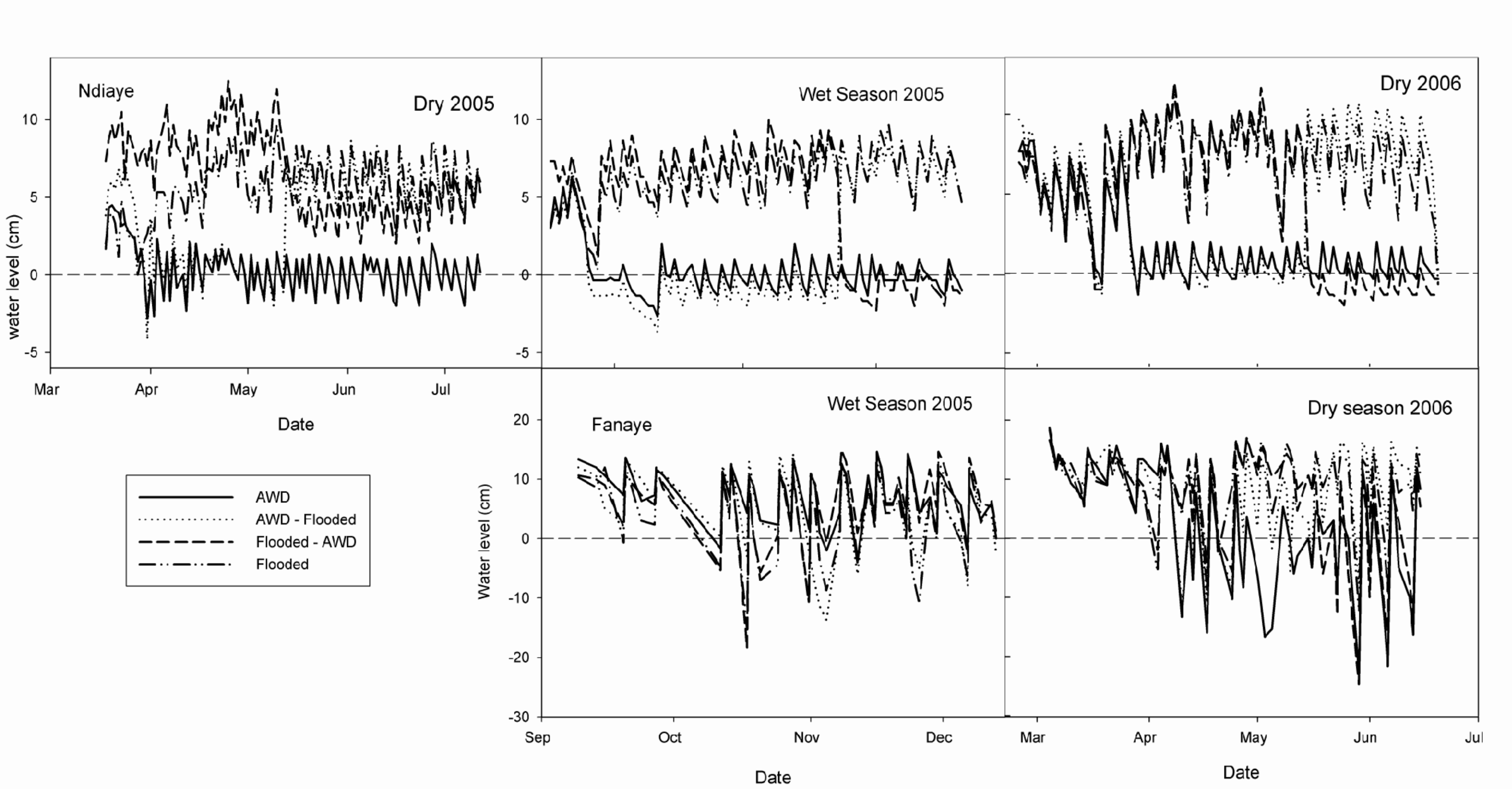

Figure 2.2: Flood water level (cm) relative to the soil, for five experiments at two sites (Ndiaye and Fanaye), over three seasons, 2005 dry, 2005 wet and 2006 dry. Each line represents the water level in one irrigation treatment.

Water use of the season-long AWD treatment was equal (DS 2006) or lower (DS and WS 2005) than of the other water-saving methods whereas that of the flooded treatment was consistently higher than any other treatment. Averaged over three seasons, AWD used 61% of the flooded treatment in Ndiaye.

In Fanaye, water use with AWD was 53 (WS) and 95% DS) of the flooded treatment, respectively. Percolation rates were very high in the DS of 2006, probably due to cracking and preferential flow of water. As a result, irrigation water use was similar in AWD, AWD-flooded and flooded-AWD in the 2006 DS, but in the DS of 2005 irrigation water use differed among water regimes.

3.1.2 Flood water salinity

Flood water salinity was always below 1.0 dS m^{-1}, irrespective of irrigation regime in all experiments in Ndiaye (data not shown). Irrigation water had a constant salinity of 0.19 dS m^{-1}.

3.2 Yield and yield components

3.2.1 Water regimes

Yields ranged from 2.3 to 11.8 t ha^{-1} under different water regimes, when recommended weed control and nitrogen fertilizer rates were applied (Table 2.5). The yields in the dry seasons were greater than those in the WS, due to higher radiation (Figure 2.1) and a longer growing cycle (Table 2.1). The AWD treatment resulted in the lowest yields, but main effect of irrigation treatment were not significant in three of the five experiments. Plant density after germination was daily checked visually for the first two weeks of the experiments and found to be equal among treatments. In the WS at both sites, the mixed treatments of AWD and flooded regimes resulted in significantly higher yields than the flooded treatment. By contrast the flooded treatment out-yielded other treatments in the DS, with the exception of AWD in Fanaye. In the DS of 2006, field water fell to a lower level in Fanaye than in Ndiaye (Figure 2.2), but at Fanaye average yield was greater (11.2 t ha^{-1} vs. 9.4 t ha^{-1}). Irrigation volumes were not different among treatments at that site in the DS. The large differences between seasons and sites were mainly due to the climatic differences. In the DS, both low night temperatures that slowed down initial development rate, and a high solar radiation increased biomass accumulation (Figure 2.1).

Table 2.5: Yield (t ha^{-1}), irrigation water use (mm), water use relative to flooded treatment per experiment (%) and water productivity (kg grain m^{-3} water) (WP) of five experiments with four irrigation treatments: continuously alternating wetting and drying (AWD); AWD until panicle initiation (PI), rest of the season flooded (Fld.); flooded until PI, then AWD, and continuously flooded. Weeds were controlled at 21 days after sowing, and N was applied at the recommended rate of 150 kg ha^{-1}.

Site	**Season**	**Irrigation treatment**	**Yield** (t ha^{-1})	**Irrigation** (mm)	**Relative water use** (%)	**WP**[a] (kg grain m^{-3})
Ndiaye	Dry 2005	I1 AWD	4.9	880	59	0.57
		I2 AWD- Fld	6.1	1310	87	0.47
		I3 Fld-AWD	6.4	1110	74	0.57
		I4 Fld	7.4	1490	100	0.49
SED			*0.4*			*0.05*
Ndiaye	Wet 2005	I1 AWD	2.3	480	60	0.32
		I2 AWD- Fld	4.9	630	78	0.57
		I3 Fld-AWD	5.0	550	68	0.63
		I4 Fld	4.1	800	100	0.39
SED			*0.3*			*0.13*
Ndiaye	Dry 2006[b]	I1 AWD	7.6	760	66	1.00
		I2 AWD- Fld	9.7	810	70	1.19
		I3 Fld-AWD	9.7	760	66	1.28
		I4 Fled	10.7	1160	100	0.93
SED			*0.7*			*0.15*
Fanaye	Wet 2005[b]	I1 AWD	3.7	710	53	0.31
		I2 AWD- Fld	4.7	810	61	0.44
		I3 Fld-AWD	5.2	810	61	0.49
		I4 Fld	3.7	1330	100	0.23
SED			*0.4*			*0.07*
Fanaye	Dry 2006[b]	I1 AWD	11.8	1060	95	1.12
		I2 AWD- Fld	10.8	1000	91	1.08
		I3 Fld-AWD	10.6	1060	96	1.00
		I4 Fld	11.7	1110	100	1.06
SED			*1.1*			*0.17*

[a] Water productivity is calculated as the grain yield divided by the sum of irrigation water applied and rainfall received , which was 240 and 260 mm in Ndiaye and Fanaye respectively, wet season only.
[b] No significant main effects of irrigation treatments on yield were observed, see Table 2.4.

Both the duration in days as well as in degree days were different in all experiments (Table 2.2), ranging from 2120°Cd to 2300°Cd, although the same cultivar was used. Yields of the AWD treatment, averaged over different sites and seasons were significantly less (6.1 t ha^{-1}) than that of the flooded control (7.4 t ha^{-1}) and other two irrigation regimes (7.3 t ha^{-1} and 7.4 t ha^{-1}) (SED = 0.5). In the WS of 2005, spikelet sterility was significantly higher for the AWD treatment compared with the other three irrigation treatments in Fanaye (Table 2.6), but in Ndiaye, only the difference between the flooded and AWD-flooded treatment was significant. However, the total sink size in terms of number of filled spikelets m^{-2} did not differ significantly between treatments. In the WS of 2005 in Ndiaye, tiller number m^{-2} at PI was significantly negatively affected ($P<0.05$) by AWD (data not shown). In Fanaye, the trend was reversed, though barely significant ($P=0.056$). In other seasons, tiller number was not affected by irrigation regime. In Ndiaye, DS 2005 yields were less than in the DS 2006, due to earlier sowing dates and consequently higher cumulative solar radiation.

Table 2.6: Percentage sterile spikelets and number of spikelets m^{-2} of two experiments in WS of 2005, at Ndiaye and Fanaye, using four different water management regimes (I1-I4).

Irrigation treatment	**Ndiaye**		**Fanaye**	
	Sterility (%)	10^4 spikelets m^{-2}	Sterility (%)	10^4 spikelets m^{-2}
I1 AWD	28	5.7	34	7.2
I2 AWD-Flooded	18	5.7	21	5.9
I3 Flooded-AWD	26	6.0	19	5.4
I4 Flooded	34	6.4	22	5.1
SED	*6.7*	*0.97*	*5.0*	*0.43*

3.2.2 Weed management

Weed control significantly increased grain yield in both seasons in Ndiaye (Table 2.4), although the timing of herbicide application was never significant. In Ndiaye, weed control increased yields of flooded rice by 4.4 t ha^{-1} in the DS and by 2.8 t ha^{-1} in the WS (Table 2.7). In Fanaye, no significant effect of weed control was observed in the flooded treatment. In Ndiaye, under irrigation regimes AWD and AWD-flooded, lack of weed control resulted in grain yields of 1.0 t ha^{-1} or less. At the same site in the no weed control treatments, flooded-AWD and flooded irrigation regimes resulted in an average yield increase of 0.3-4.5 t ha^{-1} compared with the AWD regime. Additionally, chemical control and hand weeding in the flooded-AWD and fully flooded treatments, increased yields to 3.7-7.4 t ha^{-1} compared with no weed control. In the DS of 2005, the treatment without weed control resulted in significantly less tillers m^{-2} at PI in irrigation regimes that started with AWD ($P<0.05$) in Ndiaye (data not shown). In the WS, tiller numbers m^{-2} at PI decreased significantly ($P<0.001$) in all irrigation treatments, when no weed control was applied. In Fanaye, no significant effects of flooding, timing of weed control or interactions between irrigation and weed control on rice yield or tiller numbers were observed.

3.2.3 Weeds

The most abundant weed species, in terms of number and biomass in the first month of each experiment, were *Echinochloa colona* (L.) Link. and *Cyperus difformis* L. In the WS in Ndiaye, *Ludwigia erecta* (L.) H. Hara. was abundant, especially in the second half of the season in the 'no weed management' treatment when it outgrew the rice crop by approximately one meter in height. At Fanaye, there was less weed pressure than in Ndiaye, and weeds were distributed less evenly.

3.2.4 Nitrogen management

Nitrogen application increased yields significantly ($P<0.001$) at both sites in all water management treatments (Table 2.8). At the highest N rates, grain yields were as high as 11.7 t ha^{-1} under flooded conditions. There were no significant main effects of irrigation treatments and no significant irrigation × nitrogen interactions (Table 2.4), due to the absence of differences in water regime in Fanaye in the DS of 2006 (Table 2.5; Figure 2.2). Without N fertilization, yields in Ndiaye were significantly ($P=0.001$) greater than those in Fanaye (3.5 vs. 2.7 t ha^{-1}), whereas at the highest N rate, yields in Ndiaye (9.4 t ha^{-1}) were significantly smaller than those in Fanaye (11.2 t ha^{-1}). Without N application no differences between irrigation treatments were observed at any site.

3.3 Resource use efficiencies

3.3.1 Water productivity

In four of the five experiments, the WP was largest for the Flooded-AWD treatment (Table 2.5). The exception was Fanaye DS 2006, which also showed the smallest water-savings. Poor yields in the WS under the AWD treatment at both Ndiaye and Fanaye resulted in low WP. WP was consistently high in the

DS of 2006 at both locations, ranging between 0.93 to 1.28 kg grain m^{-3} water, but in the DS of 2005 and in the wet seasons it was much smaller, between 0.23 and 0.63 kg grain m^{-3} water.

Table 2.7: Grain yield (14% moisture) (t ha^{-1}) under four different irrigation regimes (I1-4) and three weed control (W1-3) at two sites in wet and dry seasons of 2005. The standard error of differences among combinations of irrigation and herbicide treatment is given for each experiment.

Experiment	**Weed control timing treatment**	**Irrigation treatment**				
		I4 Flooded	I3 Flooded-AWD	I2 AWD-Flooded	I1 AWD	*SED*
Ndiaye	W1 21 DAS	7.4	6.4	6.1	4.9	*0.7*
DS '05	W2 35 DAS	6.9	6.2	6.4	6.3	
	W3 none	3.0	4.7	0.2	0.2	
Ndiaye	W1 21 DAS	4.1	5.0	4.9	2.3	*0.7*
WS '05	W2 35 DAS	3.7	4.2	3.4	2.1	
	W3 none	1.3	2.8	1.0	0.3	
Fanaye	W1 21 DAS	3.7	5.2	4.7	3.7	*0.7*
WS '05	W2 35 DAS	3.9	3.0	5.0	3.6	
	W3 none	4.0	4.0	5.0	2.8	

Between experiments, there was an increase in grain yield with increased water input (Figure 2.3). However, within experiments, this effect was not observed, and may be due to other factors than irrigation water saving that were not taken into account in this study. In the DS of 2006, WP was very high in Fanaye.

3.3.2 Nitrogen use efficiency parameters

Agronomic N use efficiency (ANUE) ranged between 30 and 77 kg grain kg^{-1} N applied (Table 8). At Ndiaye, ANUE was significantly greater at 90 kg N ha^{-1} than at 150 kg N ha^{-1}, with on average 51 and 40 kg grain kg^{-1} N, respectively. The same trend was observed in Fanaye, but differences were not significant.

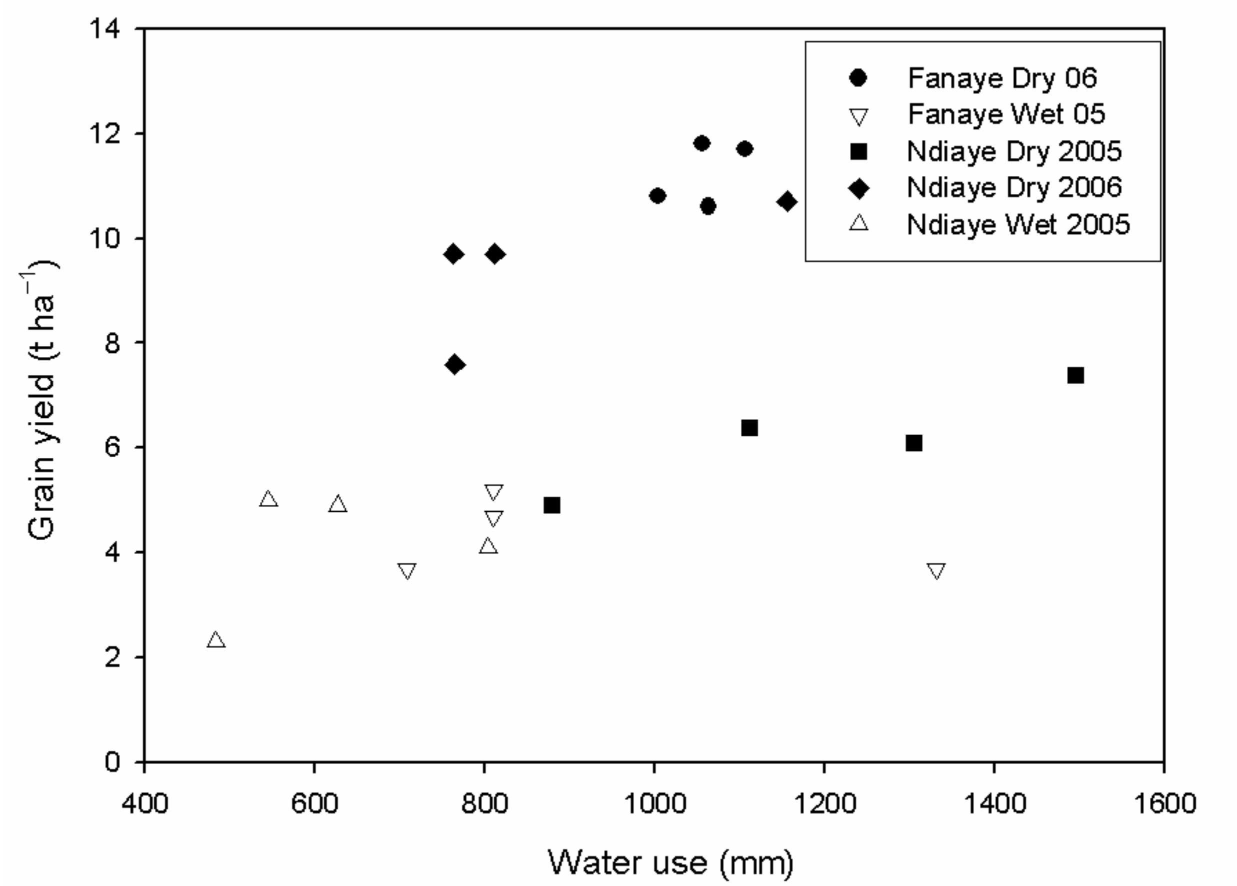

Figure 2.3: Relationship between water input (mm) and grain yield (t ha^{-1}) for all five experiments. Each symbol represents the grain yield (14% MC) for one of the four water treatments, weeds were controlled 21 days after sowing and 150 kg N ha^{-1} was applied.

Seventy percent of the nitrogen was applied in the first half of the season, before the irrigation treatments AWD-Flooded and Flooded-AWD had switched. This means that at the time of N application there were in fact two irrigation treatments: AWD and permanently flooded. Average values were combined accordingly to facilitate comparison of ANUE when N is applied under AWD to the ANUE following applications under permanently flooded conditions. In Ndiaye, the average ANUE was significantly poorer in the plots that were AWD (39 kg grain kg^{-1} applied N) at the time of application, than the ones that received fertilizer under the permanently flooded conditions (52 kg grain kg^{-1} applied N) (SED = 4.1). In Fanaye, no such difference was found.

The fertilizer N recovery fraction ranged from 0.22 to 0.84. In Ndiaye, N recovery was significantly greater at 90 kg N ha^{-1} than at 150 kg N ha^{-1} under the AWD-flooded and flooded-AWD treatments.

Table 2.8: Yield (t ha^{-1}), agronomic nitrogen use efficiency (Δkg grain kg N^{-1}), nitrogen fertilizer recovery fraction (kg kg^{-1}) and internal N efficiency (kg grain kg plant N^{-1}) of rice variety Sahel108 under four different irrigation regimes; combinations of alternate wetting and drying (AWD) and flooded, and three levels of nitrogen in the dry season of 2006 at Ndiaye and Fanaye.

Site	**Irrigation treatment**	**N level** kg ha^{-1}	**Yield** t ha^{-1}	**Agr. N use eff.** Δ kg grain kg^{-1} N	**N recovery fraction** kg kg^{-1}	**Int. N eff.** kg grain kg^{-1} plant N
Fanaye DS '06	I1 AWD	0	2.2	-	-	109
		90	7.8	62	0.67	97
		150	11.8	64	0.84	82
	I2 AWD-Fld	0	2.8	-	-	123
		90	9.7	77	0.80	104
		150	10.8	53	0.65	90
	I3 Fld-AWD	0	3.0	-	-	89
		90	9.5	72	0.59	110
		150	10.6	51	0.53	104
	I4 Fld	0	2.7	-	-	115
		90	7.6	54	0.49	113
		150	11.7	60	0.79	83
SED	*Irrigation*		*0.9*	*6.8*	*0.09*	*5.7*
	Nitrogen		*0.4*	*5.4*	*0.08*	*4.5*
	I × N		*1.1*	*11.1*	*0.16*	*9.3*
Ndiaye DS '06	I1 AWD	0	3.1	-	-	74
		90	6.8	41	0.28	86
		150	7.6	30	0.22	76
	I2 AWD-Fld	0	3.6	-	-	73
		90	7.4	42	0.51	60
		150	9.7	41	0.36	76
	I3 Fld-AWD	0	3.8	-	-	78
		90	8.9	57	0.54	74
		150	9.7	39	0.40	73
	I4 Fld	0	3.5	-	-	73
		90	9.1	62	0.55	79
		150	10.7	48	0.53	59
SED	*Irrigation*		*0.8*	*5.3*	*0.13*	*6.2*
	Nitrogen		*0.5*	*3.8*	*0.07*	*8.9*
	I × N		*1.1*	*8.0*	*0.18*	*15.7*

In the other irrigation treatments, no differences in recovery fraction were found among N application rates. In Fanaye, the opposite (greater recovery fraction at 150 than at 90 kg N ha^{-1}) was true only for the flooded treatment.

In Fanaye, the recovery fraction was significantly greater under AWD than under permanently flooded conditions during the vegetative stage (P=0.05), while at Ndiaye, it was significantly poorer under AWD than under flooded conditions. In Ndiaye, maximum internal N efficiency (IEN) was 86 kg grain kg^{-1} N, whereas at Fanaye it was 123 kg grain kg^{-1} N. IEN at Fanaye decreased significantly with N application rates, except for the flooded-AWD treatment. The AWD treatment had the poorest IEN. No irrigation × nitrogen interaction effects on IEN were observed in Ndiaye. The relation between total plant N uptake and grain yield was linear for yields up to 8 t ha^{-1} in Ndiaye and up to 10 t ha^{-1} in Fanaye (Figure 2.4), suggesting that yields were mainly constrained by N-supply. IEN in Fanaye was better than in Ndiaye, especially for grain yields higher than 8 t ha^{-1}.

4 Discussion

4.1 Water saving and yield

In the current study, the irrigation water use in water saving treatments was 72% on average, ranging between 53 and 96%, of the volume irrigated in the permanently flooded treatments. Yields of the irrigation water saving treatments were 92% on average, ranging between 56 and 141%, of the flooded treatment. Main effects of the irrigation treatments on rice yield were significant (P<0.05) in two of the five experiments. In three experiments (Ndiaye WS 2005, Fanaye WS 2005 and Ndiaye DS 2006) water regime I3 (Flooded-AWD) gave equal or larger yields than the flooded control. In dry seasons the irrigated volume of water was larger, although in the WS, initial soil water contents were higher due to rainfall. The longer growing period, in calendar and degree days, the hotter and drier climate and absence of rainfall, contributed to a larger volume of irrigation water in the DS. In Fanaye in the DS of 2006, no significant reduction in yield was observed despite large percolation losses, possibly because the frequent irrigations kept the soil moist.

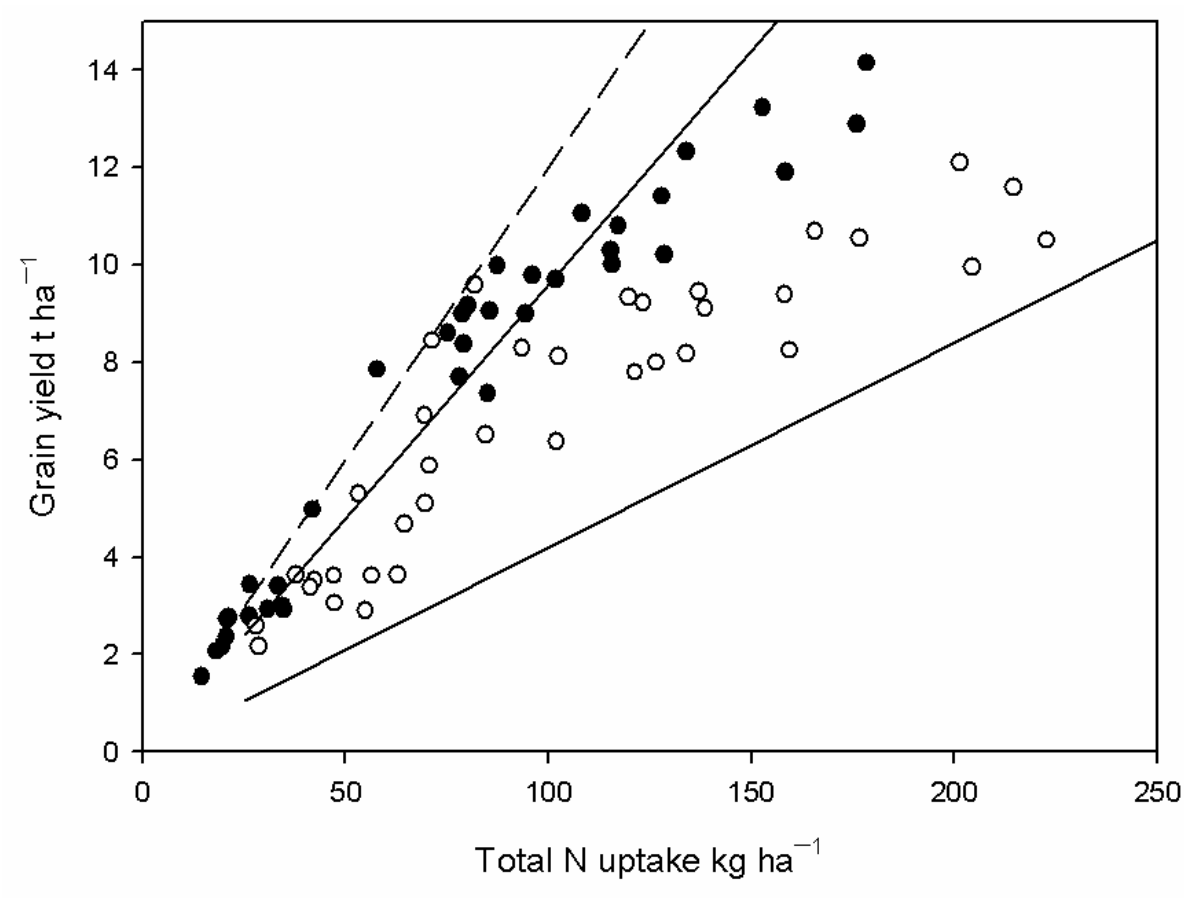

Figure 2.4: Total plant nitrogen uptake (kg ha^{-1}) and grain yield (t ha^{-1}) (14% MC) at two sites in the dry season of 2006. Dashed line is maximum dilution (slope = 0.112) found by Haefele *et al.* (2003a). Solid lines form an envelope that can be used to predict fertilizer requirements, with slopes of 0.96 and 0.42 of upper and lower boundaries (Witt *et al.*, 1999). Open symbols represent the Ndiaye site and closed symbols represent the Fanaye site.

Although the water levels fell to more than 20 cm below the soil surface, much faster than those observed by Haefele (2001) on the same site, irrigation replenished the soil water content before water stress took place. Water saving technologies can save 10-30% of the water in areas with a shallow water table (Belder *et al.*, 2004), as in Ndiaye where up to 40% irrigation water was saved, but with substantial yield losses. When a deep water table is present, in a free draining soil without a compacted plough layer, as in Fanaye, water savings can be 50%, but yield losses are around 20%. Yield was found to be independent of water table depth when a plough sole was present (Bouman *et al.*, 2007a; Tabbal *et al.*, 2002). This is confirmed by the large water savings observed in the WS at Fanaye (47%) without concomitant yield losses. In the DS, however, savings were minimal (5%), probably because percolation rates were high, which resulted in the need for frequent irrigation to avoid crop water stress. The effects of site on rice yield was large, due to both climatic differences and chemical and physical soil properties. The high percolation rates at Fanaye influenced the water management treatments, and differences in water management treatments were smaller in Fanaye than in Ndiaye. Although a saturated infiltration rate of 2.5 mm d^{-1} was measured (Haefele, 2001), not uncommon in heavy clay soils, water levels dropped by an order of magnitude faster. Based on daily field observations on the bunds and canals surrounding the treatments, seepage can be excluded as an important contributor to these water losses. Sub-surface cracks, on the other hand, could have played an important role in the relatively high infiltration (Tuong, 1994). The experiments were carried out on plots that were smaller and that had a higher bund: surface ratio than farmers' plots (0.39 versus 0.1). Consequently, seepage through and under bunds in the flooded treatments of these experiments is probably overestimated. Although the plots were lined with plastic, under-bund losses could have taken place (Tuong, 1994). However, seepage losses were probably a minor part of the water balance given the physical properties of the soils. In our experiments the flooded treatments had water levels of 7-12 cm above the soil surface, in farmers' fields water levels can be up to 30 cm, which will increase the irrigation water use, and increases the potential for irrigation water savings. Experiments in Asia have shown a yield decline under continuous aerobic rice cropping (Peng *et al.*, 2006): recently, increasing root-knot nematode populations and micro-nutrient deficiencies have been identified as possible causes (Kreye *et al.*, 2009a; 2009b). Further research should focus on investigating whether these long-term effects would also occur under the proposed water regimes in Sahelian environments.

In the WS of 2005, planting was delayed by two weeks in Fanaye, which increased the sterility in the AWD treatment significantly. As shown by Dingkuhn *et al.* (1995b), planting date has a strong influence on cold induced sterility in the Sahel, which is related to flood water temperature. Williams and Angus (1994) observed yield reduction in shallow water (5 cm) compared with deep water (20 cm) at an air temperature of 15°C. In our experiments the minimum air temperatures in the WS of 2005 were 20°C for Ndiaye and 15°C for Fanaye. The AWD treatment could have had more extreme flood water temperatures, and hence suffered more from cold induced sterility, especially at the Fanaye site.

Measured salinity levels were always lower than 1.0 dS m^{-1}, which is well below the threshold of 2.0 dS m^{-1} above which the crop is damaged (Asch and Wopereis, 2001).

4.2 Weed control and nitrogen rates

Weed pressure was much lower in Fanaye than in Ndiaye. The shallow water table in Ndiaye makes the top soil moist even before the rice crop is sown, stimulating weed germination. In Fanaye, the soil remains dry until land preparation, and the deep water table added to a high percolation rate causes the soil to dry quickly, giving the pre-germinated rice seeds an important competitive advantage over weeds. Differences in timing of weed control were more pronounced in the WS due to higher temperatures at the onset of this season, compared with the beginning of the DS. Yields obtained with the cultivar Sahel108 at an application rate of 150 kg N ha^{-1} in the DS of 2006 were comparable to the potential yield of 10 t ha^{-1} for this type of cultivar calculated by Dingkuhn and Sow (1997b) (Table 2.5).

4.3 Resource use efficiencies

Water productivity in the current study was in the same range as found by Bouman and Tuong (2001) in the Philippines, but higher than observed in India. Bouman and Tuong (2001) attributed high water productivity to large potential yields coupled with small seepage and percolation losses. In pot experiments, without seepage and percolation losses, water productivities of up to 1.90 kg grain m^{-3} water were reported (Bouman and Tuong, 2001), while the maximum found in this study was 1.28 kg grain m^{-3} water. Tuong *et al.* (2000) reported water productivities of 0.24 to 0.84 kg grain m^{-3} water in the field, less than what we found in Senegal. Kato *et al.* (2009) recently reported an increase of WP to 0.8-1.0 kg grain m^{-3} water in aerobic rice grown under sub-tropical conditions which is less than we found in the DS of 2006 (1.0-1.3 kg grain m^{-3} water), while Bouman *et al.* (2005) obtained WP values of 0.46-0.68 kg grain m^{-3} water, in a DS experiment on aerobic rice in the Philippines.

The fertilizer nitrogen recovery fraction in the current study ranged from 0.22 to 0.84, while 0.5 is found under good management (Cassman *et al.*, 1993). In Ndiaye, agronomic nitrogen use efficiency was smaller in the AWD treatments, which indicates substantial N losses. In Fanaye, when the AWD treatment saved only 5% of the irrigation water, this effect was not observed. The AWD treatment was wetter in Fanaye, due to more frequent irrigations;

hence the soil status (aerobic or anaerobic) of all water treatments was similar. In Ndiaye, increased denitrification could have played a role. Reddy and Patrick (1986) demonstrated that nitrogen mineralisation and nitrification occur when the water table falls below the soil surface, and the released nitrate could be susceptible to loss by denitrification when the soil rewets.

The poorer IEN obtained at Ndiaye compared with Fanaye suggests that yields in Ndiaye were constrained by other factors than N. Haefele *et al.* (2003a) calculated IEN and found a maximum of 115 kg grain kg^{-1} plant N for fertilized flooded-rice fields in West-Africa. In the current study, IEN ranged from 59 to 123 kg grain kg^{-1} plant N. Witt *et al.* (1999) proposed an envelope composed of threshold values for maximum dilution and minimum accumulation to predict fertilizer requirements, based on data from 15 sites in six Asian countries. The values obtained in this study fall mostly within the proposed envelope, and when the maximum IEN found by Witt *et al.* (1999) is taken into account, all but one fall within the envelope (Figure 2.4). In our study, the maximum yields were higher than in the two previous studies by Witt *et al.* (1999) and Haefele *et al.* (2003a), 14 versus 10 t ha^{-1}, and the results can be used to increase the application domain of the framework for fertilizer recommendation that was proposed by Haefele *et al.* (2003b).

Straw N content at harvest was not measured, but estimated based on the relation previously identified by Witt *et al.* (1999). This may have resulted in a less accurate determination of the IE. N-content was only measured at harvest, whereas total N uptake peaks between flowering and harvest, hence total N uptake is perhaps underestimated. Mean grain yields in Fanaye were 9% higher than in Ndiaye under non-stress conditions, due to higher solar radiation. In all experiments the same cultivars were used, but growing duration in degree days varied (2120 – 2510°Cd), with a longer duration in the DS tan in the WS, similar to observations by Dingkuhn (1995). One of the causes of the variation may be the linear approach to calculation of growing degree days: a non-linear model often gives more accurate results (Yin *et al.*, 1995).

4.4 Outlook

Extrapolation of irrigation water savings found on experimental fields to farmers' fields is difficult (Lampayan *et al.*, 2004). Further irrigation water savings may be impossible in the DS in the Sahel, because the full AWD treatment resulted in significant yield decreases. There are examples of yield decline due to salinization or alkalinization in Sahelian rice production systems in Mauritania (e.g Van Asten *et al.*, 2003) and Senegal (Wopereis *et al.*, 1998). In these specific environments it would be unwise to decrease irrigation volume, as it may lead to an accumulation of (alkaline) salts in the root zone. We used the most popular medium duration rice variety of the region, but significant yield increases from better adapted (aerobic) rice varieties can be expected (Atlin *et al.*, 2006). Adoption of water saving technologies will require efforts in selecting the best fit environment based on socio-economic factors (Zhou *et al.*, 2008). Given these difficulties, crop models that include a water balance could play an important role to develop scenarios for water saving technologies (Belder *et al.*, 2007).

5 Conclusion

Our results clearly demonstrate that it is possible to attain major savings of irrigation water with little yield penalties in a Sahelian environment. The sites, selected for the current study encompass a range of rice growing conditions of Sahelian environments. It can, therefore, be concluded that in the Sahel during the wet season irrigation water savings of 22-39% are possible for rice with no or little yield loss. In the dry season, the flooded treatments produced on average 1.0 t ha^{-1} more than any combination of flooded and AWD, and 1.8 t ha^{-1} more than the season-long AWD treatment.

This study focused on the interactions between water and nitrogen and water and weed management, whilst other factors, such as land preparation methods or crop establishment were not considered. These factors could also have large influences on water consumption. This research shows that an irrigation regime for rice that starts as conventional (flooded), and then changes to AWD shows promise to save water and improve water productivity without yield loss, while maintaining a low weed pressure and an efficient use of nitrogen.

Chapter 3

Adaptability of irrigated rice to temperature change in Sahelian environments*

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* This chapter is published as:
de Vries, M. E., P. A. Leffelaar, N. Sakané, B. V. Bado & K. E. Giller. 2011. Adaptability of irrigated rice to temperature change in Sahelian environments. Experimental Agriculture 47: 69-87.

Abstract

To assess genotype adaptability to variable environments, we evaluated five irrigated rice genotypes, three new varieties, WAS161, a NERICA, IR32307 and ITA344, and two checks: IR64 and Sahel108, which is the most commonly grown in the region. In a field experiment conducted at two locations, Ndiaye and Fanaye, along the Senegal River, rice was sown on 15 consecutive dates with one month intervals starting in February 2006. Yield (0-12.2 t ha^{-1}) and crop cycle duration (117-190 days) varied with sowing date, genotype and site. Rice yield was very sensitive to sowing date and the associated temperature regimes. Spikelet sterility due to cold stress ($T < 20^oC$) was observed when the crops were sown in August (Ndiaye), September (Ndiaye and Fanaye) and October (Ndiaye and Fanaye), and heat stress ($T > 35^oC$) resulted in spikelet sterility when sowing took place in April (Ndiaye and Fanaye) and May (Fanaye). For all experiments the source and sink balance was quantified, which showed that yield was most limited by sink size when sowing between July and October. Variety Was161 was least affected by genotype × environment interactions, resulting in lower interactive principal component values. An increase in minimum temperature of 3^oC could decrease spikelet sterility from 100 to 45%. These changes in temperature are likely to force rice farmers in the Senegal River to adjust the cropping calendar, (e.g. to delay planting), or to use heat tolerant genotypes.

Keywords: AMMI analysis, Climate change adaptation, Spikelet sterility.

1 Introduction

Irrigation schemes in the Sahel provide farmers with a reliable water-supply that is highly valued in a region with scarce and unreliable rainfall (Connor *et al.*, 2008). Rice (*Oryza sativa* L.) production in these schemes is one of the most important activities, with 50 000 ha being cultivated in Senegal (SAED, 2007). Among the decisions farmers have to take, choosing between double and single cropping, and, more specifically, selecting the sowing date are among the most critical (le Gal and Papy, 1998; Poussin *et al.*, 2003).

In Sahelian rice production, temperature affects two processes critically: the length of the growing cycle and spikelet sterility, induced by either heat or cold stress (Dingkuhn and Miezan, 1995). High temperatures (>35°C) at anthesis result in decreased pollen production and poor dehiscence of anthers, leading to poor pollen shed and fewer pollen grains intercepted by the stigma. Overall, this leads to a decrease in spikelet fertility (Endo *et al.*, 2009; Prasad *et al.*, 2006). Jagadish *et al.* (2010b) showed that there were genotypic differences in heat tolerance at anthesis, originating from differences in protein expression. Stress due to low temperatures is caused by flood-water temperatures below 20°C around booting stage. It induces spikelet sterility that increases sharply with decreasing temperature resulting in complete sterility at 15°C (Shimono *et al.*, 2005). Genotypes appear to have similar critical low temperatures for spikelet sterility (Dingkuhn *et al.*, 1995b).

Surveys among farmers in the Senegal river valley have revealed that farmers are aware of the relation between low temperatures and yield decline in the wet season (Haefele *et al.*, 2002a), and that they tend to respect the optimal sowing date, with an average sowing date of 4 August in 2004 (Diagne, 2006b). Wassmann *et al.* (2009) show that rice production will be significantly influenced by climate change. Predictions from downscaling global circulation models indicate that an increase in surface temperatures of 1.5-3°C can be expected by 2030 in the Sahel (Boko *et al.*, 2007; Jury and Whitehall, 2010). Given the sensitivity of rice to both high and low temperatures at critical stages, which drive a potential yield reduction, both the sowing window and varietal preferences may alter in the coming decades.

Genotypes developed from inter-specific crosses of *O. sativa* × *O. glaberrima* (NERICA) for upland conditions have good potential yield (Dingkuhn *et al.*, 1998), and their performance was stable across upland sites in

West-Africa (Sanni *et al.*, 2009). Similarly, lowland NERICA genotypes have been developed (Rodenburg *et al.*, 2006), and subsequently released in Sahelian countries (Sie *et al.*, 2007). To date, information is lacking on the yield potential of lowland NERICA genotypes under irrigated conditions, and their ability to cope with the highly variable Sahelian climate. In Sahelian environments, farmers need varieties on which they can rely to perform well under a wide range of conditions. Gauch and Zobel (1997) developed an elegant method using an additive main effect and multiplicative interactions (AMMI) approach where the interaction term of the analysis of variance is analysed using principal components to assess genotype × environment interactions (G × E). Their tools aid breeders in determining which genotype wins in which environment, enabling selection for specific environments, and screen genotypes for their likelihood to be affected by G × E.

This study focused on evaluating the effect of different sowing dates on new rice genotypes, and how these varieties are adapted to possible changes in temperature which could influence the rice production system.

2 Materials and Methods

2.1 Site description

Field experiments were conducted between February 2006 and July 2007 at Ndiaye (16°11'N, 16°15'W) and Fanaye (16°32'N, 15°11'W) in Senegal. Both are experimental research stations of the Africa Rice Center (AfricaRice). The sites were located in the delta (Ndiaye), 35 km inland, and middle (Fanaye), 150 km inland, of the Senegal river valley. For a detailed description of the physical and chemical properties of the soils see Bado *et al.* (2008) and De Vries *et al.* (2010).

2.2 Climate

Climate at both sites is typically Sahelian: a nine month dry period followed by a short wet season and large amplitudes in temperature (Figure 3.1). Meteorological data were recorded using an Onset Hobo© weather station, installed in a rice field next to the experiments.

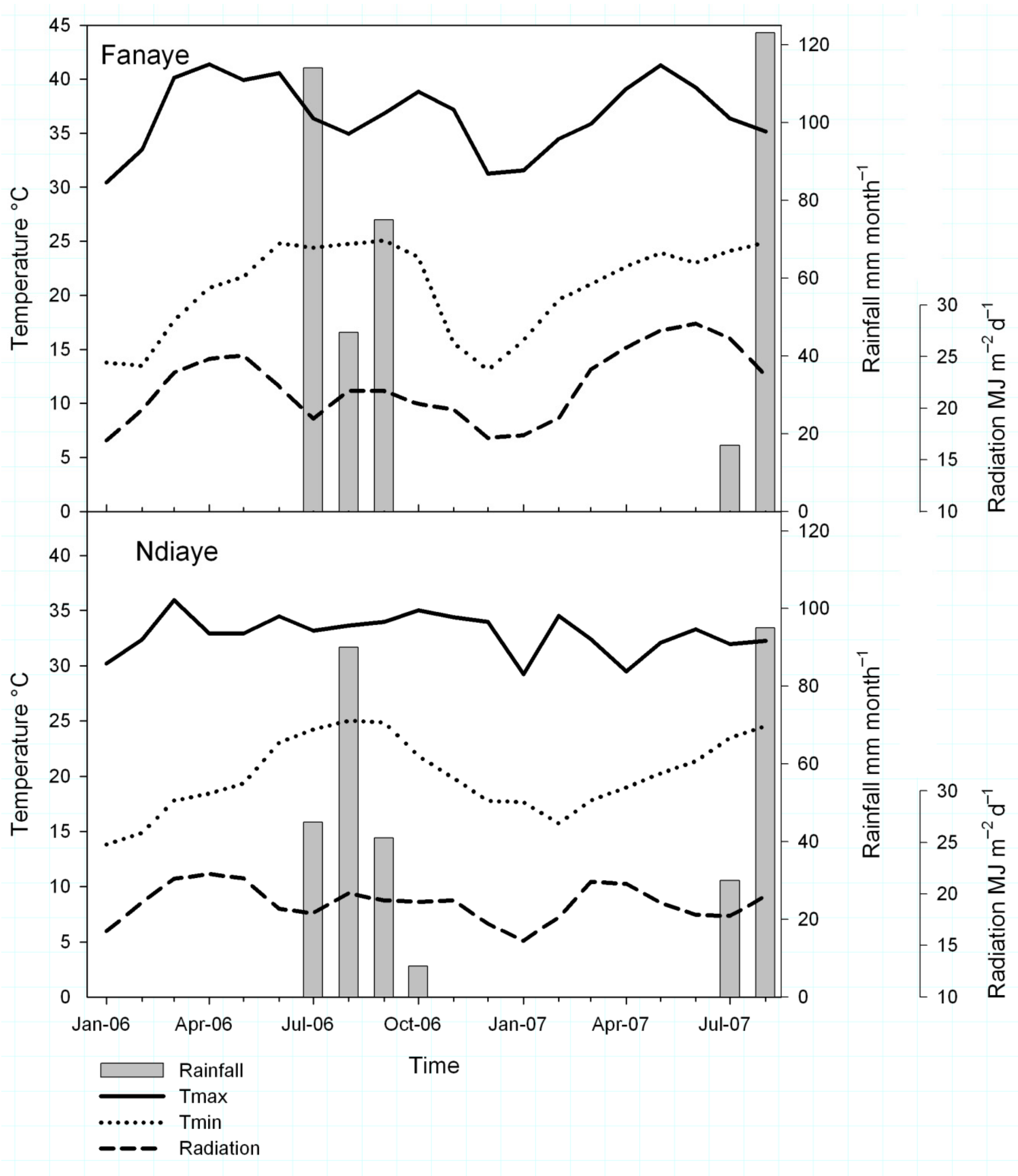

Figure 3.1: Weather in Fanaye (top) and Ndiaye (bottom) between January 2006 and August 2007: monthly mean maximum (full line) and minimum (dotted line) temperatures (°C), solar radiation (dashed line) (MJ $m^{-2}d^{-1}$), and monthly rainfall (mm $month^{-1}$).

All instruments were mounted at 2 m above the soil. Hourly data were recorded, from which minimum and maximum temperatures, cumulative total global radiation and total rainfall were derived on a daily basis. Between March and July, solar radiation and maximum temperatures are higher at Fanaye than in Ndiaye. The highest temperature observed in Fanaye was 46°C on May 19, 2007, while in Ndiaye it was 44°C on June 16, 2007. Between November 2006 and March 2007, minimum temperatures were lower in Fanaye than in Ndiaye. In Ndiaye, the lowest temperature recorded was 11°C on January 27, 2007, while at Fanaye it was 8°C on January 8, 2007. Rice production by farmers takes place twice a year, from February to June in the hot dry season and from August to November in the wet season.

2.3 Experiment

A set of sowing date experiments was conducted at the two sites: for 15 consecutive months an experiment of five varieties was sown on the 15th day of each month. The experiments were sown in randomized complete blocks and replicated three times. Each plot, comprising one variety, measured 5 × 5 m and was bunded so that it could be irrigated and drained independently. Each sowing date was treated as an individual experiment, although consecutive sowing date experiments were adjacent. The first experiment was sown on 15 February 2006 and the crops of the last sowing dates were harvested at 27 and 28 August 2007 for Ndiaye and Fanaye, respectively.

2.4 Genotypes and crop management

Five genotypes were compared: 1) Sahel108 (IR 13240-108-2-2-3), the most popular short-duration variety in the region; 2) IR64, as an international check variety; 3) WAS161-B-9-2, an interspecific cross between IR64 (O. sativa) and TOG 5681 (*O. glaberrima*), back-crossed four times with IR64 and released in The Gambia and Burkina Faso (Sie *et al.*, 2007); 4) ITA344, a medium-duration variety, newly released in Senegal as Sahel 208; 5) IR32307-107-3-2, a short-duration variety, newly released in Senegal as Sahel 159, and used by farmers in Mali.

Apart from differing in sowing date, management was kept as uniform as possible between the different sowing date experiments and conformed with local recommendations to ensure optimal growing conditions. Seeds were soaked in water for 48 h to ensure homogeneous and rapid germination, after which the seeds were sown in a seed-bed. Twenty-one days after sowing, the seedlings were transplanted at 2-3 plants per hill at 0.2 × 0.2 m distance. When the seedlings had recovered from transplanting shock, they were thinned to two plants per hill. The plots were kept weed-free by frequent hand-weeding. All crops were fertilized uniformly with N and P in the form of urea and diammonium phosphate (DAP).

DAP was broadcast at transplanting (21 kg P ha^{-1} and 18 kg N ha^{-1}), and urea was broadcast in three splits: 42 kg N ha^{-1} at the beginning of tillering, 60 kg N ha^{-1} at panicle initiation and 30 kg N ha^{-1} at heading stage. The total rate of fertilizer application was 150 kg N ha^{-1} and 21 kg P ha^{-1}, which is the recommended rate for a dry season crop. Urea was broadcast into a 0.05 m layer of water. No significant pest or disease damage was observed. After transplanting, the water level in the plots was raised from 0.05 m to 0.15 m at booting stage. Two weeks before estimated maturity, the plots were drained to ensure homogeneous ripening of the crop.

2.5 Measurements

Flowering was recorded as the day when 50% of the plants flowered; maturity was noted as the day when 80% of the plants were mature. At maturity, an area of 2 × 3 m in the centre of the plot was harvested; straw and grain were separated and weighed. Moisture content of the grains was determined, and grain yield was corrected to 14% moisture content. Harvest index was calculated as (dry) grain yield divided by total above-ground dry biomass. Yield components were determined from a separate sample of 0.4 × 0.4 m. From the sample all spikelets were counted to obtain the number of spikelets m^{-2}; filled and un-filled spikelets were separated and counted to obtain the percentage fertile and sterile spikelets. Grains were weighed to determine the 1000-grain dry matter weight.

2.6 Statistical analysis

A one-way analysis of variance (ANOVA) was carried out to assess yield, growing cycle duration, sterility, harvest index, 1000-grain weight and spikelets m^{-2} for each experiment. To analyse the effects of sowing date, site and genotype, an unbalanced ANOVA was performed, using only sowing dates that gave some yield. Inclusion of the zero values would violate the assumptions of homogeneous variance error across variety × sowing date combinations in the ANOVA. To further analyse the performance of the different varieties in different environments, an additive main effect and multiplicative interactions (AMMI) analysis was performed, as described by Gauch and Zobel (1997). AMMI combines the ANOVA (with additive parameters) and principal component analysis (PCA) (with multiplicative parameters) into a single analysis. A principal components model is fitted to the residuals from the ANOVA and the resulting scores, called the I (for interaction) PCA scores, along n axes, are calculated for both the genotypes and environments. When

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constructing the analysis-of-variance table, AMMI assumes that the replicates arise from the use of a randomized block design within each environment. In the AMMI analysis, the model for phenotypic performance X of genotype j tested in environment i can be expressed as:

$$X_{ij} = \mu + e_i + g_j + \sum_{1}^{n} \left(\lambda_n \alpha_{in} \gamma_{jn} \right) + \theta_{ij}$$

where μ = grand mean; e_i= additive effect of environment i; g_j= additive effect of genotype j; λ_n= eigenvalue of PCA axis n; α_{in}= i^{th} genotype PCA score for PCA axis n; γ_{jn} = j^{th} environment PCA score for PCA axis n; θ_{ij}= residual. The performance, X_{ij}, can vary with the objective of the study, usually grain yield or growing cycle duration. We treated each experiment as an environment. This resulted in 23 environments: 14 in Fanaye and nine in Ndiaye. In 2006 as well as in 2007, sowing took place in February, March and April. These sowing dates were used to assess the effect of different sowing years. A factorial design with year, site, sowing date and genotype as factors was used. For all analyses, the software package GenStat 11th edition (VSN international) was used.

3 Results

3.1 Yield

Variation in yield between sowing dates was large (Figure 3.2A). The largest yield at Ndiaye (12.2 t ha^{-1}) was obtained with IR64 sown in March 2007, while some sowing dates resulted in complete crop failure. At Fanaye, IR64 sown in February 2006 gave the largest yield of 11.2 t ha^{-1}. The analysis of variance, using only non-zero values, showed that the principal effects and interactions of sowing date, site and variety were highly significant ($P<0.001$), except for the variety × site interaction (Table 3.1). Yield was significantly different between cultivars with 11 of the 14 sowing dates in Fanaye and only with two of the 11 sowing dates when yield was obtained in Ndiaye (data not shown). Averaged over all experiments, including crop failures, IR64, WAS161 and Sahel108 yielded 5.1 t ha^{-1} of grain, ITA344 followed with 4.9 t ha^{-1} and IR32307 with 4.7 t ha^{-1}. Due to the more frequent crop failures at Ndiaye, overall average grain yield at Fanaye was larger, 6.0 versus 4.0 t ha^{-1}. At both sites the overall pattern was similar, with peak harvests recorded in experiments sown in March and April. However, there were some striking differences between the two locations: sowing in September, October and

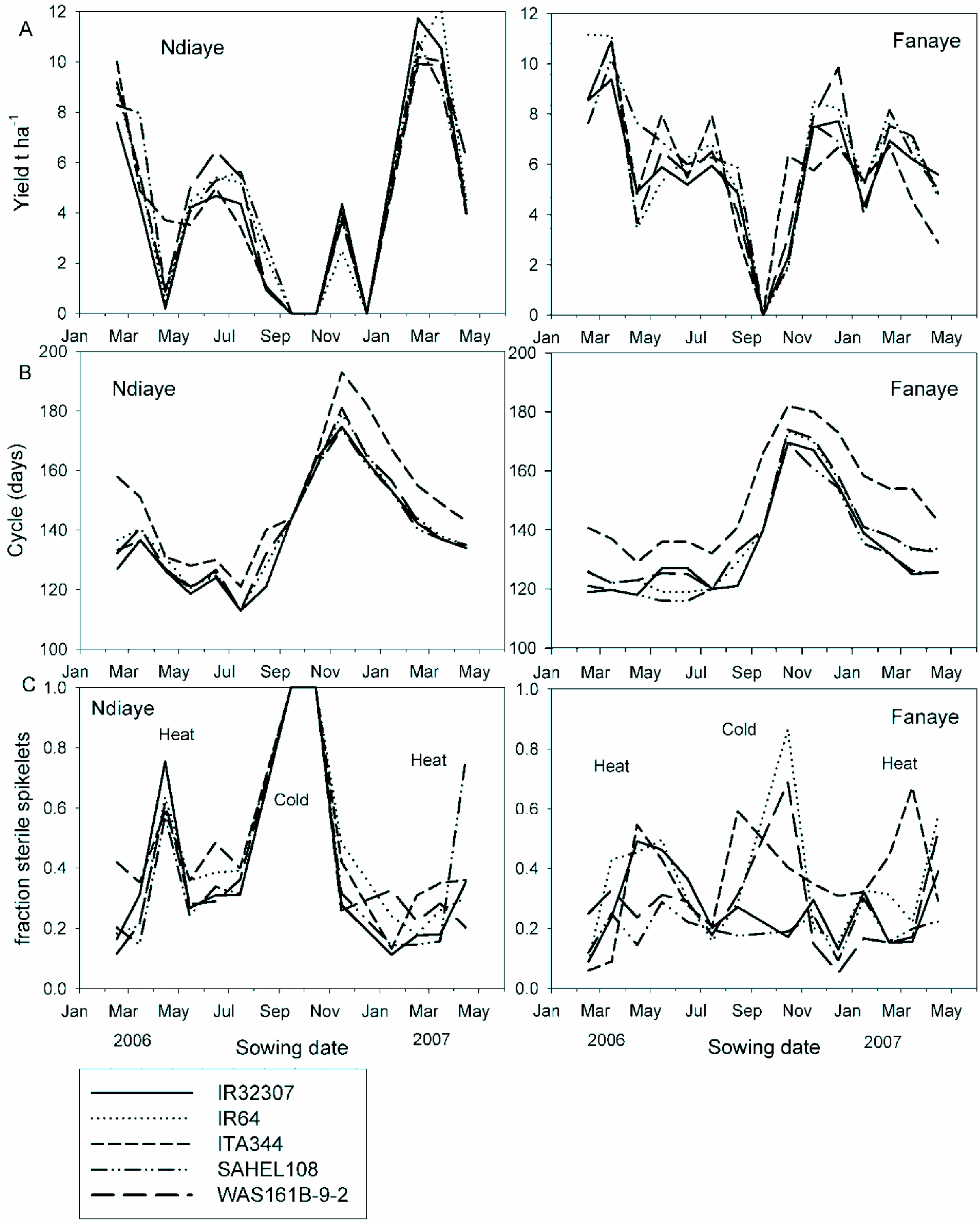
December resulted in crop failure in Ndiaye, while the only crop that failed in Fanaye was sown in September, and the December sowing resulted in high yields (7-10 t ha^{-1}). Between the sowing dates of March and April, yield was most sensitive to sowing date: averaged over both years and sites each day delay in sowing after March 15th resulted in a loss of 140 kg ha^{-1}.

Table 3.1: Analysis of variance for all sowing dates with non-zero values for yield using an unbalanced design.

Source	d.f.	Variance ratio	*P* value
Replications within sowing dates and sites	56	2.3	
Variety (V)	4	4.42	0.002
Site (S)	1	64.7	<.001
Sowing month (M)	13	142.1	<.001
V × S	4	1.25	0.196
V × M	52	5.79	<.001
S × M	10	69.6	<.001
V × S × M	39	3.52	<.001
Residual	192		
Total	371		

3.2 Length of growing cycle

Both in Fanaye and Ndiaye, the crop duration was longest with sowing in October and November, whereas June and July resulted in the shortest duration (Figure 3.2B). In Ndiaye, the duration varied from 113 days for four varieties sown in July to 193 days for ITA344 sown in November. In Fanaye, Sahel108 sown in May and June had the shortest cycle of 116 days, while ITA344 sown in October had the longest cycle of 182 days. Sowing in July and September resulted in the same duration at both sites for four varieties, whereas sowing in June and August resulted in small differences (3-8 days) between the varieties at both sites. In Ndiaye, variety IR32307 had its shortest duration of 139 days averaged over all sowing dates; ITA344 had an average duration of 150 days. In Fanaye, Sahel108 had the shortest duration (131 days), here IR32307 took 134 days to mature, whereas ITA344 had the longest duration of 150 days, the same as in Ndiaye. Although overall IR32307 had the shortest duration, it responded differently in Ndiaye and Fanaye.


A
Ndiaye
Fanaye
Yield t ha-1
B
Cycle (days)
C
fraction sterile spikelets
Heat
Cold
Jan Mar May Jul Sep Nov Jan Mar May
2006
2007
Sowing date
IR32307
IR64
ITA344
SAHEL108
WAS161B-9-2

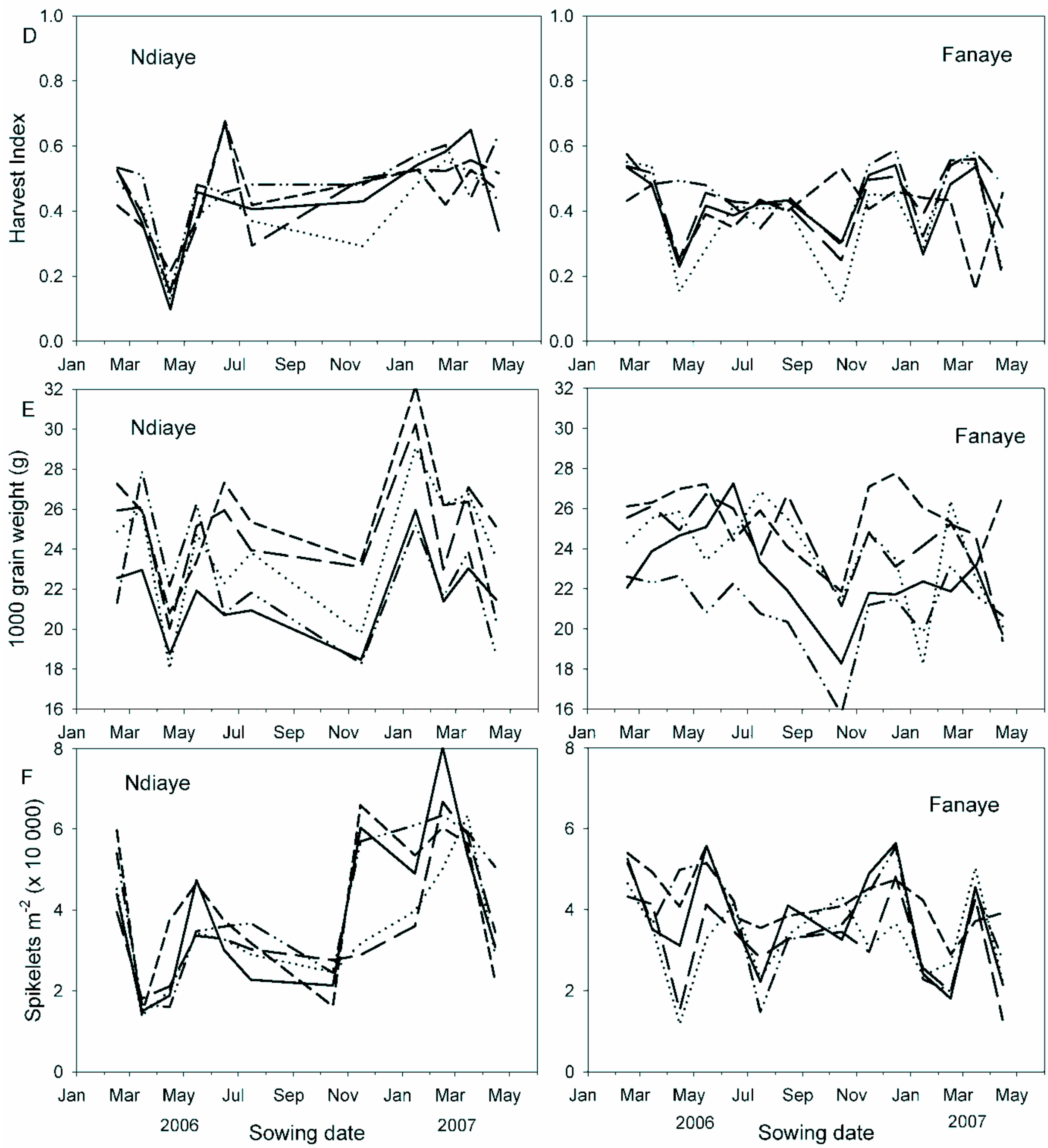


Figure 3.2A-F: A; Grain yield (t ha⁻¹), B; cycle duration (days), C: Fraction sterile spikelets (-), D; Harvest index (-), E; 1000-grain weight (g), F; spikelets (10^4 m^{-2}) from 15 subsequent sowing date experiments with five varieties (IR32307, IR64, ITA344, Sahel108 and Was161 B-9-2) at Ndiaye (left) and Fanaye (right) in Senegal between February 2006 and April 2007.

In the experiments sown from April to June in Fanaye, it had the second longest duration. Overall, the duration increase between sowing in August and November was 53 days for all varieties and at both sites.

3.3 Spikelet sterility

Spikelet sterility can be induced by both high (>35°C) and low (<20°C) temperatures. Both occurred in this experiment (Figure 3.1 and 3.2C). The effect of genotype on sterility was significant (P <0.05) in six out of 12 cases in Ndiaye, and in eight out of fourteen cases in Fanaye (data not shown). In Ndiaye, there were peaks in sterility when the crop was sown in April, September and October. There was a large difference in sterility between sowing in April 2006 and 2007. In 2006 all varieties had more than 57% sterile spikelets, whereas in 2007 only variety Sahel108 was affected with 76% sterility (P < 0.001; SED =6%). All spikelets of all varieties were sterile at the sowing dates September and October. Variety ITA344 had a higher percentage sterile spikelets than other varieties in two sowing dates, June 2006 (P = 0.095) and January 2007 (P <0.05; SED = 6%). The longer duration cycle of ITA344 is a likely cause.

Sterility had less impact in Fanaye and complete sterility was never observed. The peaks in percentage sterile spikelets were observed in the same months as in Ndiaye. ITA344 had the largest proportion of sterile spikelets, on average 35%, followed by IR64 (31%), while Sahel108 had the least sterile spikelets (19%; P <0.001; SED= 2.2%). Only in July '06, November '06, January '07 and April '07, no significant differences were found between genotypes. At all other sowing dates significant differences between genotypes were observed.

3.4 Yield components

Differences in harvest index (HI) between varieties were significant (P < 0.05) for four of 11 sowing dates in Ndiaye and six of 14 sowing dates in Fanaye (Figure 3.2D). In cases of crop failure, no harvest index could be calculated. In Fanaye the average HI was 0.42, and the maximum value was 0.59. In Ndiaye, the average HI was 0.45, and the maximum 0.68, obtained by ITA344 sown in June. The ranking between the varieties was similar at both sites. Overall, the largest HI (0.49) was recorded for Sahel108, and the smallest for IR64 (0.41; SED = 0.08). The ranking between genotypes in 1000-grain weight was constant over sowing dates (Figure 3.2E), although between sowing dates, the weight varied from 18.7 g to 32.1 g in Ndiaye and from 15.8 g to 28.1 g in Fanaye. In Fanaye, 1000-grain weight decreased up to sowing in October, after which it increased, although the January 2007 sowing of IR64 was an exception with a very small 1000-grain weight of 18.5 g. Varieties ITA344 and WAS161 had on average the largest 1000-grain weight, 25.4 and 24.7 g, respectively, while Sahel108 had the smallest 1000-grain weight of 21.6 g (SED = 1.6). The varieties differed significantly in 1000-grain weight in Ndiaye in six out of the 12 sowing dates and in Fanaye in ten out of 14 sowing dates.

In Ndiaye the most spikelets were recorded in February 2007: 8.0 x 10^4 m^{-2}, the fewest were 1.3 x 10^4 m^{-2} (Figure 3.2F). In Fanaye, the maximum was markedly lower (5.6 x 10^4 m^{-2}), while the minimum was similar (1.2 x 10^4 m^{-2}). The maximum spikelet density coincided with the greatest yields in Ndiaye. On average, ITA344 had the most spikelets per unit area (4.1 x 10^4 m^{-2}), followed by Sahel108 (4.0 x 10^4 m^{-2}), IR32307 (3.8 x 10^4 m^{-2}), while IR64 and WAS161 both had 3.3 x 10^4 m^{-2} (P <0.001; SED = 1.6 x 10^3 m^{-2}).

3.5 Genotype × Environment interactions

The results of the AMMI analysis show that all effects were highly significant (P<0.01), except for the replicates within environments effect (Table 3.2). The effect of the factor 'environment' was by far the most important, accounting for 84.8% of the variation (sum of squares), 'genotype' accounted for 0.8%, and their interaction for 14.4%. Of the variation not explained by regular ANOVA, i.e. the G × E interaction, the principal component axis IPCA1 explained 43%, IPCA2 33%, and IPCA3 14%.

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Table 3.2. Results from the ANOVA of the AMMI model.

Source	d.f.	SS	MS	Variance ratio
Replications within environments	46	42.9	0.93	1.0
Genotypes (G)	4	15.2	3.81	4.1**
Environments (E)	22	1632.9	74.22	79.6***
G x E	88	276.5	3.14	3.4***
IPCA1	25	118.2	4.73	5.1***
IPCA2	23	92.0	4.00	4.3***
IPCA3	21	39.5	1.88	2.0**
Residuals	19	26.8	1.41	1.5
Error	184	170.8	0.93	
Total	344			

**: P < 0.01; ***: P < 0.001.

SS: Sum of squares; MS: Mean sum.

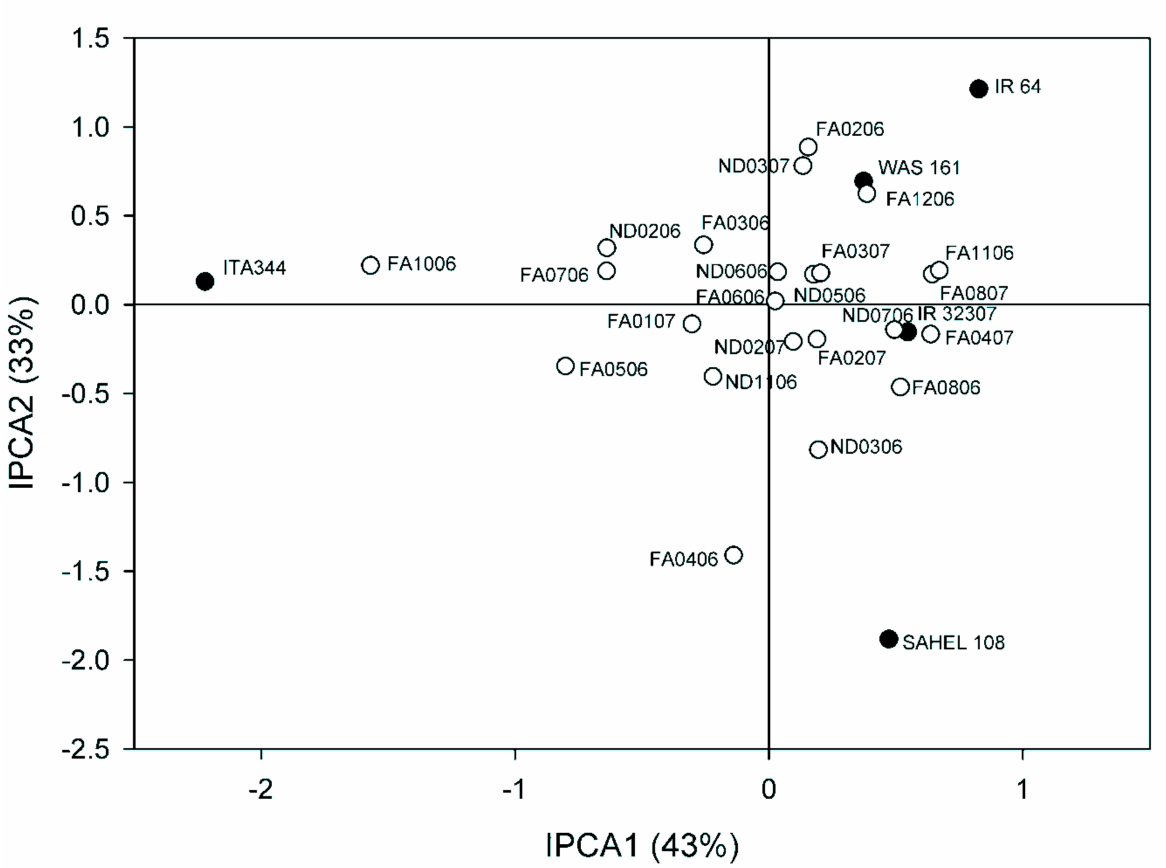

Figure 3.3: Biplot of two principal component axes: IPCA1 vs. IPCA2. IPCA scores for grain yield are shown for five genotypes (closed circles), with genotype names adjacent to circles, and for 23 environments (open circles) with environment codes adjacent to circles: Nd = Ndiaye, Fa = Fanaye. First two digits after site indicate sowing month, second two digits indicate sowing year.

Together they explained 90% of the G × E interaction, and it was not deemed necessary to increase the number of IPCAs. The greater the IPCA score of a genotype in a given environment, the better its performance in that environment. The more IPCA scores of a genotype approximate to zero, averaged across environments, the more constant a genotype performs across environments. High IPCA scores for environments indicate a strong G × E interaction. Genotypes can be compared on the basis of mean yield over environments using their IPCA1 score as a measure for stability. In the bi-plot of IPCA1 versus IPCA2 (Figure 3.3), the genotype closest to the origin is the most stable across environments, which is IR32307 followed by WAS161. Variety ITA344 was well adapted to environment of Fanaye in October 2006, but less to other environments, similarly Sahel108 had low general adaptation, but was suited to Fanaye in April 2006. Of the environments, Fanaye in June

2006 was situated almost in the origin, with a weak potential for G × E interactions, while the two adjacent sowing dates, May 2006 and July 2006 were relatively far from the origin, indicating that the G × E potential interaction was highly dynamic with sowing date. No significant correlations between measured traits (crop cycle duration, HI, spikelet sterility and 1000-grain weight) and IPCA scores were found. Averaged over all experiments, the AMMI model predicted for IR64 and WAS161 the largest average yields of 7.8 and 7.7 t ha^{-1}, respectively. The cultivar ranking based on absolute IPCA1 scores was WAS161 (0.37), Sahel108 (0.47), IR32307 (0.55), IR64 (0.83) and ITA344 (2.23).

Table 3.3: IPCA1 scores for all site and sowing date combinations used in the AMMI analysis. Ranking of first three varieties for each environment is based on yield estimate by the AMMI model.

Site and sowing date	IPCA 1 Score	Variety ranking		
		1st	2nd	3rd
Fanaye Nov 06	0.67	IR64	WAS161 B-9-2	SAHEL108
Fanaye March 07	0.64	IR64	WAS161 B-9-2	SAHEL108
Faanaye April 07	0.64	SAHEL108	IR64	WAS161 B-9-2
Fanaye August 06	0.52	SAHEL108	IR32307	WAS161 B-9-2
Ndiaye July 06	0.49	SAHEL108	IR64	WAS161 B-9-2
Fanaye December 06	0.39	IR64	WAS161 B-9-2	IR32307
Ndiaye May 06	0.21	IR64	WAS161 B-9-2	SAHEL108
Ndiaye March 06	0.21	SAHEL108	IR32307	WAS161 B-9-2
Fanaye February 07	0.19	SAHEL108	WAS161 B-9-2	IR64
Ndiaye April 07	0.18	IR64	WAS161 B-9-2	SAHEL108
Fanaye February 06	0.16	IR64	WAS161 B-9-2	IR32307
Ndiaye March 07	0.13	IR64	WAS161 B-9-2	IR32307
Ndiaye February 07	0.11	SAHEL108	WAS161 B-9-2	IR64
Ndiaye June 06	0.03	IR64	WAS161 B-9-2	SAHEL108
Fanaye June 06	0.03	IR64	WAS161 B-9-2	SAHEL108
Fanaye April 06	-0.14	SAHEL108	ITA344	IR32307
Ndiaye November 06	-0.22	SAHEL108	ITA344	WAS161 B-9-2
Fanaye March 06	-0.26	ITA344	IR64	WAS161 B-9-2
Fanaye January 07	-0.30	ITA344	SAHEL108	WAS161 B-9-2
Ndiaye Febraury 06	-0.64	ITA344	WAS161 B-9-2	IR64
Fanaye July 06	-0.64	ITA344	WAS161 B-9-2	IR64
Fanaye May 06	-0.81	ITA344	SAHEL108	WAS161 B-9-2
Fanaye October 06	-1.57	ITA344	WAS161 B-9-2	IR64

Given the comparable yield of IR64 and WAS161, the latter was the best variety in these environments based on its yield stability, i.e. it has a high general adaptability. When the rankings of the best three yielding varieties are compared for each environment (Table 3.3), WAS161 was the second best yielding variety in 14 out of 23 cases. However, it never gave the best yield. Variety ITA344 was the best yielding variety in environments with relatively high negative IPCA1 scores, of which 5 out of 6 were in Fanaye. Variety ITA344 was the genotype with the longest cycle duration, which can explain its specific adaptability to certain environments. The experiment sown in October in Fanaye had the largest IPCA1 score (-1.57), while sowing dates in June at both Ndiaye and Fanaye had small IPCA 1 scores of 0.03. This indicates that varietal testing is more reliable in the latter two environments than in the first, and that it is difficult to recommend a specific cultivar for October sowing in Fanaye.

The effect of different years was assessed in an ANOVA using the first three sowing dates of 2006 and 2007 at both sites. The principal effects were significant except for the effect of site, all two-way interactions were significant ($P<0.01$), except for the genotype × site interaction (Table 3.4). In both years, yield decreased at later sowing dates, halving between February and April sowing. There was a significant year × site interaction ($P <0.001$). In 2006, yields in Ndiaye were higher compared to 2007, while in Fanaye the opposite trend was observed. Differences in solar radiation are a likely cause of the variation in yield.

4 Discussion

4.1 Rice Yield

We found that rice yield varied strongly with sowing date in this Sahelian environment, in accordance with earlier studies (Dingkuhn and Sow, 1997b; Poussin *et al.*, 2003). There was strong variation in yield of the tested varieties which was sensitive to sowing date, especially around sowing time for the wet season crop (July-August), which is the main cropping season for rice in the Sahel. The experimental results show that peak yields are recorded when sowing takes place in March; July is another good sowing month. This coincides with the dry (March) and wet (July) season sowing as recommended practice in the Senegal River valley. However, farmers often sow later in the wet season, and risks of yield loss or failure are high, e.g. sowing in September. Advancing the dry season sowing to February is necessary for successful double-cropping. In an earlier study at the same sites, Dingkuhn and Sow (1997b) found that the potential yield of IR64 at Ndiaye amounted to 10.8 t ha^{-1}, and was obtained when the crop was sown in February. In our study, IR64 yielded 12.2 t ha^{-1} when sown on the 15th of March 2007 in Ndiaye. Although a relatively old cultivar was used, it yielded more than those found in recent studies on peak yields with New Plant Type or “super” hybrid cultivars in Asia (Katsura *et al.*, 2008; Zhang *et al.*, 2009). The lowland NERICA variety WAS161 had a peak yield of 10.9 t ha^{-1} sown in March 2006 in Fanaye. High levels of solar radiation are a likely cause of this phenomenon.

Crop cycle duration shows a similar variability with sowing date, in accordance with previous research (Sie *et al.*, 1998). The weather conditions were representative for the climate at both sites, and results could be interpreted as valid for the climatic conditions in the Senegalese and Mauritanian Sahelian zone (Dingkuhn, 1995). Over the course of the year different factors, such as heat and cold stress affect rice yield in different ways. Low temperatures decrease development rate, increasing growing cycle duration, which can have a positive effect on yield because of increased biomass production and a longer grain filling period (demonstrated by November sowing in Fanaye). Temperatures below 20°C around booting stage cause spikelet sterility, e.g. September sowing in Fanaye. High solar radiation interception pushed yields at both sites to above 10 t ha^{-1} when the crop was sown in February and March, but sowing in April resulted in an average decrease of 4.7 t ha^{-1}. This can partly be explained by the spikelet sterility (30-75%) and partly by the growing cycle duration, which was reduced by 7.4 and 3.7 days in Ndiaye and Fanaye, respectively. In most experiments there were significant differences between varieties, which can be due to differences in the day of anthesis or panicle initiation or differences in timing of flowering. Prasad *et al.* (2006) showed that *O. glaberrima* cultivar CG14 had an anthesis peak early in the morning and hence escaped heat stress. Detailed measurements of the genotypes used in this study could reveal whether this effect determines sensitivity to heat stress in a similar way. Cold induced sterility can be explained by the minimum air temperature between PI and flowering (Figure 3.5). It decreases from 100% at 12°C to maximum 45% at 15°C. Shimono *et al.* (2005) found a similar relationship using water temperature, with a ceiling of 100% sterility at 15°C. Hence in our case, floodwater probably buffered 3°C.

In a recent paper we have shown that it is possible to reduce the layer of standing water in a rice field to save irrigation water (De Vries *et al.*, 2010). In combination with this study we can conclude that an increase in temperature of 3°C will match the buffering capacity of floodwater, making it possible to save irrigation water while the risk for cold induced sterility remains at the present level.

4.2 Yield components

The differences in yields between varieties can be explained by differences in yield components. Low harvest indices coincided with small 1000-grain weight in April and October, resulting in poor yields. High harvest indices (>0.55) were measured at Ndiaye in June in varieties ITA344 and WAS161 that recorded the largest 1000-grain weights, the fraction sterile spikelets was largest for ITA344, and as a result WAS161 gave the highest yield. Poor yields can either be the cause of sink or source limitation. To further investigate whether the crop was limited by source or sink size, potential straw mass was compared with actual measured straw, as an indicator of source size. Potential straw mass was determined as potential grain yield/ $HI_{optimum}$ – potential grain yield. Potential grain yield is an indicator of sink size, and determined by grain weight × number of spikelets per unit area × sterility percentage. $HI_{optimum}$ was set at 0.5, as described by Mann (1999). In Figure 3.4, the results of the differences between potential straw and measured straw are shown; when the difference is positive it indicates source limitation, and negative differences suggest sink limitation. Between July and October, yield was limited by strength of the sink at both Ndiaye and Fanaye, with the exception of August in Ndiaye. In 2007 in Ndiaye, yield was limited by the size of the source. The average absolute difference can be used as an indicator of genotype stability, a balance between source and sink strength indicating a more stable genotype. In this experiments it was smallest for WAS161 (4.1) followed by Sahel108 (4.3), IR64 (4.4), ITA344 (4.7) and IR32307 (5.0), confirming the results of the AMMI analysis.

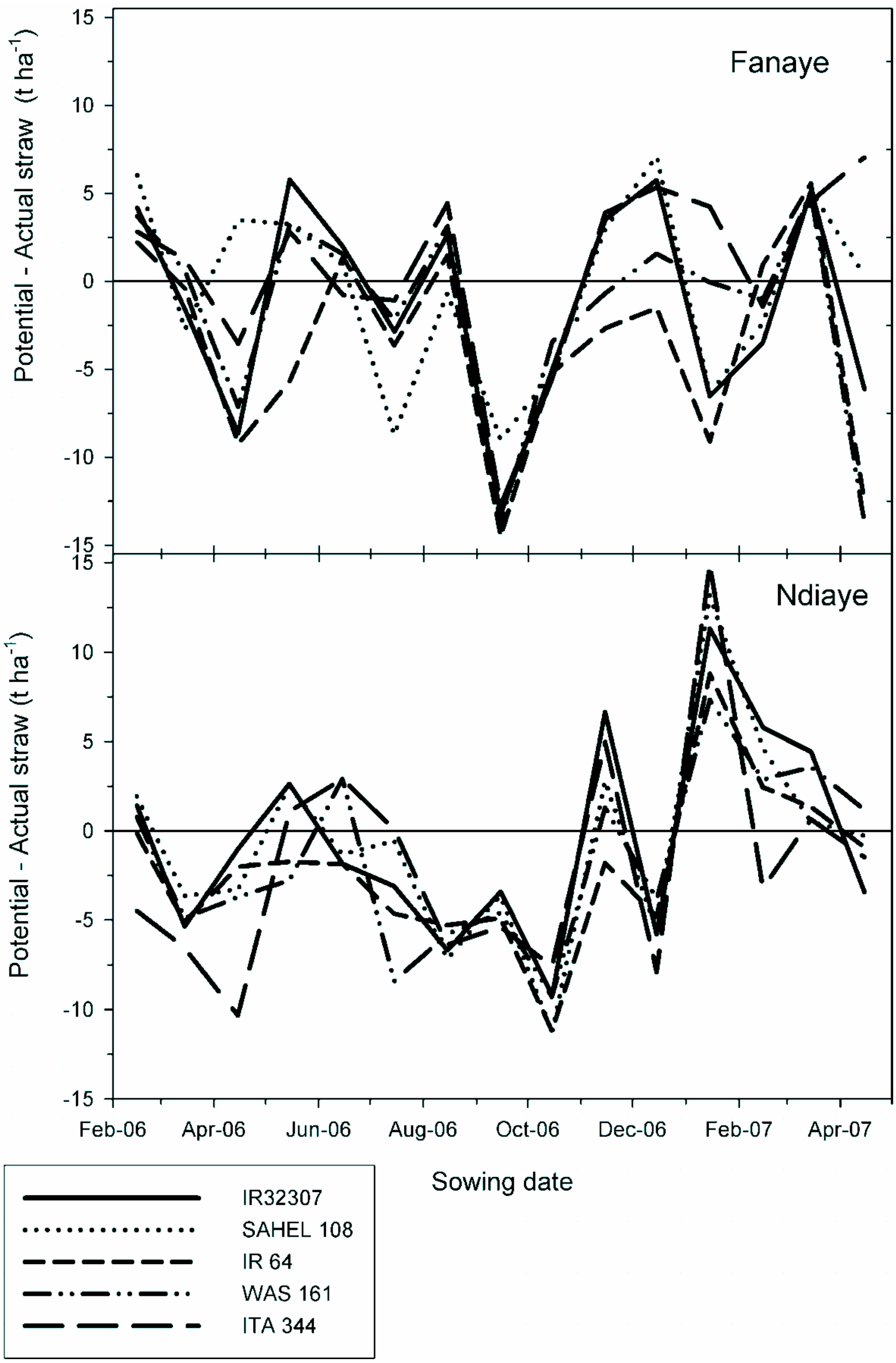

Figure 3.4: Difference between potential straw (calculated as potential grain yield / optimum HI – potential grain yield. Potential grain yield was determined as grain weight × number of spikelets per unit area × percentage sterile spikelets) and actual measured straw for five varieties sown at 15 consecutive dates at Fanaye (top) and Ndiaye, Senegal.

4.3 Genotype × Environment interactions

The effect of environment was larger than the effect of the G × E interaction or genotype, accounting for 85%, 14% and 1% of the variation, respectively (Table 3.2). In a study comprising different tropical and subtropical sites in Asia, Jing *et al.* (2010) found that, although the factors had the same order, the variation due to environment was less (72%), the G × E accounted for less variation (9%), but the genotype component was more important (8%), compared with our study. Four of the five cultivars were of the same maturity type, i.e. short duration, decreasing the variability among the cultivars. The NERICA cultivar WAS161 resulted from four backcrosses with IR64, in theory they are genetically similar for 94%, reducing the overall genetic variability of this study. Variety IR32307 was the genotype with the shortest duration, whereas ITA344 was the one with the longest duration. Hence, IR32307 is in some cases a resource-efficient option: reduced duration hence reduced time of cultivation, without yield loss, e.g. sowing at both sites in November, February and March. Variety WAS161, genetically close to IR64, was more stable in its performance than its parent, expressed in IPCA1 scores of 0.37 and 0.83 for WAS161 and IR64, respectively. It shows the advantage of this lowland NERICA cultivar over its recurrent parent.

The most popular short duration variety Sahel108 had a low IPCA1 score (0.47). Yield stability is an important trait, appreciated by farmers, notably in environments where annual variation is large and when management is sub-optimal so that the full genetic potential is not realised. Neither PCA1 nor PCA2 was significantly correlated to measured crop traits. An explanation could be that different traits were most determining for yield at different sowing dates.

Variety IR32307 had different growing cycle durations when sown in Ndiaye and Fanaye in February and March. Both sites are almost at the same latitude; hence day-length could not have been a factor. In this period, maximum temperatures were higher in Fanaye, above the maximum for development of 36^{o}C (Yin, 1996a), which may have lead to the observed increase in crop cycle duration.

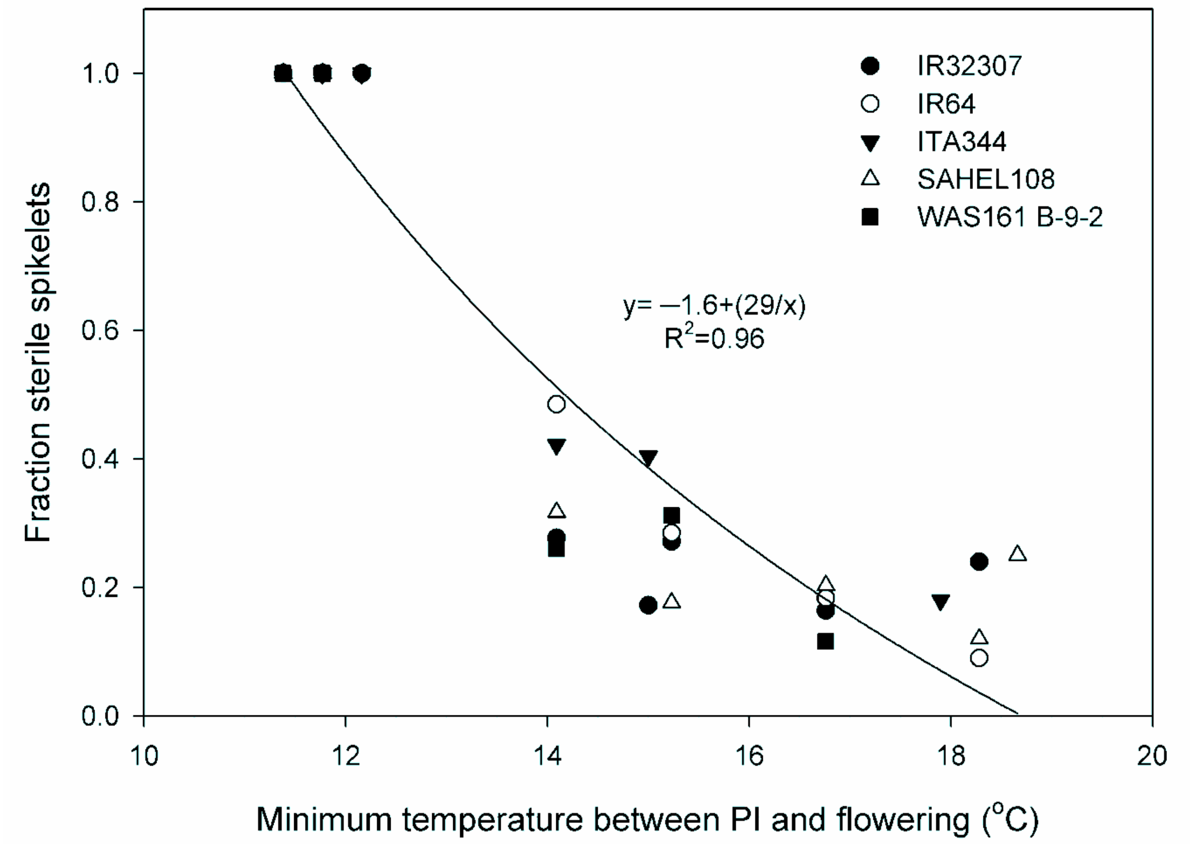

Figure 3.5: Relation between the minimum temperature between panicle initiation and flowering stage (°C) and fraction of sterile spikelets for five varieties, grown during months in which no heat stress occurred.

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4.4 Projected temperature change effects

The projected increase in temperatures by 1.5-3°C will have a serious impact on the present rice cropping system in the Senegal River Valley. The sensitive period for cold sterility is between panicle initiation and onset of flowering. The minimum temperatures below 19°C in the sensitive stage, using sowing dates during which no heat stress occurred, are plotted in Figure 3.5. It is possible that minimum temperatures increase from 12 to 15°C, reducing cold sterility from 100% to less than 45%, irrespective of genotype. Hence, the risks for complete crop failure will be eliminated. Moreover, the increase in temperature will increase potential yield and postpone the ultimate planting date in the wet-season of 15th of August to later in the year. The farmers will have more time to prepare for the season, which they now often lack (Diagne, 2006b). On the other hand with the same rise in temperature, heat induced sterility will become more frequent, forcing farmers to plant their dry-season crop either in January or February, with a yield penalty on delay of sowing.

Varietal improvement could improve heat tolerance, but for there is less genetic variation for cold tolerance (Dingkuhn, 1995). The risk of cold sterility has a critical period of several weeks (Figure 3.5), whereas the risk of heat sterility is a matter of hours, when the flowers open at anthesis. In this study, these precision data were not recorded. Another consequence of the rise in temperature is an increase in development rate at sub-optimal temperatures, and similarly a decrease in development in the supra-optimal temperature range. As a consequence, planting around December could result in shorter a crop cycle duration, but planting in May in a longer duration. In the Senegal River Valley, timing of management operations and timely availability of inputs are important reasons for large yield-gaps (Haefele *et al.*, 2002a; Poussin *et al.*, 2006), which stresses the necessity for other stakeholders in the rice production chain to adjust to the cropping calendar. Changes in planting date and growing cycle duration will affect timing of management operations and peak demand of inputs by famers. Similarly, harvests could be delayed and supply of rough rice by farmers to traders affected.

5 Conclusion

From this study, we conclude that rice yield is very sensitive to sowing date in the Sahelian environment of the Senegal river. The newly-introduced cultivars have a better general adaptability than existing ones, thereby decreasing the risk for yield loss for farmers. Spikelet sterility reduced sink size, constraining yield when the crop was sown between August and October. A rise in minimum temperature will decrease the risk of spikelet sterility thus widening the planting window, which could lead to an improvement of timing of crop management to close yield-gaps. Moreover, the complete rice production chain could be affected, and would have to adjust to new periods of supply of rice and demand of inputs by farmers. For a sound analysis of the consequences of an increase in temperature it is necessary to use dynamic models that simulate the feedback between different temperature related processes.

Chapter 4

Describing phenology of new rice varieties in the Senegal river valley with the aid of simulation models*

4

* Parts of this chapter were presented as:

de Vries, M. E., A. Sow, B. V. Bado & N. Sakané. 2010. Prediction of potential yields of new rice varieties in the Senegal River Valley using simulation models. Presented at Africa Rice Congress 22-26 March, 2010. Bamako, Mali.

and published as:

de Vries, Michiel E., Sow, Abdoulaye, Bado, Boubié V. and Sakane, Nomé. 2011**.** Simulation of potential yields of new rice varieties in the Senegal River Valley. *In*: Kihara, J., Fatondji, Jones, J., Hoogenboom, G., Tabo, R. and Bationo, A. (Eds.) Improving Soil Fertility Recommendations to Smallholder Farmers in Africa through the Use of Decision Support Tools. Springer, Dordrecht

Abstract

Irrigated rice in the Sahel has a high yield potential, due to favourable climatic conditions. Crop growth simulation models are tools that can be used to calculate potential yield and perform yield gap analyses under known climatic conditions. Experimental data were used to calibrate both the DSSAT and ORYZA2000 models, whereas the model ORYZA_S was already calibrated previously. According to ORYZA2000, the same cultivars needed 400°Cd more in Fanaye than in Ndiaye to complete their growing cycle. Calibrated ORYZA2000 simulated phenology well, but yield was underestimated. After calibrating DSSAT, different sets of genetic coefficients gave similar results. Genetic coefficients that reflected the observed phenology well resulted in lower than observed yields. Simulations using the calibrated genotypic parameters by ORYZA_S and ORYZA2000 resulted in a trend of simulation error with sowing date. The sensitivity analysis of the effect genotypic parameters on phenology simulation showed that ORYZA2000 was equally sensitive for all parameters, whereas, ORYZA_S was particularly sensitive to a decrease in base temperature and an increase in optimum temperature. The performance of both ORYZA2000 and ORYZA_S was better than DSSAT4, and effects of parameters changes could be better quantified. Crop growth simulation is a powerful tool to predict yields, but local calibration at the same sowing date is needed to obtain useful results.

Keywords: Cardinal temperatures, Phenology, Sensitivity analysis, Crop development simulation.

1 Introduction

Irrigated rice production supplies a large portion of the national diets of Sahelian countries and demand for rice has been grown at 5.6% per annum (AfricaRice, 2006a). Yield potential of irrigated rice has been estimated at 6-12 t ha^{-1}, depending on cultivar, sowing date and site (Dingkuhn and Sow, 1997b). High incident radiation and temperatures create a favourable environment for irrigated rice cultivation. Double cropping of rice is possible in most Sahelian irrigation schemes, although in practice less than 10% of the area is under rice twice a year (Vandersypen *et al.*, 2006b). To be able to plant twice a year and yet to avoid critical periods of heat and cold stress, farmers need to be aware of optimum sowing dates (Dingkuhn *et al.*, 1995b; Poussin *et al.*, 2003; Segda *et al.*, 2005). Spikelet sterility due to cold (<20°C) or heat (>36°C) stress can cause large yield losses in the Sahel and new irrigated rice genotypes are selected to yield well a range of temperature regimes (De Vries *et al.*, 2011). Notably NERICA genotypes (*Oryza sativa* × *O. glaberrima*) are a promising new source of germplasm for lowland conditions (Heuer *et al.*, 2003; Saito *et al.*, 2010a). Decision support tools are needed to determine optimum planting dates for the Sahelian zone and to quantify the influence of climate on newly developed varieties. In climate change studies, crop growth simulation models are commonly used (Matthews *et al.*, 1997; Xiong *et al.*, 2009). Such tools have been developed for rice: e.g. RIDEV (Dingkuhn *et al.*, 1995a) and ORYZA1 (Kropff *et al.*, 1994). The model RIDEV has been used to simulate spikelet sterility and optimum sowing date for rice in West Africa (Dingkuhn, 1995; Segda *et al.*, 2005) and Nepal (Shrestha *et al.*, 2011). A combination of these two models, ORYZA_S, was developed to simulate potential yields in West-Africa (Becker *et al.*, 2003; Dingkuhn and Sow, 1997a). Simulation of phenology is a key process in all crop growth models, which is based on thermal time accumulation until a following phase in the development of the crop has been attained (Penning de Vries *et al.*, 1989; Vergara and Chang, 1985). Until flowering, rice phenology can be divided in three phases: a basic vegetative phase, a photoperiod sensitive phase, and a post-photoperiod sensitive phase (Yin *et al.*, 1997). Determination of parameter values that accurately describe the length of these phases, independent of environment, is difficult because transition from one phase to the next cannot be measured directly, and has to be derived from detailed experiments (Dingkuhn and Miezan, 1995; Yin, 1997).

More complex models have been developed that integrate water and nutrient limitation, including DSSAT4 (Jones *et al.*, 2003) and ORYZA2000 (Bouman *et al.*, 2001). These models need to be locally calibrated in order to become useful for further research. ORYZA2000 has been evaluated for N-limitation (Bouman and Laar, 2006) and water limitation (Feng *et al.*, 2007) and for photoperiod sensitive varieties (Boling *et al.*, 2011). It has been used under a variety of conditions in India (Arora, 2006), Indonesia (Boling *et al.*, 2010) and various sites across Asia (Jing *et al.*, 2008). In two reviews Timsina and Humphreys (2003; 2006a) show that CERES-rice, a component of DSSAT4 was calibrated and evaluated using experimental data from more than one site or from more than one season only by Pathak *et al.* (2004). It has been used to simulate the rice-wheat system in India (Sarkar and Kar, 2006; Saseendran *et al.*, 1998) and for regional yield forecasts in China (Xiong *et al.*, 2008). Both models have extensively been used in Asia, Australia and the America's, but up to now, not in Africa. In this paper, we evaluate ORYZA2000 and DSSAT4 under Sahelian environments and compare them with ORYZA_S, which has specifically been developed for the Sahel. In all models, phenological development, including partitioning and initiation of spikelets, is key to simulate plant growth and yield. Correct simulation of phenology is prerequisite to reliably simulate potential yield predictions.

This study evaluated the performance of three commonly used rice growth simulation models, focusing on the phenology of new irrigated rice varieties in Sahelian environments.

2 Materials and methods

2.1 Field experiment

A field experiment with five varieties was conducted to obtain data needed to calibrate the simulation models. The treatments were: five rice varieties planted at two sites, at fifteen sowing dates with three replicates: a spilt-plot design was with site as block, sowing date as plot and variety as sub-plot. The varieties used were: 1) IR64, 2) WAS161-B-9-2, an irrigated NERICA (a cross between IR64 and TOG5681, an *Oryza glaberrima* variety) 3) ITA344, 4) IR32307-107-3-2-2 and 5) Sahel108 (IR13240-108-2-2-3). Full details and results of the experiments are presented in Chapter 3.

Phenology of all plots was observed, flowering was determined as the day that 50% of the plants attained anthesis, and maturity as the day that 80% of the plants were mature. Meteorological data were recorded on-site, using Onset Hobo© weather stations. Data for temperature, solar radiation, wind speed and air humidity were recorded at hourly intervals from which daily values were derived, a graphic representation of the weather data can be found in Chapter 3. The number of days to reach flowering was subjected to a factorial ANOVA for analysis of differences between sowing dates, sites and genotypes.

2.2 Models

The generic and dynamic simulation model CERES-Rice, which is part of the DSSAT system, was used (Jones *et al.*, 2003). Although CERES-rice has only been partially described in different publications, it is widely used (Timsina and Humphreys, 2006b). The model operates on a daily time-step and calculates biomass production, which is then partitioned to the leaves, stems, roots and grain, depending on the phenological stage of the plant. The model uses genetic coefficients for different cultivars as model inputs to describe crop phenology in response to temperature and photoperiod (Boote and Hunt, 1998). An overview of the genetic coefficients used in the DSSAT4 model for rice is given in Table 4.1. The genetic coefficients can be divided into two categories. Firstly photothermal ones: P1 and P5, governing thermal time needed to complete a growth stage; and P20 and P2R, defining photoperiodism, and secondly morphological ones, G1, G2 and G3 defining number of spikelets, grain weight and tillering, and G4 which is a temperature coefficient. DSSAT4 has been calibrated for the cultivar IR64. Hence we used data from the experiments to calibrate and validate the performance of DSSAT4.

ORYZA2000 also dynamically simulates potential, water-limited and nitrogen-limited yield. Earlier versions comprise ORYZA1 (Kropff *et al.*, 1994), ORYZA_W (Wopereis *et al.*, 1994) and ORYZA_N (Ten Berge *et al.*, 1997). The program is written in the FST/FSE language (Van Kraalingen *et al.*, 2003) and the source code is publicly available http://www.knowledgebank.irri.org/oryza2000/. ORYZA2000 was calibrated as described in Bouman *et al.* (2001). The model uses observed phenological and climatic data to generate crop stage specific growth rates.

Table 4.1: Code and description of genetic coefficients for rice used in DSSAT 4.

Code	Description
P1	Time period (expressed as growing degree days [GDD] in °C above a base temperature of 9°C) from seedling emergence onwards during which the rice plant is not responsive to changes in photoperiod. This period is also referred to as the basic vegetative phase of the plant.
P20	Critical photoperiod or the longest day length (in hours) at which the development occurs at a maximum rate. At values higher than P20 developmental rate is decreasing, hence there is a delay due to longer day lengths.
P2R	Extent to which development from the basic vegetative phase to panicle initiation is delayed (expressed as GDD in °C) for each hour increase in photoperiod above P20.
P5	Time period in GDD °C from beginning of grain filling (3 to 4 days after flowering) to physiological maturity with a base temperature of 9°C.
G1	Potential spikelet number as estimated from the number of spikelets per g of main culm dry weight (less lead blades and sheaths plus spikes) at anthesis. A typical value is 55 per g.
G2	Single grain weight (g) under potential growing conditions, i.e. non-limiting light, water, nutrients, and absence of pests and diseases.
G3	Tillering coefficient relative to IR64 cultivar under ideal conditions. A higher tillering cultivar would have coefficient greater than 1.0.
G4	Temperature tolerance coefficient. Usually 1.0 for varieties grown in normal environments. G4 for japonica type rice growing in a warmer environment would be 1.0 or greater. Likewise, the G4 value for *indica* type rice in very cool environments or season would be less than 1.0.

Model inputs are daily meteorological data (solar radiation, minimum and maximum temperature, early morning vapour pressure, wind speed and rainfall), genotypic parameters, some of which can be calculated using the calibration program DRATES, and crop management data. Development rate is determined by genotypic parameters for each growth stage. ORYZA2000 was calibrated for all varieties involved in the experiments. Data from the first sowing date were used for calibration and data of the second sowing date for validation.

ORYZA_S belongs to the same model family as ORYZA2000. The major difference is its adaptation to Sahelian conditions by Dingkuhn and Sow (1997a). It is based on the models RIDEV (Dingkuhn *et al.*, 1995a) and ORYZA1 (Kropff *et al.*, 1994). ORYZA_S differs from ORYZA1 in that it takes leaf canopy architecture into account, effects of temperature on partitioning and spikelet sterility as function of phenology. ORYZA_S simulates energy and temperature limited growth. Phenology calculations are different from ORYZA1, the functions, including genotypic parameters, of RIDEV are used. Model inputs are daily solar radiation, minimum and maximum temperature, latitude and some genotypic constants. The model has been calibrated for two genotypes (IR64 and Sahel108) used in this study by Dingkuhn and Miezan (1995).

3 Results

3.1 Experimental results

The five varieties differed in phenology; on average was Sahel108 the earliest genotype (104 days until flowering), while ITA344 was the latest (122 days until flowering) (Figure 4.1). The time to flowering of ITA344 was longer than of the other four varieties (P<0.001). Sowing date had a large effect (P<0.001) on the time to reach flowering, it ranged from 89 to 159 days in Ndiaye and from 81 to 150 in Fanaye. Shortest cycles were observed when sowing took place in July, and longest when sowing took place in November, with 90 and 140 days respectively. In Ndiaye, the shortest cycle was observed in Sahel108 and IR32307 (both 109 days), while in Fanaye, Sahel108 and IR32307 reached flowering after 98 and 102 days, respectively.

3.2 Simulations

The DSSAT model was parameterized with genetic coefficients of the rice variety IR64. The original coefficients as supplied with the software package were 500°Cd for P1, 450°Cd for P5 and 1.0 for G4 (Tables 4.1 and 4.2). The original coefficients resulted in a short vegetative growing stage, 69 days simulated versus 100 observed, and a good yield estimation of 9.6 t ha^{-1} versus 9.4 t ha^{-1} observed, for Ndiaye (Table 4.2).

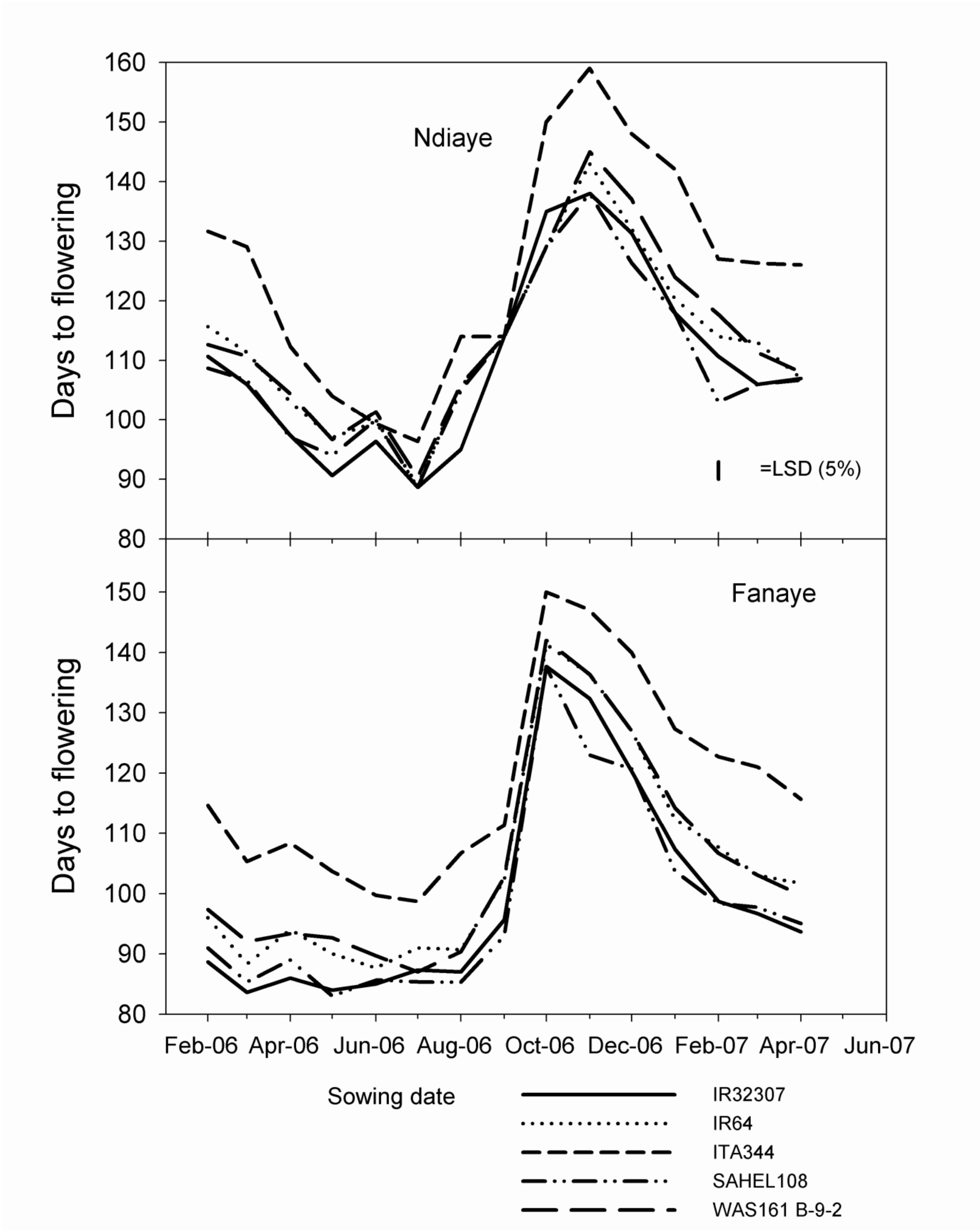

Figure 4.1: Number of days from emergence to flowering for five varieties: IR32307, IR64, ITA344, Sahel108 and WAS161 B-9-2, sown at fifteen consecutive dates in 2006 at Ndiaye (top) and Fanaye (bottom), Senegal.

The same trend was found in Fanaye, where the vegetative growth stage was simulated at 64 days, against 95 days observed, and 7.5 t ha^{-1} simulated against 11.1 t ha^{-1} observed. Hence, the original crop coefficients were not successful in simulating the phenology. Due to the dependence of all other processes on development stage, the coefficients needed to be calibrated in order to simulate better the observed data. The coefficients that were chosen to be modified were P1 and P5 that govern the length of the vegetative and generative growth stage, respectively, and G4, which regulates temperature responses (Table 4.1). Decreasing P1 reduced the duration from sowing to flowering, and similarly, decreasing P5 from 700 to 450°Cd reduced the duration from flowering until maturity (Table 4.2). The two sets of genetic coefficients, which performed well (P1=872, P5=600 and G4 =1 at Ndiaye and P1 = 1000, P5 =450 and G4 =1 at Fanaye), were used to evaluate the simulation of biomass partitioning with DSSAT4 at both sites (Figure 4.2). The simulations were compared with measured stem weight. Simulation of stem weight showed a linear increase of stem weight up to 12 t ha^{-1} and 10 t ha^{-1} at Ndiaye and Fanaye, respectively. Measurements at Fanaye are well in line with the simulated values, however at Ndiaye, the simulations overestimate stem weight, and consequently grain yield. The simulations show that at the onset of grain filling, stem weight decreases sharply, while grain weight increases to several tonnes ha^{-1} in one day.

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ORYZA2000, after being calibrated at each location using the DRATES program, simulated phenology well. However, simulated yields for cultivar IR64 were 5.0 and 2.0 t ha^{-1}, in Ndiaye and Fanaye, respectively, which was low compared to 9.4 and 11.1 t ha^{-1} observed yields (Table 4.3). To further test the performance of ORYZA2000, the model was calibrated for each variety at both locations, using data obtained at the first sowing date. The calibrated model was used to simulate the second sowing date, one month later. The calibrated ORYZA2000 model simulated flowering in Ndiaye at 108 DAE, averaged over the five varieties, an underestimation of only five days (Table 4.3). Maturity was simulated at 130 DAE, underestimating post-flowering stage by five days, to arrive at a total underestimation of 10 days. In Fanaye, the pre-flowering period was on average overestimated by 10 days, whereas at maturity the difference was only two days.

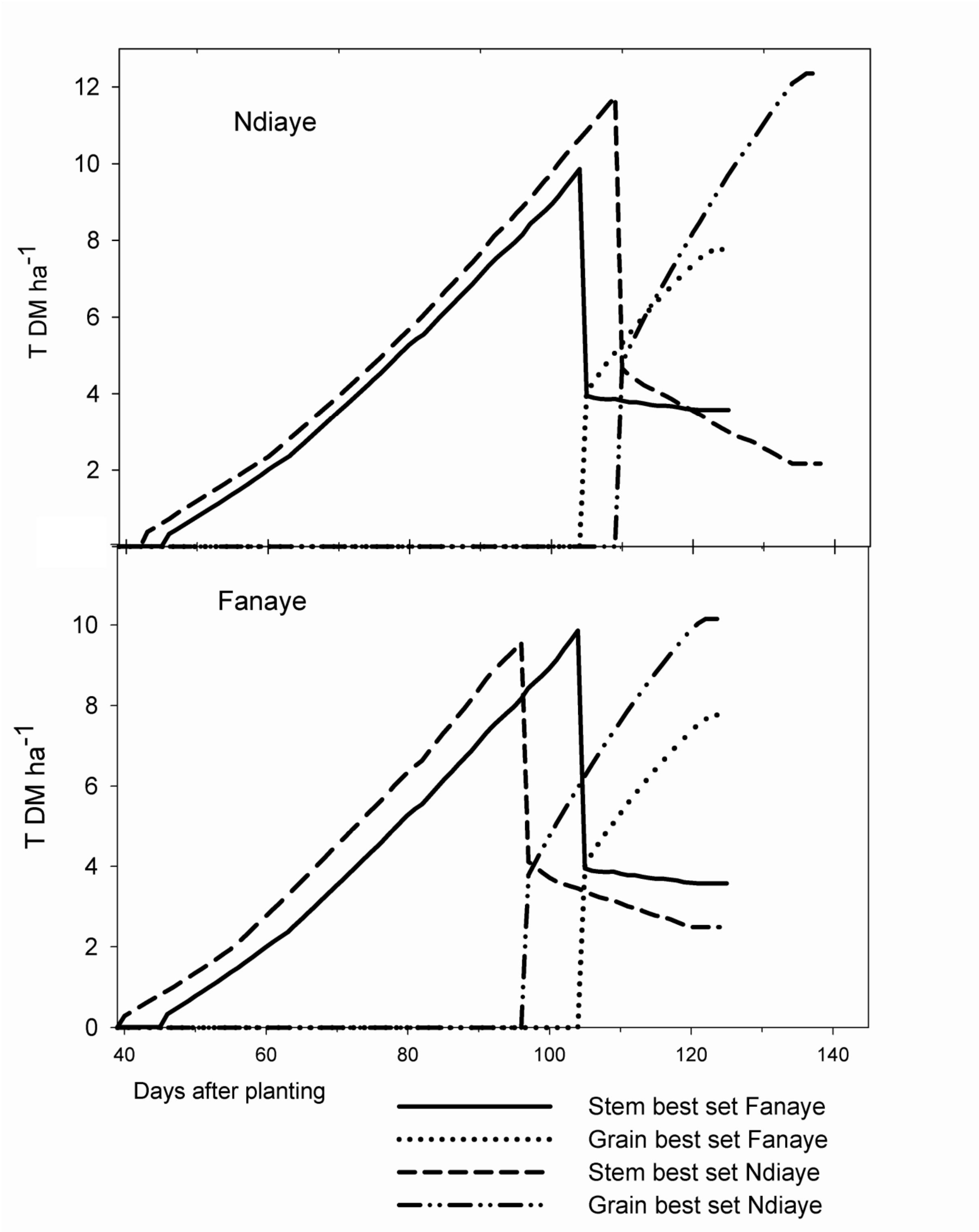

Figure 4.2: Simulation of stem and grain weight by DSSAT 4 over time, using two calibrated sets of genetic coefficients; Best set Fanaye: P1=1000 and P5=450, and best set Ndiaye: P1=872 and P5=600. Both sets were simulated using weather data of the 2006 dry season in Ndiaye (top) and Fanaye (bottom), Senegal.

Fifteen consecutive sowing dates were simulated, and compared with observed flowering and maturity dates (Figure 4.3). The RMSE of flowering and maturity date simulated by ORYZA2000 was 16.6 and 18.9 days, respectively.

Table 4.2: Results of phenology (simulation of days after emergence [DAE] to flowering [flow.] and days to maturity), and grain yield (t DM ha^{-1}), using different sets of genetic coefficients (P1, P5 and G4) for DSSAT4 (upper part of table). Results of ORYZA2000 after calibration, compared to observations for variety IR64 in the dry season of 2006 in Ndiaye and Fanaye, Senegal (lower two lines of table). Observations are from Chapter 3.

Parameter set			Ndiaye			Fanaye		
P1 (°Cd)	P5 (°Cd)	G4 (-)	Flow. (DAE)	Maturity (DAE)	Yield (tha^{-1})	Flow. (DAE)	Maturity (DAE)	Yield ($t\ ha^{-1}$)
200	450	1.0	46	81	5.7	44	74	2.7
500	450	0.8	68	103	8.7	57	85	6.3
500†	450	1.0	69	105	9.6	64	94	7.5
500	450	1.3	81	118	9.1	79	113	0.0
800	450	1.0	94	125	11.7	84	112	8.3
800	450	1.3	107	141	7.6	103	136	0.0
872	450	1.0	100	130	12.0	88	116	9.0
872‡	600	1.0	100	137	12.4	88	123	10.2
872	700	1.0	94	137	12.2	84	123	8.6
872	450	1.3	113	147	5.3	108	142	0.0
950	450	1.0	106	136	12.4	94	121	8.5
1000§	450	1.0	109	139	12.5	96	124	7.8
Oryza2000			113	134	5.0	93	124	2.0
Observed			100	136	9.4	95	126	11.1

† = Original genetic coefficient set of DSSAT for IR64
‡ = Best performing set in Ndiaye
§ = Best performing set in Fanaye

For the model that was developed for Sahelian conditions, ORYZA_S, genotypic constants of two varieties, IR64 and Sahel108 (IR13240) were earlier determined by Dingkuhn and Miezan (1995). Table 4.4 shows the genotypic constants of the varieties: IR64 has a higher optimum temperature, it has a higher thermal time requirement to reach flowering; Sahel108 is less sensitive to photoperiod and has a longer basic vegetative stage. Fifteen consecutive sowing dates were simulated, and compared to observed flowering and maturity dates (Figure 4.3). The RMSE of flowering and maturity date simulated by ORYZA_S was 15.1 and 12.8 days, respectively. Similar to the results from ORYZA2000, the largest deviations were observed when sowing took place between day 250 and 350. Largest deviations were found in Fanaye. However, magnitude of the deviations was smaller for ORZA_S than for ORYZA2000 (Figure 4.3).

3.3 Parameter sensitivity

The sensitivity of the DSSAT4 to changes of genetic coefficients was tested by changing the coefficients one by one (Table 4.2). By changing P1 from 500 to 200 °Cd, the vegetative growth stage became even shorter, decreasing from 69 to 46 days. When coefficient G4 was changed, from 1.0 to 0.75, the phenology simulation of the growing cycle for Ndiaye decreased by two days, but in Fanaye it decreased by nine days, and yield decreased in both sites. When G4 was increased to 1.25, the cycle increased, from 105 to 118 days, but yield decreased by 481 kg ha^{-1} in Ndiaye, while in Fanaye, the cycle increased by 19 days, but in all three cases, no yield was produced. The crop failure is probably due to high temperatures, for which sensitivity is defined by G4. To improve simulation results for Ndiaye, we increased factor P1 to 872°Cd to match the observed phenology. To simulate the generative phase, P5 was increased to 600°Cd. It gave good simulation results of phenology, but yield was overestimated by 2.9 tons ha^{-1}. The same set of coefficients at the Fanaye site underestimated the vegetative growth stage by seven days, and overestimated the generative phase by three days. Contrary to results from Ndiaye, yield in Fanaye was underestimated by 3.3 t ha^{-1}. The set of coefficients that accurately simulated phenology in Fanaye was 1000 for P1, 450 for P5 and 1 for G4, the same set overestimated both the complete cycle and yield in Ndiaye.

The genotypic parameters DVRI, DVRJ, DVRP and DVRR were calibrated using the DRATES program for variety Sahel108 in Fanaye, using the first sowing date. Then, the parameters were increased and decreased by 10%, and the difference in time to flowering and to maturity, between the original and the modified parameter set was calculated. The effect of an increase in the parameters was always -2 days and a decrease resulted in +3 days for the number of days to flowering and maturity, except for DVRR, which had only an effect after flowering (Table 4.5). The standard deviations were small, and the effects were constant with sowing date.

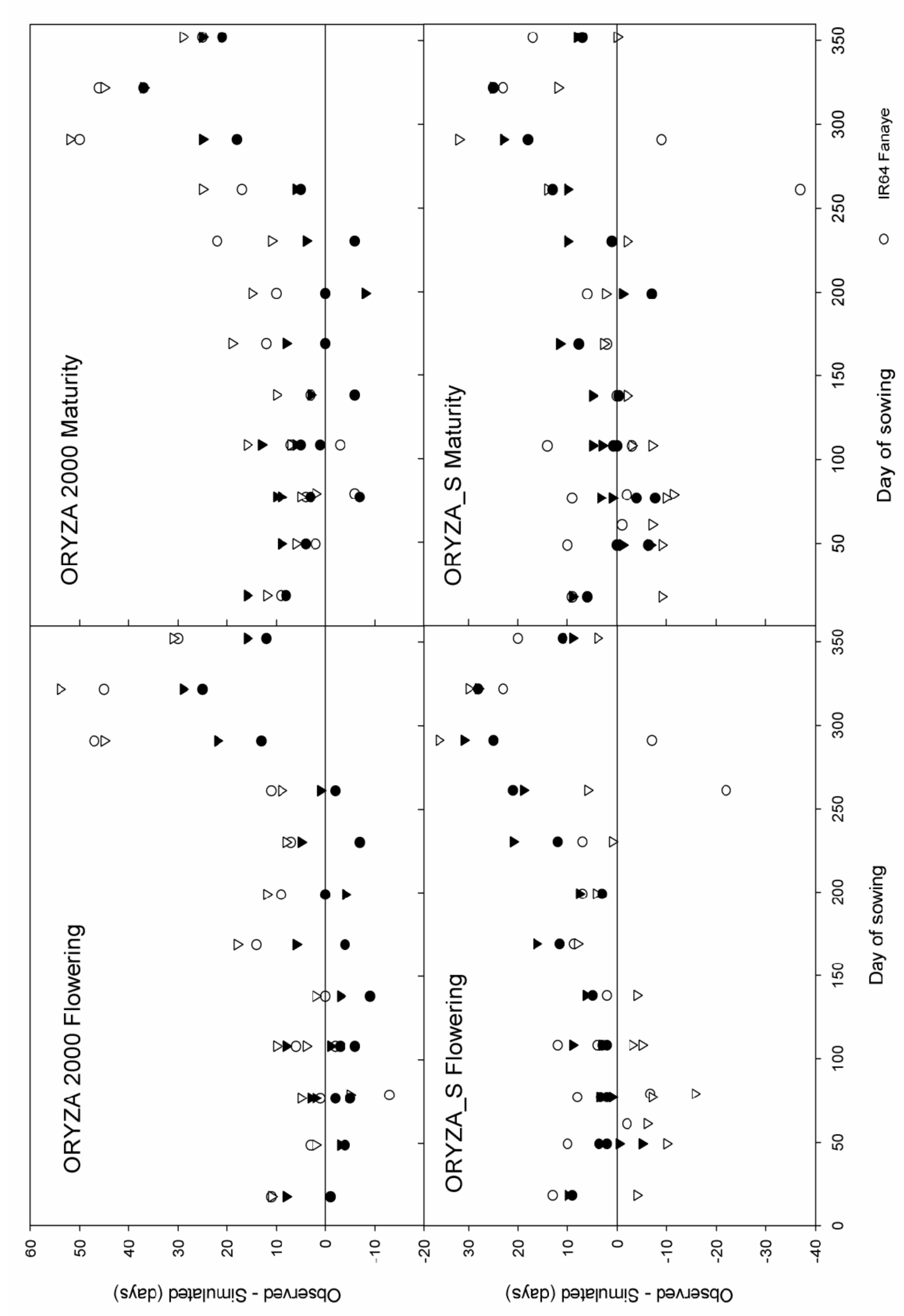

Figure 4.3: Observed – simulated days to flowering (left) and to maturity (right), using simulation models ORYZA2000 (top) and ORYZA_S (bottom) for fifteen consecutive sowing days (Julian day) in 2006 and 2007 at Fanaye (open symbols) and Ndiaye (filled symbols) sites for varieties IR64 (circles) and Sahel108 (triangles). Observed data used in the calculations are from Chapter 3.

A change of 10% in a genotypic parameter results in a change of 2-3% in time to flowering or maturity, the relative sensitivities of the parameters are within a small range: 0.21 – 0.38, which indicates that all parameters have similar weights.

Table 4.3: Validation of ORYZA2000: observed and simulated phenology (panicle initiation [PI], flowering and maturity [DAE]) and yield (t ha^{-1}) of five rice varieties in Ndiaye and Fanaye (Senegal), sown at 14 and 16 March 2006, respectively. For the simulation ORYZA2000 was calibrated for each location, using a data-set of an experiment that was sown 30 days before the simulated data-set. Observed yield and maturity from Chapter 3.

Variety	**Observed**				**Simulated**			
	Phenology (DAE)			Grain yield (t ha^{-1})	Phenology (DAE)			Grain yield (t ha^{-1})
	PI	Flowering	Maturity		PI	Flowering	Maturity	
Ndiaye site								
WAS161	57	111	141	5.6	57	108	127	7.4
IR64	57	111	141	5.5	57	105	124	7.3
ITA 344	59	129	151	4.9	59	123	149	9.7
IR32307	55	106	137	4.4	55	101	127	9.2
Sahel108	55	107	136	8.0	55	102	125	8.4
Fanaye site								
WAS161	64	92	122	11.1	68	93	121	2.6
IR64	59	88	122	10.9	69	99	123	2.4
ITA 344	75	105	137	10.9	86	120	137	6.3
IR32307	57	84	120	9.4	61	94	117	2.6
Sahel108	61	85	120	10.2	64	96	119	2.5

Table 4.4: Topt, optimum temperature for development (°C); Tbase, base temperature for development (°C); Tsum, thermal time required for flowering at 11 h daylength (°Cd); Cpp, photoperiodic constant indicating the increase for Tsum in % per h increase in daylength above 11 hours; Bvp, estimated mean basic vegetative stage (d) across photo-thermal environments; Toptm, optimal temperature during maturity phase.

Genotype	Topt	Tbase	Tsum	Cpp	Bvp	Toptm
				% of Tsum		
	°C	°C	°Cd	(h >11 h)$^{-1}$	d	°C
Sahel108	26.0	9.66	1148.8	4.24	40	30
IR64	27.5	9.55	1218.0	6.71	20	30

The combination of increasing or decreasing all parameters at the same time resulted in a change in time to flowering or maturity which was the sum of the individual effects. Hence, there were no interactions between parameters. The sensitivity of the genotypic parameters Toptd, Tbased, Tsum, Cpp, Bvp and Toptm was tested for ORYZA_S (Table 4.6). Similar to the approach with the ORYZA2000 parameters; they were all increased and decreased by 10%. Both a 10% decrease in Toptd and a 10% increase in Tbased resulted in a decrease in the number of days to flowering and maturity by 11 and 13, respectively. Both positive and negative changes in parameters CPP and Toptm resulted in the same decrease in time to flowering.

Table 4.5: Sensitivity analysis for five genotypic parameters of ORYZA2000: DVRI; Development rate at initial growing stage, DVRJ; development rate at juvenile growing stage, DVRP; Development rate at photoperiod sensitive growing stage, DVRR; development rate at reproductive growing stage. All parameters have been changed 10% and the difference with the base runs of Sahel108 sown in Fanaye on fifteen sowing dates has been calculated. The average difference in time to flowering and to maturity between the base runs and runs with modified parameters is shown. Between brackets the standard deviation. Sensitivity of the parameters has been determined as the difference in input parameter over the difference in response variable.

Parameter	**Δ**	**$\bar{\Delta}$ time to flowering** (d)		**Relative sensitivity***	**$\bar{\Delta}$ time to maturity** (d)		**Relative sensitivity***
DVRI	+10%	-2	(0.5)	0.23	-2	(0.4)	0.18
	-10%	3	(0.6)	0.34	3	(0.7)	0.25
DVRJ	+10%	-2	(0.7)	0.27	-2	(0.6)	0.21
	-10%	3	(0.5)	0.38	3	(0.7)	0.30
DVRP	+10%	-2	(0.6)	0.21	-2	(0.5)	0.30
	-10%	3	(0.5)	0.30	3	(0.5)	0.23
DVRR	+10%	0	(–)	–	-2	(0.5)	0.22
	-10%	0	(–)	–	3	(0.5)	0.28
All combined	+10%	-6	(1.1)	0.78	-8	(1.4)	0.80
	-10%	8	(0.8)	0.98	11	(1.4)	1.00

* Relative sensitivity is calculated as (Δ parameter / default parameter value) / (Δ response variable /default response variable value).

Combinations of changes of all parameters resulted in changes in time to flowering and maturity that were different from the sum of the individual changes. Hence, interactions between parameters were observed. Standard deviations were larger than for the ORYZA2000 parameters, and large differences were found between the October-December sowing dates and the February-March sowing dates. The relative sensitivity of the different parameters indicated that a decrease of Tbased and an increase in Toptd had the largest effects in time to flowering and maturity. The model was not sensitive for an increase in Tsum however, very sensitive to a decrease (Table 4.6).

Table 4.6: Sensitivity analysis for five genotypic parameters of ORYZA_S: Tbased; base temperature for development, Toptd; optimum temperature for development, Toptm; optimum temperature, Cpp; photoperiodic constant indicating the increase for Tsum in % per h increase in daylength above 11 hours, Tsum; temperature sum to complete growing cycle. All parameters have been changed 10% and the difference with the base runs of Sahel108 sown in Fanaye on fifteen sowing dates has been calculated. The average difference in time to flowering and to maturity between the base runs and runs with modified parameters is shown. Between brackets the standard deviation.

Parameter	Δ	$\bar{\Delta}$ time to flowering (d)		Relative sensitivity*	$\bar{\Delta}$ time to maturity (d)		Relative sensitivity*
Tbased (°C)	+10%	4	(1.8)	0.46	5	(2.8)	0.43
	-10%	-11	(5.0)	1.20	-13	(5.7)	1.02
Toptd (°C)	+10%	-11	(6.0)	1.18	-13	(5.6)	1.00
	-10%	3	(4.8)	0.35	2	(8.1)	0.16
Toptm (°C)	+10%	-6	(4.8)	0.64	-11	(5.7)	0.82
	-10%	-6	(4.8)	0.64	-4	(5.6)	0.28
Cpp (-)	+10%	-6	(5.0)	0.61	-7	(5.7)	0.57
	-10%	-6	(5.0)	0.67	-8	(5.6)	0.63
Tsum (°Cd)	+10%	2	(5.2)	0.22	1	(6.5)	0.05
	-10%	-16	(4.8)	1.70	-18	(5.3)	1.38
All combined	+10%	1	(5.5)		-3	(6.4)	
	-10%	-14	(6.0)		-11	(6.9)	

* Relative sensitivity is calculated as (Δ parameter / default parameter value) / (Δ response variable /default response variable value).

4 Discussion

4.1 Observations

Sowing date had a large effect on the time to flowering, confirming results of Dingkuhn *et al.* (1995b). Four of the varieties belonged short to medium duration group, and one (ITA344) to the medium to long duration group. Although both sites were on similar latitude, hence similar photoperiod, responses of variety IR32307 and Sahel108 were different between the sites.

Differences in temperature amplitude could have been the cause (Yin, 1996a), in Chapter 3 it was shown that in Fanaye larger temperature amplitudes than in Ndiaye occur.

4.2 DSSAT4

The genetic coefficients used as default values in DSSAT4 did not produce satisfactory results under Sahelian conditions. It underestimated the time to flowering by 30% at both sites. When the program was calibrated at the site, it did not simulate rice yield accurately, hence not all crucial growth processes were simulated correctly. In Ndiaye it overestimated rice yield by 32%, and in Fanaye it underestimated yield by 30%. When calibration sets of parameters for Fanaye and Ndiaye were used for the other site, the phenology simulation was not satisfactory. An explanation could be that the effects of extreme temperatures on yield are not simulated adequately. From the model description it is not clear how heat and cold stress and the resulting spikelet sterility are simulated, but in light of their importance in yield determination in the Sahel, they should be emphasized in future efforts to improve the model. Our results support the conclusions from Timsina and Humphreys (2006a), that DSSAT4 requires local calibration for each variety and each sowing date. Thus, DSSAT4 is not suitable for large scale explorations, as genotypic parameters, assumed to be constant, vary inter environment.

4.3 ORYZA2000

Simulation of rice under Sahelian conditions using ORYZA2000 resulted in an underestimation of yield in Fanaye, and an overestimation in Ndiaye (Tables 4.2 and 4.3). Phenology was in both cases not always accurate, with both over and underestimations of occurrence of panicle initiation, flowering and maturity. As Sheehy *et al.* (2006b) have pointed out, temperature responses of the model are not always accurate. For ORYZA2000, calibration was done at each site and simulation results were validated using a sowing date one month later. Phenology was underestimated in Ndiaye by ORYZA2000, but not in Fanaye (Table 4.3), while the temperature at the second sowing date was higher, indicating that under high temperatures development is slower than simulated by ORYZA2000. When the model was calibrated, it overestimated yield in Ndiaye of variety Sahel108 by 5% at 8.4 t ha^{-1}, which can be used as an indication of potential yield of this combination of variety and sowing date in the delta area of the Senegal river. Bouman and Van Laar (2006), Belder *et al.* (2007) and Boling *et al.* (2007) showed that ORYZA2000 was well suited to simulate nitrogen and water limited rice growth under tropical Asian conditions, hence we can assume that the performance of ORYZA2000 under Sahelian conditions was largely affected by the difference in climate rather than by either nitrogen or water limitations. We can conclude that ORYZA2000 needs to be calibrated for each site and sowing date. The sensitivity analysis showed that all three genotypic parameters had equal impact on the phenology: a 10% increase in parameter value resulted in a two days decrease in growing period, while a 10% decrease in parameter value resulted in a three day increase in growing period. When relative sensitivities are less than 0.5, the parameter is regarded as relatively insensitive, as in this case (Adam *et al.*, 2011). The combination of parameters resulted in a change in growing period equal to the sum of changes of all individual parameters.

4.4 ORYZA_S

The ORYZA_S model was developed for Sahelian conditions; however, simulation of previously calibrated varieties resulted in both over and under estimation of development rate. There are a number of reasons for these discrepancies: essential phenological processes are not yet captured in the model or changes in climate are outside the validity domain of the model. Our study points out the importance of local calibration of the crop growth simulation models, however, only one of the evaluated models (ORYZA2000) has calibration routines to determine parameter values for varieties. Improvements in simulation models should include calibration routines that allow users to calibrate new varieties using their own data.

4.5 Outlook

For both ORYZA_S and ORYZA2000, there was a trend in the difference between simulation results and observations with sowing date, which makes predictions with these models delicate: only specific sowing dates can be used with these models. Specific sowing dates are associated with daylength and (quality of) radiation, these could be among the processes whose effect on phenology have not yet been understood well enough. There is need for further research to increase performance of simulation models as there are still essential processes in rice phenology, which have not been captured by these models, such as a variation in optimum temperature for development with plant age temperature (Yin, 2008). There is evidence that daily temperature amplitude has an effect on phenology, however quantification of these processes will demand very specific experiments (Yin, 1996b). Also morphology, such as a minimum number of appeared leaves has been shown the play a role (Craufurd *et al.*, 2003).

5 Conclusion

The rice simulation models ORYZA2000, DSSAT4 and ORYZA_S were evaluated for their performance to simulate phenology in the Sahel. When calibrated, ORYZA2000 and ORYZA_S performed well in simulating phenology of the same sowing date. The performance of DSSAT4 with its original genetic constants was weak. Our research shows that there is need for further research to increase performance of simulation models as there are still essential processes in rice phenology, which have not been captured by these models. Increased understanding of the physiological basis of these processes will undoubtly result in increase model performance.

Chapter 5

Exploring impacts of temperature increase in Sahelian rice-based cropping systems*

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* This chapter is submitted as:
De Vries, M. E., P. A. J. van Oort & P. A. Leffelaar. Exploring impacts of temperature increase in Sahelian rice-based cropping systems.

Abstract

In the African Sahel, temperature increases between 1.8 and 4.7°C are predicted by 2080. At certain growth stages rice is sensitive to low (<22°C) and high (>35°C) temperature stress. An adapted version of the simulation model ORYZA2000 was used to simulate effects of temperature increase on sterility and crop cycle duration of irrigated rice at two locations (Ndiaye and Fanaye) in Senegal. The calibrated model was validated with an independent data-set. Minimal and maximal predicted temperature increases were compared with the current situation. Simulation results of daily sowing dates show that crop cycle length will decrease by 10-30 days. Presently, spikelet sterility is a serious threat: cold induced spikelet sterility when sowing between September and December and heat induced sterility when sowing between November and April in Fanaye. For the minimum predicted temperature increase in Ndiaye, heat induced sterility becomes more important than the cold-sterility with a peak of 69% for rice sown in August. In Fanaye, heat-sterility is always above 56%, except for rice sown between September and November. Under the maximum predicted temperature increase, in Ndiaye heat-sterility increases, with all sowing dates resulting in more than 57% sterile spikelets, except for rice sown in October. In Fanaye a similar pattern is shown: rice production is only viable when sown from September to December (with sterility of 40%); sown in the other 8 months of the year sterility is >90%. Our study suggests that with projected temperature changes, timing of sowing and consequences of the risks for crop loss due to sterility will remain the major determinants of rice yield along the Senegal river. We show that there is an urgent need for heat tolerant rice varieties. Without adaptation, cropping calendars will change. In the worst case scenario we anticipate a change from a double to a single crop.

Keywords: Crop growth simulation models, Temperature increase, Global change, Sowing date, Spikelet sterility, Phenology.

1 Introduction

Rice production will be significantly influenced by global changes in temperature and green house gases (Ainsworth, 2008; Wassmann *et al.*, 2009). In tropical Asia, the combined impacts of elevated CO_2 and increased temperatures were predicted to decline rice yields by 3.8% (Matthews *et al.*, 1997). In the same study, it was shown that the impacts varied regionally, with most negative effects occurring in those parts where temperatures in the current climate are already close to the threshold above which heat induced sterility becomes an issue. From a large sample of farmers' fields observations, Welch *et al.* (2010) concluded that a moderate warming had a negative impact in rice yield in Asia, which concurred with a model study by Peng *et al.* (2004), although their methods were contested (Sheehy *et al.*, 2006b). For northern Japan, it was shown that the rice cropping system can be adapted to the projected temperature change (Shimono *et al.*, 2010). For sub-Saharan Africa (SSA), climate change studies often focus on the impact of water availability on crop production, e.g. (Haile, 2005; Salack *et al.*, 2011; Sultan *et al.*, 2005), but for the case of irrigated rice, temperature extremes such as found in the semi-arid Sahel and the associated heat and cold induced spikelet sterility are far more important determinants of crop production (Dingkuhn *et al.*, 1995b).

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Surveys among farmers in the Senegal river valley have revealed that farmers are aware of the relation between low temperatures and yield decline due to spikelet sterility in the wet season (Haefele *et al.*, 2002a). Predictions from downscaling global circulation models to the Sahelian region indicate that an increase in surface temperatures of 1.5-3°C can be expected by 2030 (Boko *et al.*, 2007; Jury and Whitehall, 2010). Given the sensitivity of rice to both high and low temperatures at critical stages, which drive a potential yield reduction, both the sowing window and varietal preferences may alter in the coming decades (De Vries *et al.*, 2011). Rice genotypes differ in their heat tolerance, with a difference of 3°C between tolerant and susceptible genotypes (Matsui *et al.*, 2001). Tolerance classically comprises elements of escape, i.e. the timing of panicle emergence and floret opening relative to the occurrence of the stress, and the absolute tolerance to stress of key processes, such as anther dehiscence (Jagadish, 2007). *Oryza glaberrima* cultivars CG14 and CG17 opened their spikelets at 7:00 am, more than one hour before *O. sativa* indica cultivar IR64, and under heat stress more spikelets were opened earlier (Jagadish *et al.*, 2008; Prasad *et al.*, 2006). A heat treatment at microspore stage induces spikelet sterility; Endo *et al.* (2009) identified genes that were down-regulated as a result of the treatment and proposed it as a molecular breeding tool to compare varieties. Ishimaru *et al.* (2010) showed that escape rather than tolerance per se reduced spikelet sterility in *Oryza officinalis* × *O. sativa* crosses. For cold tolerance, genotypic variation is less. More pollen increases fertility, and as anther length is strongly correlated with the number of pollen, anther length is likely to play a role in cold tolerance (Saito *et al.*, 2004).

To quantify the possible effects of an increase in temperature, dynamic crop growth simulation models are needed. ORYZA2000 is such a tool for lowland rice (Bouman *et al.*, 2001), which has been validated for N limitation (Bouman and Laar, 2006), the effects of water-table depth and varietal characteristics such as photoperiodism (Boling *et al.*, 2007; Boling *et al.*, 2011) and G × E interactions (Jing *et al.*, 2008). For the model ORYZA2000, a new calibration program was developed, that allowed optimization of variety parameters independently (Van Oort *et al.*, 2011). Validation of crop parameters and associated processes for simulation models is necessary when employing the model in a new environment (Aggarwal and Mall, 2002; Confalonieri *et al.*, 2010).

In this study we investigate the implications of an increase in temperature on a typically Sahelian rice-based cropping system. In particular the effects of a temperature increase on growing cycle and on temperature induced sterility were evaluated. The calibrated model ORYZA2000 is validated, and employed to quantify effects of forecasted temperature regimes on irrigated rice cropping systems in the Sahel, focusing on cropping cycle length and spikelet sterility, which determine yield to a large extent in these environments.

2 Materials and Methods

2.1 Cropping system

The rice-based cropping system along the Senegal river is intensive. All farmers use inorganic fertilizers (100%), herbicides (100%), certified seeds (81%) and proper field preparation (99%), and grow on average 1.3 ha of rice in the wet season (Diagne, 2006b; Van Vugt, 2007). As a consequence of favourable climate and management rice yields 3-7 t ha^{-1}, high in comparison with the average yield in sub-Saharan Africa of 2.1 t ha^{-1} (FAOSTAT, 2011; Haefele *et al.*, 2000). To facilitate the use of external inputs, farmers rely heavily on credit. Sowing the wet season crop in time is of major importance due to the risk of cold sterility, a fact farmers are aware of. However, delay in availability of credit or inputs often jeopardizes farmers' intentions (Haefele *et al.*, 2002a; Poussin *et al.*, 2003). Presently, dry season rice cropping takes place from February to July, and the wet season immediately follows from July to October. The wet season is the main cropping season, whereas in the dry season only 10% of the surface is cultivated (SAED, 2007).

2.2 Model description

The model ORYZA2000 was used to simulate rice growth. ORYZA2000 simulates potential, water-limited and nitrogen-limited yield of lowland rice (Bouman *et al.*, 2001). The program is written in the Fortran based FST language (Van Kraalingen *et al.*, 2003) and the source code is publicly available: http://www.knowledgebank.irri.org/oryza2000/. It is recommended to calibrate phenology for each experiment separately in the original version of ORYZA2000 (Bouman *et al.*, 2001). In this study we used a version of ORYZA2000 modified by Van Oort *et al.* (2011) to predict phenology, hence thorough validation of phenology simulation was needed. In the original ORYZA2000 development rates are calculated using a bi-linear model (Kropff *et al.*, 1994; Matthews and Hunt, 1994). The phenology simulation components of the modified version of ORYZA2000 were calibrated using a procedure described in detail in Van Oort *et al.* (2011). In short, a calibration set of 15 sowing dates at two locations in Senegal (Ndiaye and Fanaye) using varieties IR64 and Sahel108 was used to select an optimal phenology simulation model. The calibration program by Van Oort *et al.* (2011) considers different shapes of temperature response functions and simultaneously estimates all model parameters, including base temperature, optimum temperature, maximum temperature, transplanting shock parameters, threshold daylength for photoperiod sensitivity and photoperiod sensitivity effect. For all the models a wide range of parameter values was evaluated, and the parameter-model combination with the smallest root mean square error (RMSE) was chosen for each variety separately. The experimental data presented in Chapter 3 were used for the model calibration.

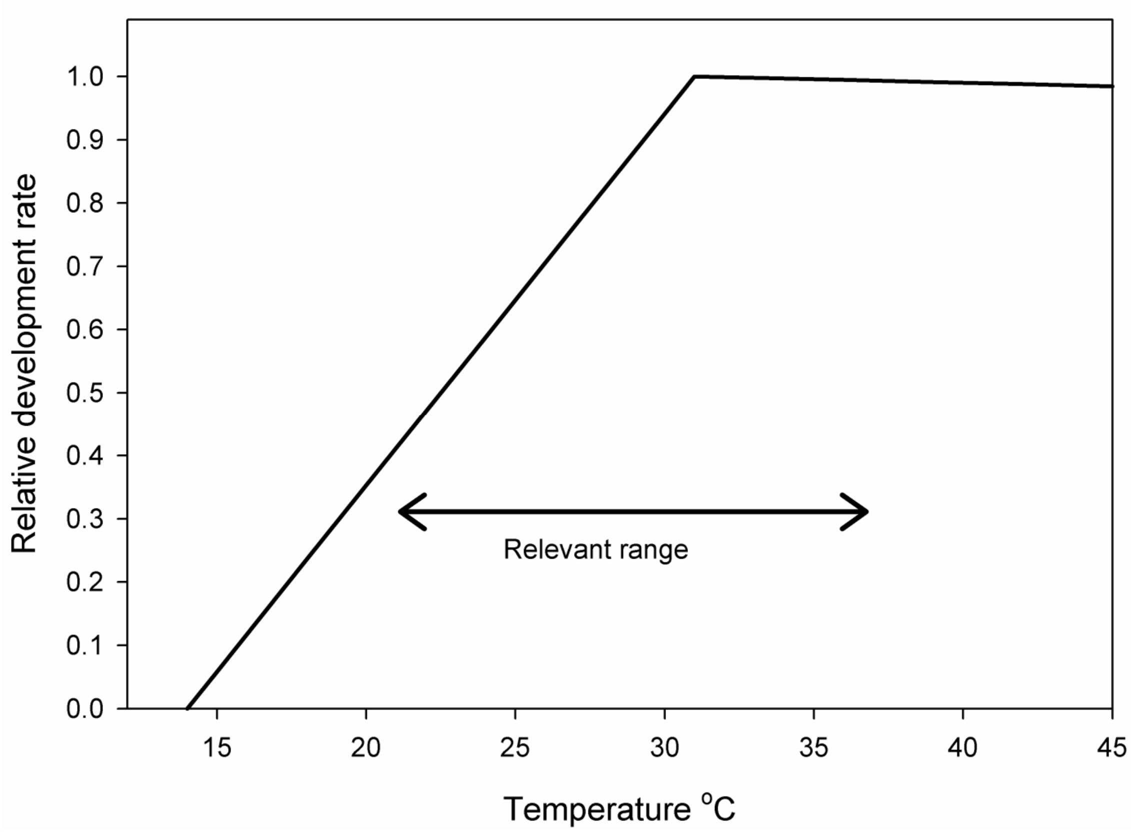

Figure 5.1: The Blackman-type relationship between temperature, in the agronomically important range of 15°C to 36°C and relative development rate for IR64 under Sahelian conditions.

These data cover a large range of temperatures (10-40°C, Figure 5.2).The mean temperature in the phase from emergence to flowering ranged from 24 to 31°C, thus we expect the phenological parameters to be valid in a wide range of temperatures. Figure 5.1 shows the temperature response function calibrated for cultivar IR64. Obviously, we do not know from the calibration data how a rice crop continuously growing at temperatures of above 40°C develops. Practically this is also irrelevant, as yields at such temperatures are zero due to heat induced sterility. However, just above the optimum of 31°C the model shown in Figure 5.1 gives much better predictions than the default response function in ORYZA2000, in which development rate drops to zero at 42°C. The revised phenology model calculates development rate as the product of relative development rate and the optimum development rate, as proposed by Yin and Van Laar (2005), where the relative development rate is scaled from 0-1 and the optimum development rate is defined as 1/time to complete a growth stage under optimum temperature. In ORYZA2000, spikelet sterility is calculated according to Horie *et al.* (1992). Cold induced sterility is simulated by accumulation of 'cooling degree days'. On days when the crop stage is between panicle initiation and flowering and when the average temperature, corrected for drought stress, drops below 22°C, the difference between the average temperature and 22 is calculated. In the model the crop stage is scaled from 0-2.0, with panicle initiation and flowering at 0.65 and 1.0, respectively. The temperature differences are summed from panicle initiation to flowering to obtain the cooling degree days. The relation between fraction of sterile spikelets (*Ster_{cold}*) and the sum of cooling degree days (*Sum_{cdd}* [°Cd]) is described as follows:

$$Ster_{cold} = 1 - \frac{\left(4.6 + 0.054 Sum_{cdd}^{\ 1.56}\right)}{100} \qquad \text{For} \quad \begin{matrix} \overline{T} \leq 22^{o}C \\ 0.65 \leq Cropstage \leq 1.0 \end{matrix} \qquad (1)$$

Only when the cooling degree days are larger than zero, Equation 1 is called in the model. It results in a cold sterility of 0.0465 when Sum_{cdd} is 1, and half of the spikelets sterile at 75°Cd. Around flowering, rice is sensitive to heat stress causing sterility at temperatures above 35°C. As flowering occurs during day time, the average daily maximum temperature during the flowering period is used to quantify heat induced sterility (Horie, 1993). In the model, the sensitive phase is limited to the period between crop stage 0.95 and 1.05. The relation between sterility fraction ($Ster_{heat}$) and temperature ($\overline{T}_{max}$ [°C]) found by Horie (1993) can be approximated by the following equation:

$$Ster_{heat} = 1 - \frac{1}{1 + e^{\left(0.853\left(\overline{T}\max - 36.6\right)\right)}} \qquad \text{For} \quad \begin{matrix} T\max \geq 35 \\ 0.95 \leq Cropstage \leq 1.05 \end{matrix} \qquad (2)$$

The implementation of the Equation 2 in the model is such that only when the temperature reaches 35°C, a sterility fraction is calculated. At 35°C, the sterility fraction is 20%, and half of the spikelets are sterile at a temperature of 36.6°C.

2.3 Weather data

Daily minimum and maximum temperatures were used as input for the models. The data were collected at two experimental locations, Ndiaye and Fanaye, between 1991 and 2006. In 2006, daily maximum temperatures were higher in Fanaye than in Ndiaye, whereas minimum temperatures were similar in Fanaye and Ndiaye (Figure 5.2 and 5.3). Between 1991 and 2006 mean minimum and maximum temperatures have not changed, although higher temperatures were recorded between 1995 and 1997 (Figure 5.3).

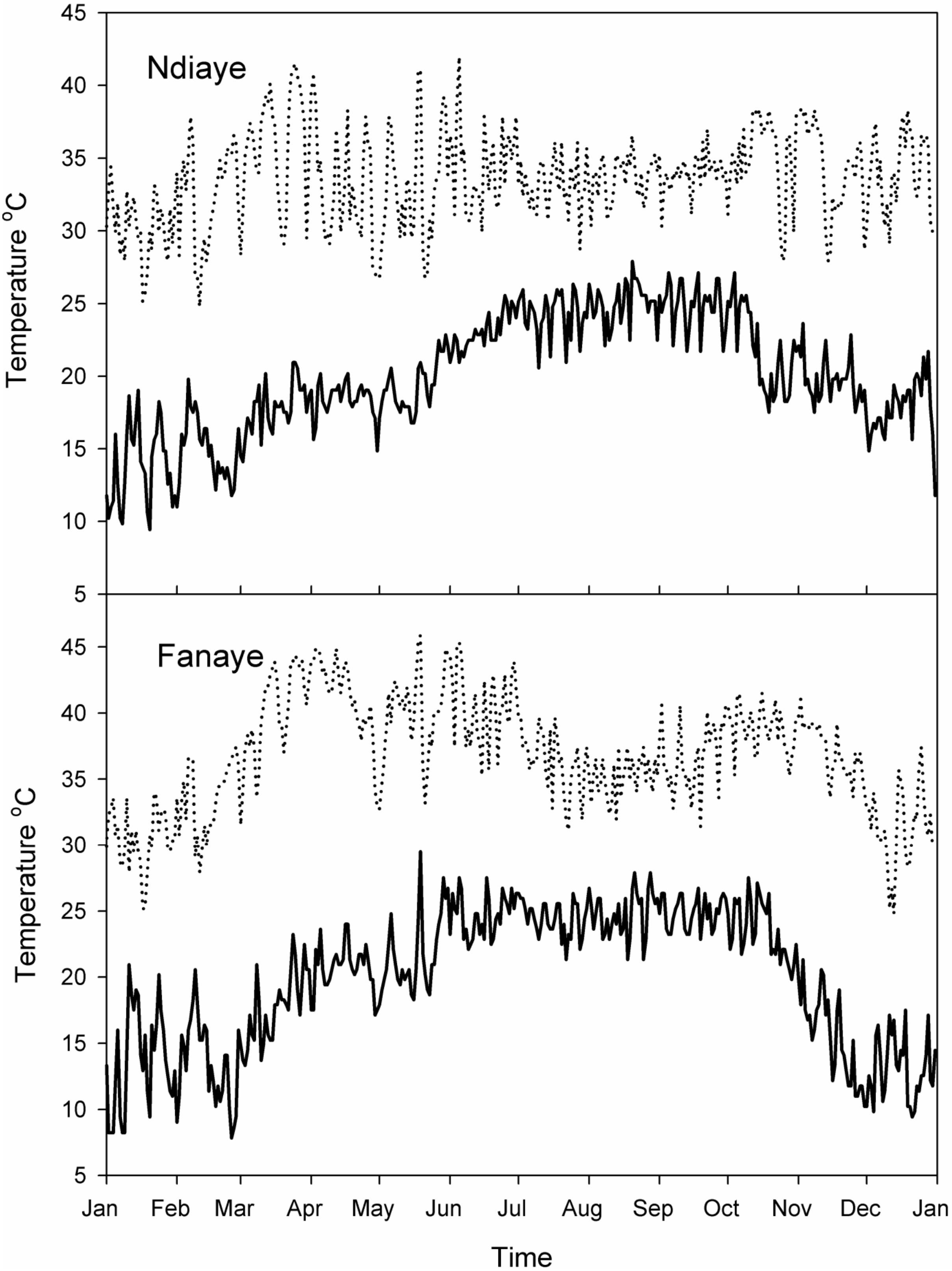

Figure 5.2: Daily minimum (full lines) and maximum (dotted lines) temperature in Ndiaye (top) and Fanaye (bottom) for 2006.

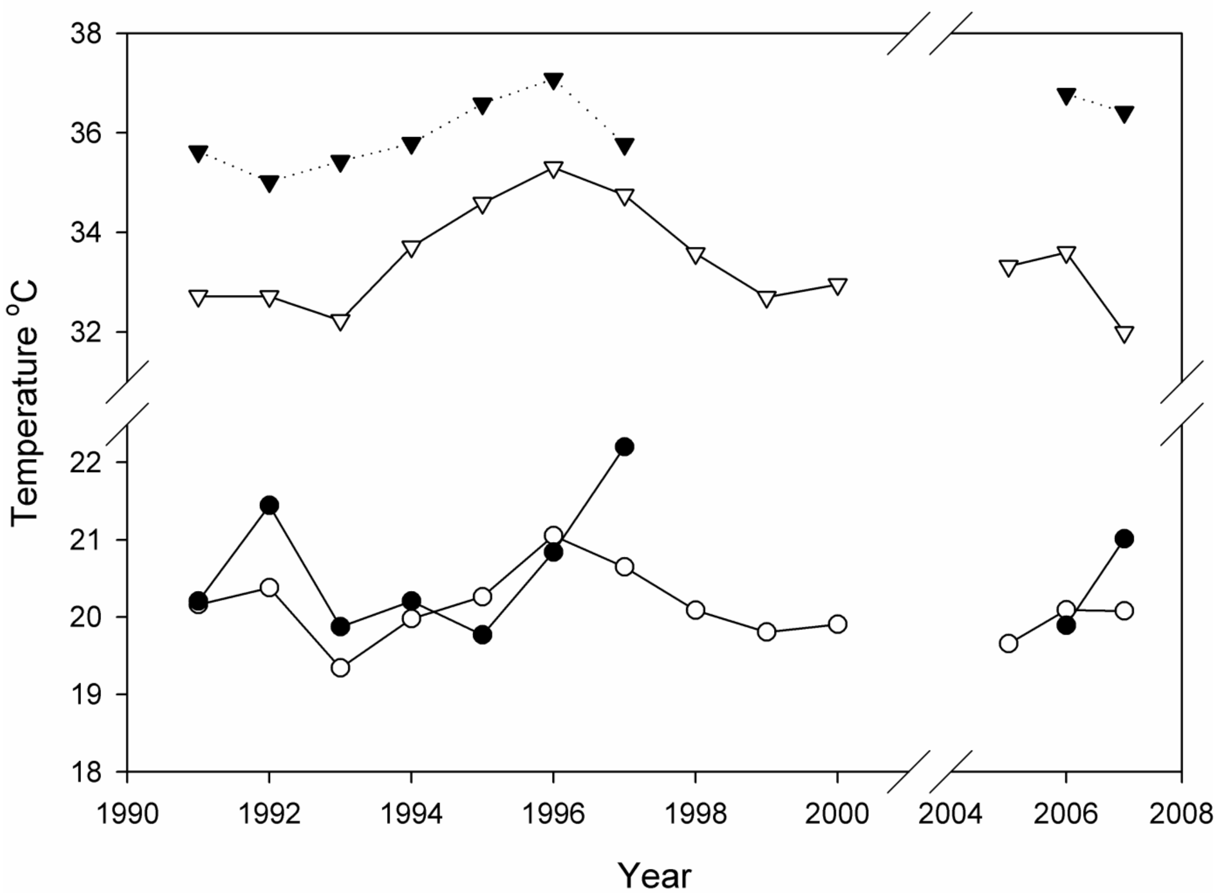

Figure 5.3: Annual average minimum (circles) and maximum (triangles) temperatures between 1991 and 2006 in Ndiaye (open symbols) and Fanaye (closed symbols).

5

Fanaye had consistently higher maxima (Figure 5.3 and Table 5.1). Mean minimum temperatures were similar, with 20 and 21°C for Ndiaye and Fanaye, respectively. Mean maximum temperatures were higher in Fanaye, with 36 against 33°C in Ndiaye. Both the absolute minimum and maximum temperature were recorded in Fanaye: 6 and 46°C (Table 5.1).

Table 5.1: Description of the minimum and maximum temperatures observed in Ndiaye and Fanaye, with number of observations (*n*), minimum recorded value (°C), 10th percentile, mean, 90th percentile, maximum recorded value (°C) and the standard deviation (σ).

Temperature data-set	*n*	Min.	10th perc.	Mean	90th perc.	Max.	σ
Ndiaye minimum	4663	8	16	20	25	29	3.7
Ndiaye maximum	4663	20	30	33	38	45	3.4
Fanaye minimum	3578	6	14	21	26	31	4.6
Fanaye maximum	3578	19	31	36	42	46	4.1

2.4 Model validation

An independent data-set to validate the phenology model was used. It consisted of field experiments at the same locations (Ndiaye and Fanaye) with the same varieties, IR64 and Sahel108. Details of the experiments are described in Dingkuhn and Miezan (1995) and Dingkuhn *et al.* (1995b). For variety IR64, 23 sowing dates in Ndiaye, from day 69 in 1991 to day 161 in 1993, with monthly intervals and 13 sowing dates in Fanaye, from day 188 in 1991 to day 189 in 1992 were used. For variety Sahel108, 12 sowing dates in Ndiaye between day 196 in 1992 and day 189 in 1993 were used. Hence, 48 independent observations from two varieties with sowing dates distributed over three years at two sites were compared with simulations, using the same sowing date and seed-bed durations. Daily weather data was recorded at both sites during the experiments; the minimum and maximum temperatures were used as model input. RMSE was used to quantify model performance.

The spikelet sterility function could not be validated from our data. We relied on detailed pot experiments undertaken by Horie *et al.*(1993). The level of detail attained in other studies that investigated sterility was not met in our experiments (Matsui, 2009; Prasad *et al.*, 2006; Shimono *et al.*, 2005).

3 Results

3.1 Validation results

The absolute average difference between simulated and observed phenology of the three variety × site combinations (n= 48) was 8.1 and 10.3 for days to flowering and to maturity, respectively. The associated root mean square errors (RMSE) were 10.0 and 12.2 days for flowering and maturity, respectively. In some cases, large variation (maximum of 20 days) was observed. Plotting average temperature versus days to flowering reveals that the simulated data reproduce the trend shown in Figure 5.4. It is striking that the validation data by Dingkuhn *et al.* show either development as predicted by our model, or faster. This could signal a deficiency in our model or in the data of Dingkuhn *et al.*, or both. The two encircled triangles are data points of variety Sahel108 sown in Ndiaye, the data point on the right is sown on July 15th 1992, the one on the left on July 8th 1993.

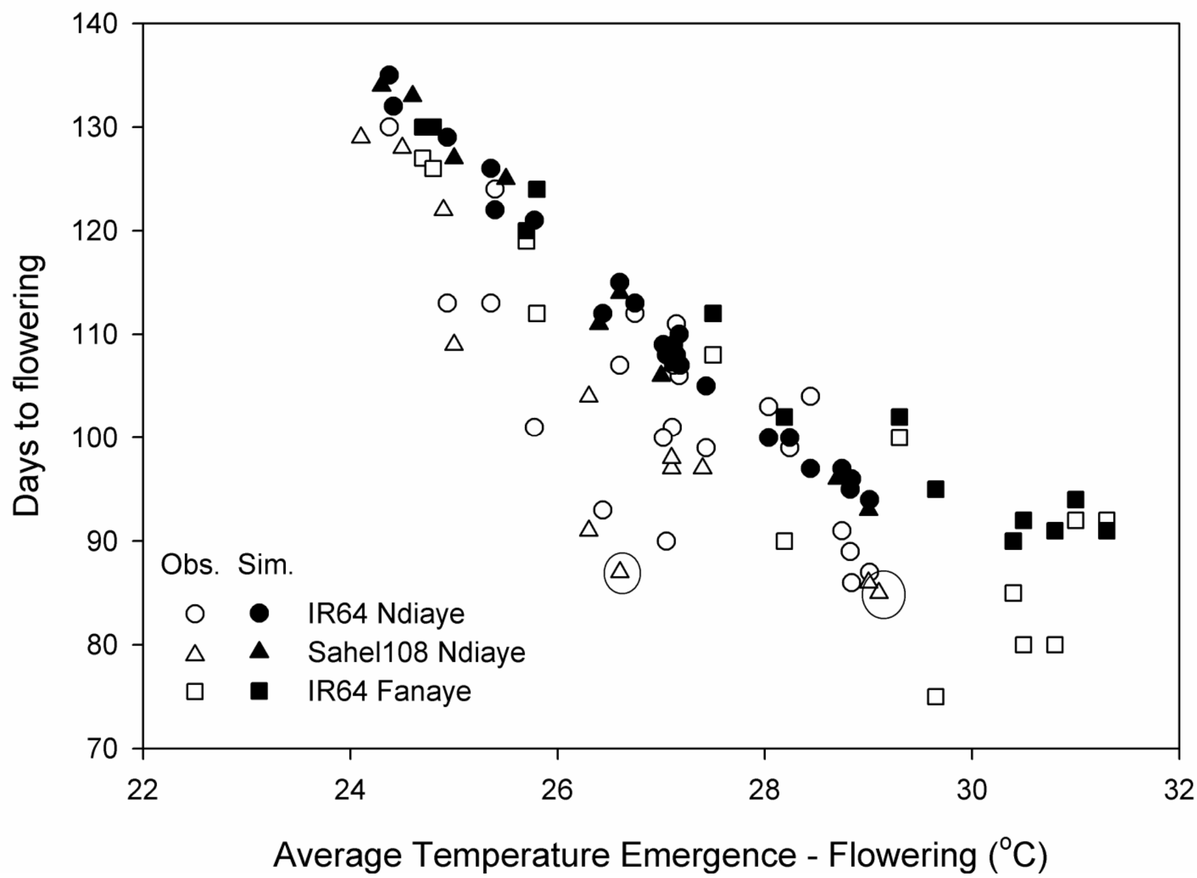

Figure 5.4: Average temperature between emergence and flowering versus days to flowering for observed and simulated data of variety IR64 in Ndiaye (circles) and Fanaye (squares), and variety Sahel108 in Ndiaye (triangles). Open symbols are observed values from Dingkuhn *et al.* (1995); closed symbols are simulations of observations. Two encircled triangles are sowings at similar dates in two different years.

The mean temperature from emergence to flowering was 2°C higher in 1992, yet flowering is at almost the same date (85 and 87 days after emergence). This seems unlikely; such patterns were not observed in our calibration data.

3.2 Scenario analysis

The IPCC developed a number of possible temperature change scenarios for the West-African region in their 4th assessment report (Table 5.2) (Solomon *et al.*, 2007). For our analysis we have used minimal and maximal temperature increases to determine the bandwidth of possible implications:

- Base line "as is", using current daily weather data
- Minimal increase of average of 1.8°C
- Maximal increase of average of 4.7°C

To analyse the effects of temperature on the growing cycle and spikelet sterility, four sets of weather data were selected. Based on availability of daily weather records, data from 1991/92, 1994/95, 1998/99 and 2006/07 from Ndiaye and Fanaye were used. The minimum and maximum temperature change was calculated by adding the temperature increases from Table 5.2 to the daily weather records. For each set of years, 365 simulations were run to simulate sowing on every day of the year. Spikelet sterility was calculated for each fortnight, averaged over the four years.

Table 5.2: Averages of temperature increase and occurrence of extreme warm, wet or dry seasons for the A1B scenario for the West-African region. The temperature and precipitation responses are averaged for each model over all available realisations of the 1980 to 1999 period from the 20th Century Climate in Coupled Models (20C3M) simulations and the 2080 to 2099 period of A1B. Computing the difference between these two periods, the table shows the minimum, maximum, median values for temperature (°C) change. The frequency (%) of extremely warm, wet and dry seasons, averaged over the models, is also presented. Projections are from climate simulations conducted for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon *et al.*, 2007).

	Temperature increase (°C)			Extreme seasons (%)		
Months	Min	Median	Max	Warm	Wet	Dry
DJF	2.3	3.0	4.6	100	21	4
MAM	1.7	3.5	4.8	100		
JJA	1.5	3.2	4.7	100	19	
SON	1.9	3.3	4.7	100	15	
Annual	1.8	3.3	4.7	100	22	

3.3 Crop cycle length

Under current conditions, the dry season crop has a cycle length of 150 days in Ndiaye and ten days less in Fanaye, while the wet season crop takes 130 days to mature at both sites (Figure 5.6). Under climate change scenarios this can decrease to 140-125 days in Ndiaye and 135-120 days in Fanaye for the dry season. For the wet season the duration decreases to 130-120 days and 125-115 days in Ndiaye and Fanaye, respectively. The largest decrease in duration occurs at both sites for sowing dates between September and January: up to 30 days.

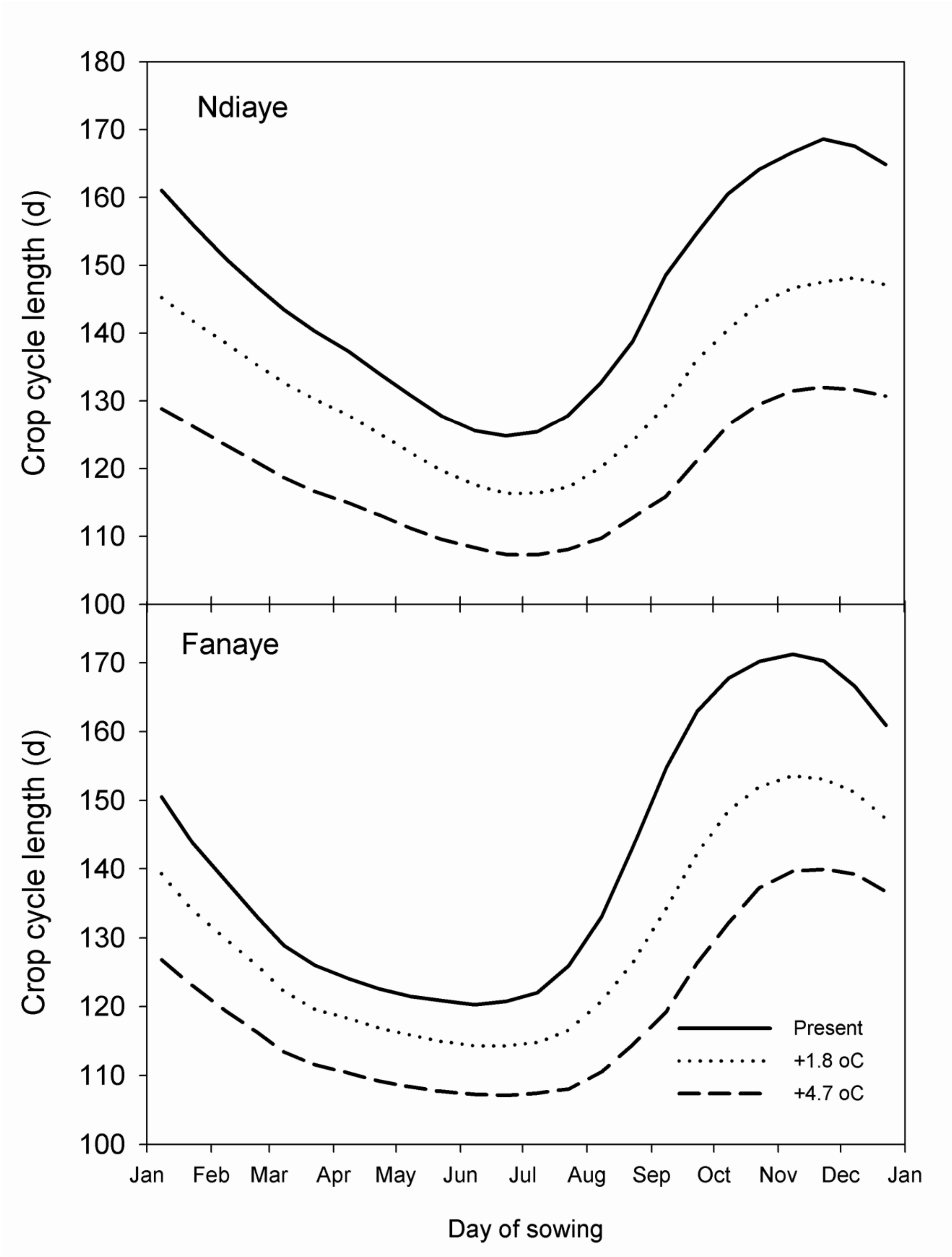

Figure 5.5: Simulated crop duration of rice variety IR64 in Ndiaye (top) and Fanaye (bottom), Senegal for the averaged weather of the reference years 1991, 1994, 1997 and 2006 and in response to minimal and maximal temperature change as a function of sowing day.

3.4 Spikelet sterility

In the present situation, cold induced spikelet sterility is a threat when sowing between September and December. Heat induced sterility occurs mainly in Fanaye, when sowing between November and April and in August. Even in the current climate, rice cropping is seriously restricted by spikelet sterility. The minimal projected temperature increase results in Ndiaye in a marked reduction in the cold induced sterility, from 92% to 55% in October. However, the heat induced sterility, which is practically absent at present, becomes more important than the cold induced sterility with a peak of 69%. In Fanaye, the minimal temperature increase scenario results in a small decrease in the cold induced sterility: from 100% to 87% in October. Heat induced sterility is always above 56%, except between September and November. Under these conditions, sterility is at least 41% when sowing in September, but for most other sowing dates it is above 60%. Under the maximum predicted temperature increase, cold induced sterility at Ndiaye is always less than heat induced sterility, peaking at 29% in October. Heat induced sterility increases, with all sowing dates resulting in more than 57% sterile spikelets, except October. In Fanaye a similar pattern is shown: between December and September, heat induced sterility is over 90%. In October and November cold induced sterility occurs, but heat induced sterility is always larger, with a minimum of 40%.

4 Discussion

4.1 Model validation

The validation results of the model show that simulation of flowering day for an independent data-set leads to an average difference with the observed values of eight days. The RMSE of 10 days for simulated flowering date is three days more than found by Van Oort *et al.* (2011). When the RMSE is expressed as percentage of the observed duration, 8.5% in this case, the model performance is in range with what was found by Van Bussel *et al.* (2011a) for a case of AFRCWHEAT2 simulating spring wheat in Germany: 4.7%. From these results we can conclude that the model is capable to simulate rice phenology with an uncertainty of 8-10 days, and that the model reproduces effects of temperature on phenology well.

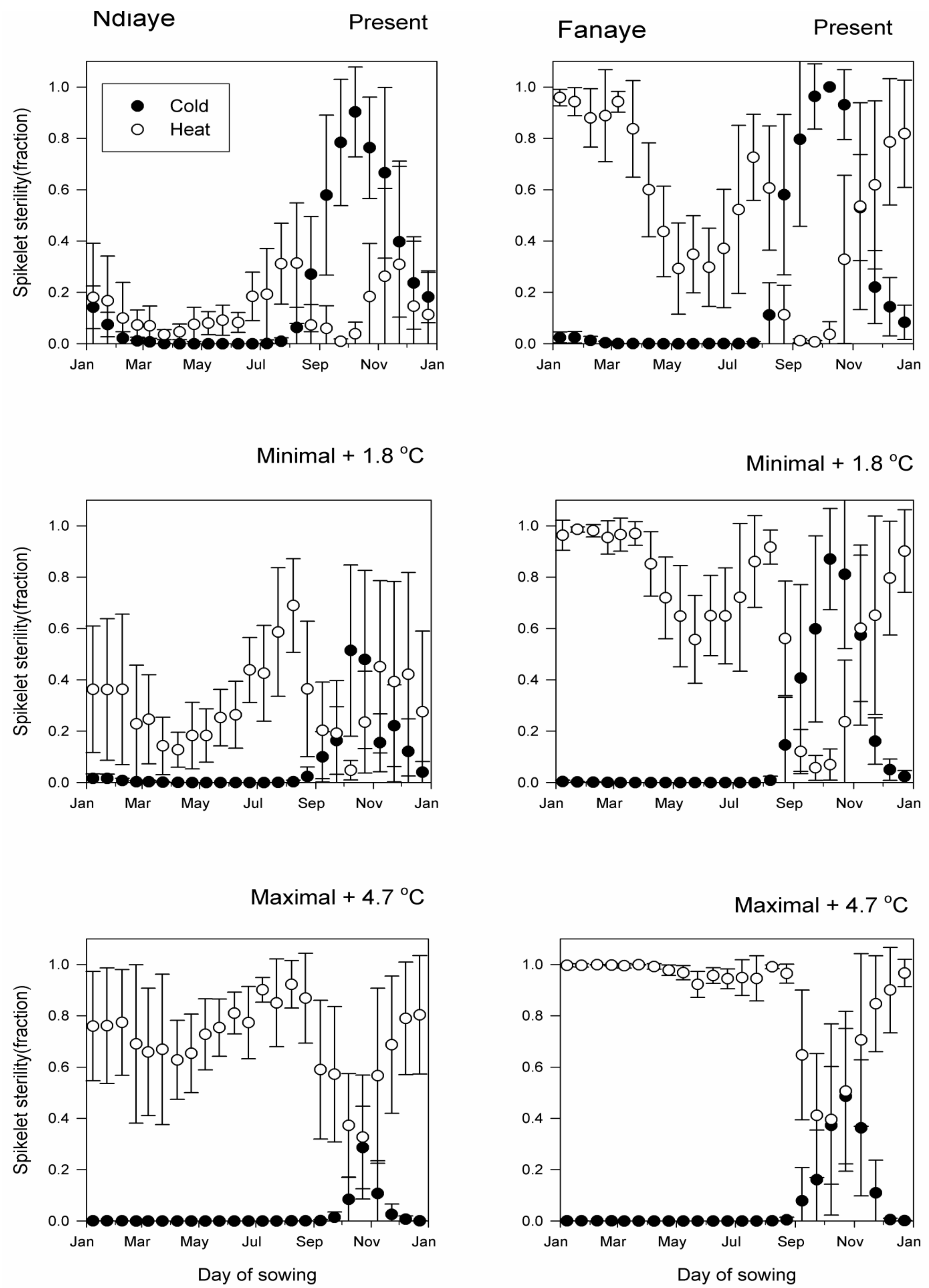

Figure 5.6: Simulated spikelet sterility due to cold (closed circles) and heat (open circles) stress of IR64 at present temperature (top), a minimum increase (middle) and a maximum increase (bottom) in Ndiaye (left) and Fanaye (right) Senegal. Each point is the mean of 15 sowing dates in four years ('91, '94, '98 and '06) and standard deviation.

From Figure 5.4 a temperature sum can be derived, using the average temperature as basis, and assuming base temperature of 10°C. At an average temperature of 25°C, the duration to flowering was 129 days, resulting in 3225°Cd, at 29°C the duration to flowering was 91 days, leading to a temperature sum of 2639°Cd. This seems counter intuitive, as the calibration program presumes a constant thermal time requirement. An explanation for this significant difference is that ORYZA calculates phenology based on hourly temperatures. Practically every day the maximum temperature is above the optimum temperature (Figure 5.1). The temperature sum calculation as above implicitly assumes a continuous linear increase of degree day accumulation. In our model, degree day accumulation is constant (i.e. not increasing) in all those hours where temperatures are above the optimum. Our results show that summation of degree days based on average temperatures will result in different outcomes for different sowing dates. It confirms our findings from Chapter 2 and shows that in the Sahel, where daily maximum temperatures are above the optimum temperature for development, the temperature sum needs to be calculated at a time step smaller than a day. From the validation we conclude that the model is appropriate for use in the scenario study performed to quantify the effects of temperature on growing cycle, while taking the uncertainty into account.

4.2 Effects of temperature change

Our study is limited to temperature responses. Effects of changes in solar radiation and CO_2 concentrations have a potentially large effect on biomass production (Matthews *et al.*, 1997; Sheehy *et al.*, 2006b; Wassmann *et al.*, 2009). However, this is all of no effect on yields if there are no fertile spikelets. According to previous work it is this sterility that has the largest impact on future yields in Senegal (De Vries *et al.*, 2011; Dingkuhn, 1995). Therefore, we have disregarded in this paper the possible effects of solar radiation and CO_2 concentrations on future yields.

The projected change in temperature affects irrigated rice in the Sahel in three ways: shortening of the crop growth cycle, a decrease in cold induced spikelet sterility, and an increase in heat-related sterility. The projected crop cycle shortening of 10-30 days will affect the rice farmers in various ways: a shorter cycle means less irrigation costs, but also a decreased yield due to a decrease in the intercepted radiation.

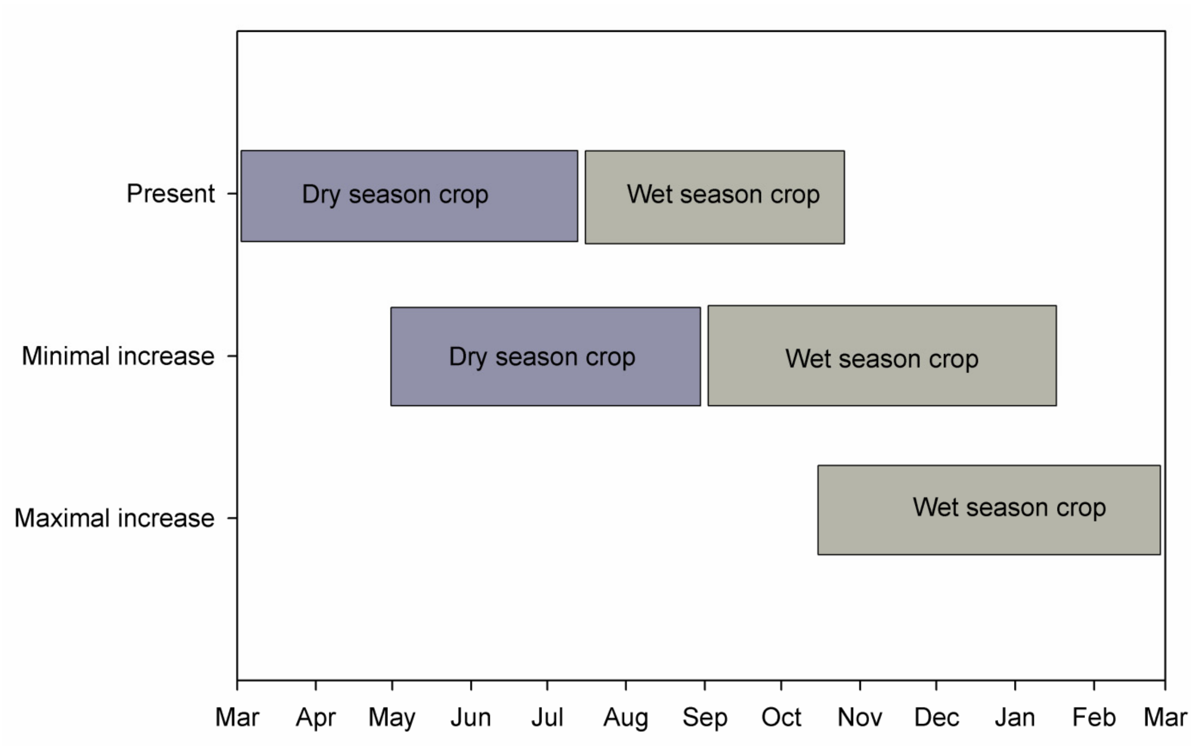

Figure 5.7: Present rice cropping calendar and possible cropping calendars under minimal and maximal projected temperature increase.

Under current circumstances farmers can avoid cold related sterility by respecting recommended planting dates (De Vries *et al.*, 2011; Dingkuhn and Sow, 1997a). Under projected temperature increases, cold related sterility will only occur when planting in October and November at both sites. On the other hand, heat-related sterility will become a serious problem. Spikelet sterility will increase to cause total crop loss under maximum temperature increases when sowing in the first half of the year in Fanaye. Presently, the cropping system includes a main wet-season rice crop and a dry-season rice crop (Figure 5.7). Under minimal temperature increase, rice double cropping is still possible, but the sowing window is small; i.e. sowing too early results in heat-sterility, sowing too late in cold- sterility. It remains to be seen whether in practice farmers are able to clear their fields from the dry season crop and prepare it at the same time for the wet season.

Under maximal temperature increase, rice cropping will be seriously jeopardized by heat sterility, while risks for cold sterility remain small. If only sowing in October is possible, risks for both cold and heat sterility remain high, around 40%. Under this scenario, rice cropping is under serious threat and heat tolerant rice varieties will be needed to minimize risks of crop failure. It is clear that the temperature changes predicted by the scenarios developed by the IPCC will have large consequences for the rice-based cropping system along the Senegal river. The current main season, sowing in July and risking cold sterility when sowing late, will shorten and possibly change to sowing in September or October, or the main rice season will shift to the period of May to August.

Unlike cold tolerance, heat tolerance can be bred for (Prasad *et al.*, 2006). Rice cultivars that flower early in the day can escape terminal heat occurring at midday. The cultivar used, IR64, is known to be moderately heat tolerant (Jagadish, 2007), and the temperature at which 50% sterility occurs was set at 36.6°C. As Matsui *et al.* (2001) show, a 3°C temperature difference in heat tolerance exists between varieties; a 5°C increase can probably be overcome by focused selection on length of the basal dehiscence, for which substantial genetic variation has been observed (Kobayashi *et al.*, 2011). Recently, Jagadish *et al.* (2010a) identified QTLs for heat tolerance, which partly overlap with regions where QTLs for drought tolerance are found. Based upon this information, marker assisted screening protocols for both these important abiotic stresses can be developed.

Farmers in the Senegal River valley are accustomed to managing risks (Connor *et al.*, 2008). The big question is, can they also cope with the growing risks of spikelet sterility that arise as a consequence of climate change. The adaptation range of 3 to 5°C for the heat spikelet sterility threshold is similar to the range of anticipated temperature increases. This suggests that with adoption of heat tolerant varieties Senegalese farmers may be able to continue the current cropping pattern. Without such adaptation, we anticipate yield reductions of more than 40% due to spikelet sterility (Figure 5.6) and in the worst case it may no longer be possible to grow two crops per year (Figure 5.7).

5 Conclusion

Our study suggests that with projected temperature changes timing of sowing and consequences of the risks for crop loss due to sterility will remain the major determinants of rice yield along the Senegal river. We show that there is an urgent need for heat tolerant rice varieties. The current genetic variation for heat tolerance suggests that with adaptation current cropping patterns can persist. More breeding and empirical testing of heat-tolerant varieties is needed. Without that, we anticipate current sterility (0 to 20%) to increase (to 20 to 90%, depending on the temperature change and sowing date). In the future climate, growing two crops per year may no longer be an option.

Chapter 6

General discussion

1 Objectives of the study

This thesis explores options for future management of irrigated rice in the Sahel. This leads to an improved understanding of the behaviour of the system. As a result, the effects of possible changes in irrigation water availability and climate could be evaluated. The methods that were used for this study were a combination of field experiments and statistical and simulation models. In this chapter, the appropriateness of the methods is discussed, followed by a discussion of the consequences of a simultaneous occurrence of temperature increase and reduced availability of irrigation water, for which the adapted model ORYZA2000 is used. Furthermore, the lessons breeders can draw from this thesis are presented. Finally, the possibilities for the extrapolation of the results of this study to other rice-based cropping systems in Africa are discussed.

2 *In silico* and *in vivo* experiments

The methods that were chosen for this study were field experiments, performed at experimental stations, statistical analyses and dynamic crop growth models. The field experiments were performed at research stations of the Africa Rice Centre, Ndiaye and Fanaye. Conducting field experiments involves thorough organisation and planning, dealing with environmental setbacks (bird attacks, storms) and manual data collection. All of these can, and have, lead to errors; in our case due to a combination of the factors mentioned only five of the eight performed water-saving experiments generated data that could be used in the study presented in Chapter 2. However, in agreement with Kaschuk (2009), important lessons were learnt from unsuccessful experiments: the unusual design of the water-saving experiments was chosen after failure of initial experiments. Results of some of the on-farm water-saving experiments are presented by Guillaume (2007). To reduce measurement errors, the same people performed the same measurements, although at the two different sites, different people performed field measurements. We reviewed our data critically and discarded data-sets that were obviously erroneous, or had high coefficients of variation (> 20%). To analyse genotype by environment interactions, two frequently used statistical analyses have been the Additive Main effects and Multiplicative Interaction (AMMI) model (Gauch and Zobel, 1997) and the Genotype main effects and Genotype Environment interaction effects (GGE) model (Yan *et al.*, 2001). In a review, Gauch (2006) showed that in all cases

AMMI was on par or better to produce an easy to interpret graphs of complex G × E interactions with least-squares errors. Dingkuhn *et al.* (1995b) performed experiments similar to those presented in Chapter 3, their methods were used as basis. To measure spikelet sterility, detailed pot-experiments with hourly counting of pollen grains have been performed to unravel the relations between high temperature and spikelet fertility (Endo *et al.*, 2009; Jagadish, 2007; Kobayashi *et al.*, 2011). Our field experiments were not apt for these detailed measurements, hence we could not validate crop models with our own sterility data-set.

Dynamic crop growth simulation models are used to predict the effects of climate change in various studies (Ewert *et al.*, 2005; Shimono *et al.*, 2010; Tao *et al.*, 2008; Xiong *et al.*, 2010), although the simulation of processes involved (Adam *et al.*, 2011; Long *et al.*, 2006; Sheehy *et al.*, 2006a; 2006b) and the interpretation of results at different scales has been debated (Challinor *et al.*, 2009; Ewert *et al.*, 2006; Van Bussel *et al.*, 2011b; Zhang *et al.*, 2008). The crop models that were used in this study were used to explore, not to predict. Hence it is difficult to determine the exact error as explorations deal with hypothetical situations. In Chapter 4 we have shown that un-calibrated crop models are not accurate, thus simulation models should only be used after proper calibration and validation. Care should be taken if crop or genotype specific parameters are used outside their calibration environments. The results of length of the growing season, as presented in Chapter 5, have a coefficient of variation of 10 days, calculated by Van Oort *et al.* (2011). The use of extensive data-sets for calibration and of a separate validation data-set with the same genotypes from the same sites increases confidence in the results of our simulations. The combination of field experiments, analysed statistically, with simulation studies was apt to explore the behaviour of how the current systems, within which the experiments were embedded could react on global change.

3 Simultaneous temperature increase and irrigation water scarcity

Irrigation water will become scarcer at a global scale (Rijsberman, 2006). As a consequence in the Senegal river valley competition among user groups will become more severe (Venema *et al.*, 1997). Hence, the irrigation regimes as explored in Chapter 3 could become viable options for some farmers. At the same time, an increase in temperature of 1.8-4.7^{o}C is expected by the IPCC (Boko *et al.*, 2007). In Chapter 5, we explored how different temperature increase scenarios would affect yield formation of the rice plant and subsequently the cropping system. Logically, we can expect these two processes to happen simultaneously. To investigate whether there would be additive interactions between water-saving irrigation regimes and an increase in temperature, we conducted a simulation study.

3.1 Modelling water-saving and temperature increase

To investigate the combined effects of temperature increase and reduction of irrigation water use, we used the model ORYZA2000, of which the phenology routine was adapted according to Van Oort *et al.* (2011). In Chapter 5 it was shown that the model simulates temperature responses to phenology well. ORYZA2000 is designed to simulate water-limited yield, which has been validated for different hydrological conditions (Belder *et al.*, 2007; Boling *et al.*, 2007). For our modelling study we studied four scenarios:

i. present climate and conventional (continuously flooded) irrigation;
ii. present climate and water-saving irrigation;
iii. maximum temperature increase and conventional irrigation;
iv. maximum temperature increase and water-saving irrigation.

These are combinations of scenarios developed in Chapters 2 and 5. Water-saving was simulated as re-irrigation at the moment when the soil layer at a depth of between 10 and 15 cm below the soil surface dried out to 80% of field capacity. At soil depths below this, ample water was available for the rice plant. To simulate conventional flooded irrigation, a continuous layer of standing water of between 5 and 10 cm was maintained. The present climate and maximum temperature scenarios were simulated as described in Chapter 5. The variety Sahel108, which was used in the water-saving experiments of Chapter 2, was used for the simulation. The phenology parameters were obtained from Van Oort *et al.* (2011), who used data from the experiments presented in Chapter 3 for calibration.

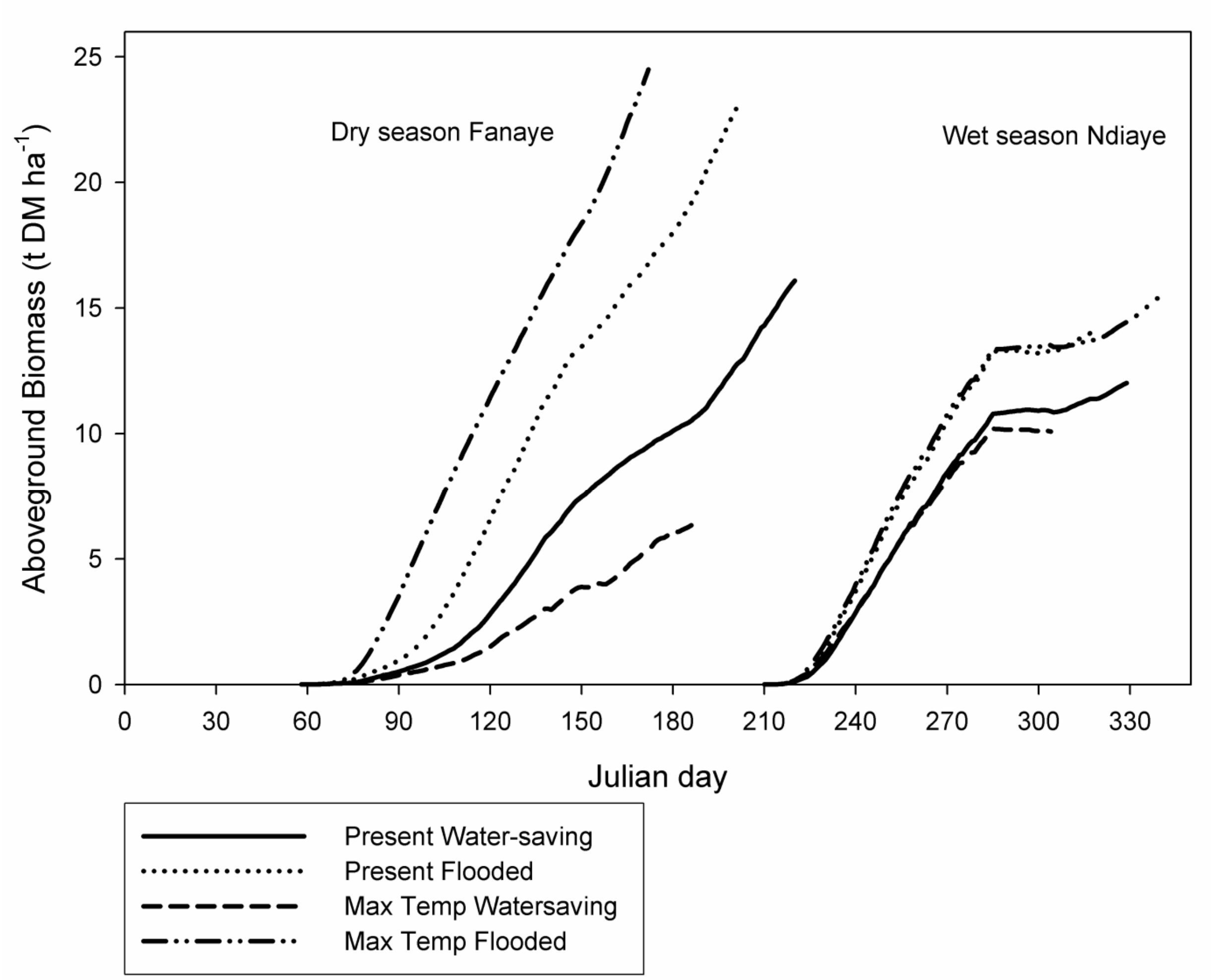

Figure 6.1: Simulation of aboveground dry matter (t ha^{-1}), from emergence to maturity, under combinations of current climatic conditions or maximum temperature increase and with water saving irrigation or flooded conditions. Simulations for the Dry season in Fanaye sown in March on the left, on the right the wet season in Ndiaye, sown in August are shown. Data for simulation are obtained from Dry season 2006 experiment for Fanaye, and wet season 2005 for Ndiaye (Chapter 2).

6

3.2 Can we save water when the temperature rises?

Two different situations were modelled: a dry season at Fanaye site, and a wet season at Ndiaye site. Biomass from emergence to maturity shows a steady increase, although in some cases the increased death rate of leaves reduces the total biomass at the end of the growing cycle (Figure 6.1). In both situations, the maximum temperature increase returned the largest biomass, while the maximum temperature increase in combination with water-saving returned the smallest biomass.

Table 6.1: Results from simulations of two sites and seasons with combinations of current climatic conditions or maximum temperature increase and with water saving irrigation or flooded conditions. Irrigation (mm), days from emergence to flowering and maturity, grain yield (t ha^{-1}, 14% MC) and spikelet sterility (fraction sterile spikelets).

Site and season	**Scenario**	**Irrigation** (mm)	**Days to**		**Grain yield** (t ha^{-1})	**Sterility** (-)
			Flow.	Mat.		
Ndiaye Wet season	Present Flooded	500	94	129	1.7	0.50
	Present Water-saving	400	107	144	3.3	0.03
	Max temp increase Flooded	500	81	109	0.7	0.90
	Max temp increase Water-saving	450	91	119	0.8	0.82
Fanaye Dry season	Present Flooded	1100	123	152	7.3	0.13
	Present Water-saving	800	141	170	6.9	0.24
	Max temp increase Flooded	800	97	122	2.5	0.91
	Max temp increase Water-saving	650	111	136	1.0	0.95

In the model, the effects of extreme temperatures (>45°C) on photosynthesis and assimilation are not well validated, and we should interpret these biomass figures with care. However, the results show that when the temperature increases, the small effects of early drought stress, such as delay in flowering, stomatal closure and early leaf rolling will be aggravated, and biomass accumulation will slow down. Even small water deficits already lead to sub-optimal growth in lowland rice (Lafitte *et al.*, 2002; Wopereis *et al.*, 1996). In various water-saving experiments in Asia, a yield decline has been observed, even when the soil was re-wetted regularly, concurring with our results presented in Chapter 2 (Belder *et al.*, 2005a; Bouman *et al.*, 2007b; Peng *et al.*, 2006). A large genotypic variation has been observed in reaction to drought stress, notably in the ability to maintain the root: shoot ratio under stress (Asch *et al.*, 2005; Suralta *et al.*, 2010). Heat induced spikelet sterility, as observed in our results may be aggravated by a combination of heat and water stress (Rang *et al.*, 2011). The water-saving treatments used less irrigation water: 10-27%, which is similar to values found in our experiments in Chapter 2 (Tables 2.5 and

6.1). The effect of water-saving on development was a delay of between 10 and 17 days to maturity. The temperature increase accelerated development by 20-34 days. Grain yield under current conditions was comparable to values from observed data. Under maximum temperature increase, it was largely affected by heat induced sterility (Table 6.1). As a result of water-stress, flowering of rice was delayed, and the growth cycle increased. In the model description by Bouman *et al.* (2001), a direct relation between effective temperature for phenological development and temperature of ponded water was not found. However, the tip of the growing point of the rice plant is submerged from emergence to somewhere between panicle initiation and flowering. It can be assumed that for that period it is rather floodwater temperature than air temperature that governs development rate, a concept used in the rice simulation model RIDEV (Dingkuhn *et al.*, 1995a). Already at present a deep water layer is used under temperate rice growing conditions (e.g. southern Australia) to decrease to risk on cold sterility (Humphreys *et al.*, 2006).

However, our data presented in Chapter 2 (Table 2.6) do not show a conclusive difference between the flooded and water-saving treatments. Flood water can also be a buffer for heat stress. Incorporating floodwater temperature in the model will require a precise simulation of depth of ponded water and simulate an energy balance to calculate the effective phenological temperature, notably in situations of alternate wetting and drying, this will be a challenge. In the example of RIDEV, which is based on field observations of water and air temperature, daily minimum temperature for air and water are assumed to be equal, while maximum and mean water temperature depend on the crop stage and the daily temperature amplitude. Van Oort *et al.* (2011) show that a sinusoid phenological model, involving a dampening factor to simulate the buffering effect of the water layer, does not improve simulation results. In our experiments the water depth over the season showed a high variability (Figure 2.2). To simulate such variations will be data demanding, and it is questionable whether such modelling detail will improve the usability of the model. Incorporating such highly site-specific information will certainly reduce its general applicability.

3.3 Adoption of water-saving

In Asia, where water-saving has been studied extensively, adoption rates by farmers were limited in the Philippines (Lampayan *et al.*, 2004), India (Senthilkumar *et al.*, 2008) and China (Zhou *et al.*, 2008). In many irrigation schemes in the Sahel the water pricing system is per surface rather than per volume and per irrigated block instead of per individual farmer (García-Bolaños *et al.*, 2011; Le Gal *et al.*, 2003; Van Vugt, 2007). Awareness of the volume irrigated at farmer level is needed to create support to save water (Tsur and Dinar, 1997). The social aspect of water management is important, but outside the scope of this thesis. However, collective action of water management increases efficiency and productivity in Sahelian irrigation schemes (Poussin *et al.*, 2006; Vandersypen *et al.*, 2007b). Often the decision tree for water management operations is hierarchical, and individual farmers do not have full control on the time to irrigate and to drain (Van Vugt, 2007; Vandersypen *et al.*, 2007a). Individual pricing per volume, similar to pricing of household water, creates awareness of water use and an incentive for saving (Tsur and Dinar, 1997). Policy makers should bear the social and organisational factors in mind when developing measures aiming at a reduction of water use for irrigated rice. Our results were obtained at field level and cannot be extrapolated directly to a whole scheme: losses through transport canals have not been taken into account and water lost through percolation in one field can become available in the root zone of another field.

4 Implications for breeding

The results of this study show that management of irrigated rice in the Sahel needs to adapt to global change in the coming decades. Development of a new rice variety takes, in spite of modern molecular tools, about 10 years. Hence, rice breeders need to take management practices of the next 10-20 years into account when selecting their breeding goals.

4.1 Water-saving irrigation

The results from Chapter 2 indicate that water-saving irrigation will be a viable management option for some farmers. Aerobic rice and related water-saving irrigation regimes need different plant types (Lafitte *et al.*, 2002). Over the past two decades, progress has been made in selecting rice genotypes for environments without a permanent layer of water (Zhao *et al.*, 2010). However, the diversity of hydrological conditions increase the G×E effects (Wade *et al.*, 1999). The main role of water-logging in irrigated rice is weed control. Decreasing the permanent layer of standing water will increase weed pressure, if not properly managed. New NERICA cultivars have been screened for their weed competitiveness (Rodenburg *et al.*, 2009) and their performance under different hydrological conditions (Saito *et al.*, 2010b). Screening protocols for selection for high-yielding and weed suppressive genotypes for irrigated rice without permanent water layer have been developed (Zhao *et al.*, 2006). Marker assisted selection has been proposed as a method to increase selection efficiency, although a proper characterization of cultivation environments is needed (Manneh *et al.*, 2007). Therefore, high quality field experiments where both management factors and the environment are well selected remain of utmost importance to characterize the genotypes under study. It is very likely that in future, quantitative trait loci (QTL) with a narrow validity will be identified to select for site and season specific environmental conditions. This thesis provides information on management options (irrigation regime, weed and N management), which will be used by farmers. Screening for 'water-saving tolerant' genotypes will need to take these into account.

4.2 Temperature stress

In Chapter 3, it was shown how newly developed irrigated rice varieties were influenced by different environments. The irrigated NERICA variety WAS161 was least influenced by G×E interactions, providing farmers with a variety that yields well under a range of conditions. Given the sensitivity of rice to both high and low temperatures at critical stages, which drive a potential yield reduction, both the sowing window and varietal preferences may alter in the coming decades. In Chapter 4, the impact of temperature change on the cropping calendar is shown. Rice genotypes differ in their heat tolerance, with a difference of 3°C between tolerant and susceptible genotypes (Matsui *et al.*, 2001). Genotypes that either have a longer time of anther dehiscence or open their spikelets earlier were less sensitive to spikelet sterility under high temperature stress (Jagadish, 2007; Jagadish *et al.*, 2008; Kobayashi *et al.*, 2011; Prasad *et al.*, 2006). Crossings between *Oryza sativa* and both *O. glaberrima* and *O. officinalis* show potential to generate high-yielding heat tolerant varieties (Ishimaru *et al.*, 2010; Jagadish *et al.*, 2008). Molecular breeding tools have been developed to screen for heat tolerance (Endo *et al.*, 2009). In a genetic analysis for QTLs for heat tolerance, Jagadish *et al.* (2010a) found promising QTLs on five different chromosomes. In the region of chromosome 1 where a QTL for heat tolerance was found, many QTLs for different abiotic stresses have been found, among others: vegetative stage drought tolerance such as leaf rolling and leaf drying (Price *et al.*, 2002), rooting response to drought (Price *et al.*, 2000) and leaf rolling under drought stress (Yue *et al.*, 2008). For cold tolerance, genotypic variation is less. More pollen increases fertility, and as anther length is strongly correlated with the number of pollen, anther length is likely to play a role in cold tolerance (Saito *et al.*, 2004). The risk of cold-induced spikelet sterility will decrease, and as such will become of lesser importance as a breeding objective.

5 Implications for lowland rice management in West-Africa

5.1 Water control

In West-Africa, lowland rice covers 55% of the 5.6 million ha under rice cultivation (Seck *et al.*, 2010). It is cultivated under a variety of hydrological conditions from purely rainfed to completely irrigated (Andriesse and Fresco, 1991). With an increasing degree of water control, farmers' yields increase: water stress due to submergence or drought is less frequent, weeds and nutrients can be better managed and land preparation and harvest can be better planned (Becker and Johnson, 2001; Johnson and Kent, 2002; Touré *et al.*, 2009). Water-control is continuous and dynamic: a small intervention such as bunding of fields in an inland valley improves water-control significantly, but is easily destroyed by seasonal floods. Within irrigated perimeters, head and tail-end fields differ in irrigation and drainage capacities. Maintenance of water control structures, such as water retention dams and canals is vital for their ability to control water. Within one perimeter or valley fields can differ in the degree of water control, and even between wet and dry seasons large differences in water-control can exist. Although methodologies to classify inland valleys have been proposed, it is generally agreed that there is a continuum from uncontrolled rainfed lowlands to fully controlled irrigated perimeters (Andriesse and Fresco, 1991; Van Duivenbooden and Windmeijer, 1995). The research presented in this thesis has been conducted under completely water controlled conditions, but are these results relevant for other lowland rice systems?

5.2 Along the water-control continuum

To give an answer to this question, it is important to sketch the differences between the rice cropping systems. Three typical sites along the water control continuum were characterized during various studies conducted by the Africa Rice Center. In Table 6.2 the main characteristics of the sites are shown. These sites can be classified in terms of water control: full at Boundoum, partial at Sapu and little at Ndour-ndour. The production intensity follows the same trend: high at Boundoum, moderate at Sapu and low atNdour-ndour. These sites are representative for the range of lowland rice cropping systems found in West-Africa (Seck *et al.*, 2010; Windmeijer and Andriesse, 1993).

Rice cultivation differed at the three sites. At Boundoum, yield (four times), fertilizer applied, labour dedicated (five times) and production costs (ten times) were higher than at the Ndour-ndour site. For all abovementioned factors, at Sapu intermediate values were found. Noteworthy is the gender shift: at low-intensive site the largest percentage of woman rice farmers was found, while at the high-intensive site virtually no woman was found. Although rice was important in both Sapu and Ndour-ndour, a number of other crops were cultivated simultaneously in the wet season, typically for rainfed lowland rice systems (Erenstein *et al.*, 2006). At the Boundoum site besides rice, tomato and onion were cultivated, however, not simultaneously. At this site farmers could devote all the available labour to rice cultivation, whereas at the other sites farmers had to divide the available labour among different crops. The results I present emerged from questions raised for rice production systems such as those at Boundoum. In Chapter 2, weed and nitrogen management are discussed in relation to the irrigation regime. In some rainfed lowlands similar water regimes are experienced. Standing water is principally used to combat weeds. It showed that application of a layer of standing water alone will increase yields by between 0.3 – 4.5 t ha^{-1}, irrespective of other weed control strategies. Further, I found that a late application of herbicides (35 days after sowing) did not reduce yields compared with a timely application, irrespective of irrigation regime. The lack of interaction between irrigation regime and nitrogen application showed that under similar conditions (soil type, hydrology) nitrogen fertilizer can be applied under flooded or wet soil conditions.

Table 6.2: Geographical and agronomical characteristics of three sites and their rice cultivation system in Senegal and the Gambia (AfricaRice, 2006b; Sadio, 1989; Van Vugt, 2007).

Characteristic		Site		
		Boundoum Senegal River Delta	Sapu Gambia River	Ndour-ndour Sine-Saloum Delta
Geography				
Climatic zone		Sahel	Soudano-Savannah	Sahelian-Savannah
Latitude (N)		16° 13’	13° 33’	14° 08’
Longitude (W)		16° 01’	14° 54’	16° 06’
Rainfall (mm y^{-1})		200	950	700
Land form		River delta	River flood plain	Wide valley bottom
Cropping system				
Rice Cropping	Dry season	Feb. – Jun.*	Mar. – Jul.	-
	Wet season	Jul. – Nov.	Jul. – Dec*	Jun. – Nov.*
Water control	Dry season	Full	Full	-
	Wet season	Full	Partial	Little
Number of crops cultivated		3	8	10
Rice cultivation				
Rank of rice in among agricultural activities		1st	1st	3rd
Amount of fertilizer applied (kg N ha^{-1})		110	54	0
Labour dedicated to rice (man-day ha^{-1})		170	89	34
Production costs for rice (1 000 FCFA ha^{-1})		309	64	30
Paddy yield (t ha^{-1})		5.4	3.1	0.8
Woman farmers (%)		1	86	76
Size of rice field in ha (st. dev.)		2.4 (2.4)	0.48 (0.15)	0.57 (0.68)

* Principal rice cropping season

However, when fields are not bunded, top-dressing of fertilizer under conditions sych as those in Ndour-ndour, is not very effective, due to dilution (AfricaRice, 2006b).

The results from Chapter 3 show that it is important to breed for varieties that yield well for a range of sowing dates, as the climatic conditions may change significantly with a short delay in sowing date. Under rainfed lowland conditions, sowing date is determined by rainfall rather than by temperature, hence sowing date varies per year. It is therefore even more important to use varieties that perform well at a range of sowing dates in the rainfed lowlands. Our results show that with an increase in temperature, the risk for heat sterility increases. Although the temperatures in West-Africa become less extreme when travelling south from the Sahel, the risk of heat sterility in the whole region will increase. Using climatic data and calibrated genotypic parameters will allow us to perform similar analyses as the one presented in Chapter 5 to quantify these effects at regional scale. The selected results show that for other rice-based cropping systems in West Africa, notably when breeding new varieties or developing agronomic options for lowland farmers, this thesis presents relevant insights.

6 Conclusion

This thesis presents management options to increase the resilience of Sahelian irrigated rice farmers to global change. These farmers have a key role as reliable food producers to increase income and food security. Therefore, it is vital to maintain current irrigated rice production. Possible adaptation strategies for Sahelian rice farmers to decreased availability of irrigation water and to increased temperatures are presented. I show that it is possible to use less irrigation water and to maintain appreciable rice yields, and thus to increase water productivity. The effects of a temperature increase on the growing cycle and spikelet sterility are quantified and show that sowing date and cultivar choice may alter and remain the most important determinants of rice production. This thesis shows that there are options for adaptive management of irrigated rice in the changing environments of the Sahel to sustain production in the 21st century.

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Summary

Given the erratic rainfall that prevails in the Sahel, irrigated agriculture is of major importance. The reliable irrigation water supply provided by large rivers such as the Senegal, Niger and Voltas increases food and income security enormously. In the majority of these areas, double cropping is possible. To harness the potential of Sahelian rice farmers to adapt to the variability of their continuously changing environments, this study experiments with rice management and explores options to sustain production in the 21st century. Detailed experiments and modelling lead to an improved understanding of the system, proposals for improved rice management in the Sahel, and set the agenda for future research. The objective was to develop management options to sustain rice production that can cope with the most prominent changes in climate and availability of irrigation water. A combination of two methods was used: field experiments and crop growth simulation models. The field experiments, performed at research stations of the Africa Rice Centre, Ndiaye and Fanaye, provided realistic and sound data which were used to calibrate existing models. Both research stations were representative for large areas of contrasting irrigated rice ecologies.

We investigated the possibility of saving irrigation water in rice production in a Sahelian environment across different nitrogen rates and weed control treatments (Chapter 2). A series of field experiments was conducted with four irrigation treatments, involving three water saving regimes using alternate wetting and drying (AWD) and a flooded control, and three weed management treatments. This was followed by two experiments with the same four irrigation treatments in combination with three nitrogen (N) application rates, at the same locations. Hence four irrigation regimes were tested over three seasons. Between 480 and 1060 mm of irrigation water was used in the water saving treatments compared with 800 to 1490 mm in the flooded rice treatment. Rice yields ranged from 2.3 to 11.8 t ha^{-1} in the water saving treatments, whereas in the flooded control the yields ranged from 3.7 to 11.7 t ha^{-1}. In the wet season (WS), the treatments in which AWD was applied during part of the season resulted in the highest yields at both sites. In the dry season (DS), the continuously flooded treatment out-yielded other treatments, with the

exception of AWD in Fanaye. At the Ndiaye site, the control of weeds increased yields from on average 2.0 to 7.4 t ha^{-1} in the DS and from 1.4 to 4.9 t ha^{-1} in the WS. No weed control, in combination with AWD during the vegetative stage, reduced yields to below 1.0 t ha^{-1} in both seasons in Ndiaye. However, when weeds were controlled, crop yields obtained with a combination of AWD and flooding were comparable with those obtained in fully flooded plots receiving the same weed management at both sites in the 2005 WS. Internal N efficiency (kg grain [kg plant N]$^{-1}$) was poorer at Ndiaye than at Fanaye suggesting that yields in Ndiaye are constrained by other factors than N. Through these experiments we demonstrated that it is possible to save irrigation water and improve water productivity in rice grown in a Sahelian environment. Maintenance of an AWD irrigation regime requires a high degree of water control. An irrigation regime for rice that starts as conventional (flooded), and then changes to AWD can save water with little or no yield loss, while maintaining low weed pressure and efficient use of N.

To assess the adaptability of rice genotypes to variable environments, we evaluated five irrigated rice genotypes, three new varieties, WAS161, a NERICA, IR32307 and ITA344, and two checks: IR64 and Sahel108, which is the most commonly grown rice variety in the region (Chapter 3). In a field experiment, rice was sown on 15 consecutive dates with one month intervals starting in February 2006. Yield (0-12.2 t ha^{-1}) and crop cycle duration (117-190 days) varied with sowing date, genotype and site. Rice yield was very sensitive to sowing date and the associated temperature regimes. Spikelet sterility due to cold stress (T $<22^{o}C$) was observed when the crops were sown in August (Ndiaye), September (Ndiaye and Fanaye) and October (Ndiaye and Fanaye), and heat stress (T $>35^{o}C$) resulted in spikelet sterility when sowing took place in April (Ndiaye and Fanaye) and May (Fanaye). For all experiments the source and sink balance was quantified, which showed that yield was most limited by sink size when sowing between July and October. Variety Was161 was least affected by genotype × environment interactions, resulting in lower interactive principal component values. An increase in minimum temperature of $3^{o}C$ could decrease spikelet sterility from 100 to 45%.

Crop growth simulation models are tools that can be used to calculate potential yield and perform yield gap analyses under known climatic conditions

(Chapter 4). Experimental data were used to calibrate both the DSSAT4 and ORYZA2000 models, whereas the model ORYZA_S, based on the model RIDEV, was already calibrated previously. According to ORYZA2000, the same cultivars needed 400°Cd more in Fanaye than in Ndiaye to complete their growing cycle. The calibrated ORYZA2000 model simulated phenology of the validation data-set well, but yield was underestimated. After calibrating DSSAT, different sets of genetic coefficients gave similar results. Genetic coefficients that reflected the observed phenology, resulted in substantially lower than observed yields. Simulations using the calibrated genotypic parameters by ORYZA_S and ORYZA2000 resulted in an increase of simulation error at sowing dates later in the year. The sensitivity analysis of the effect of genotypic parameters on simulation of phenology showed that ORYZA2000 was equally sensitive for all parameters, whereas ORYZA_S was particularly sensitive to a decrease in base temperature and an increase in optimum temperature. The performance of both ORYZA2000 and ORYZA_S was better than DSSAT4, and effects of parameter changes could be better quantified. Crop growth simulation is a powerful tool to predict yields, but local calibration at the approximate sowing date is needed to obtain useful results.

In the Sahel, temperature increases between 1.8 and 4.7°C are predicted by 2080 (Chapter 5). At certain growth stages, rice is sensitive to low (<22°C) and high (>35°C) temperature stress. An adapted version of the simulation model ORYZA2000 was used to simulate effects of temperature increase on sterility and crop cycle duration. The calibrated model was validated with an independent data-set. Minimal and maximal predicted temperature increases were compared with the current situation. The crop cycle of variety IR64, sown on every day of the year, was simulated. It resulted in a decrease of the cycle by 10-30 days, depending on sowing date. For the minimum predicted temperature increase in Ndiaye, heat induced sterility became more important than the cold induced sterility with a peak of 69% sterility for rice sown in August. In Fanaye, heat-sterility was always above 56%, except for rice sown between September and November. Under the maximum predicted temperature increase, heat-sterility increased in Ndiaye: all sowing dates resulted in more than 57% sterile spikelets, except for rice sown in October. In Fanaye a similar pattern was observed: rice production was only viable when

sown from September to December (with a maximum sterility of 40%); sown in the other 8 months of the year sterility is >90%. Our study suggests that with projected temperature changes, timing of sowing and its consequences of the risk for crop loss due to sterility will remain the major determinant of rice yield along the Senegal River. We show that there is an urgent need for heat tolerant rice varieties. Without adaptation, sowing windows will change. In the worst case scenario we anticipate a change from a double to a single crop.

The same model was used to investigate the combined effects of temperature increase and reduction of irrigation water use (Chapter 6). The simulation results showed that when the temperature increases, the small effects of early drought stress are aggravated and biomass accumulation will slow down. Under temperature increase, grain yield was largely affected by heat induced sterility. As a result of water-stress, flowering of rice was delayed, and the growth cycle increased. A temperature increase in combination with water-saving irrigation regimes will increase the risk for crop loss due to water stress.

This thesis provides information on management options (irrigation regime, weed and N management), which will be used by farmers. Screening for 'water-saving tolerant' genotypes will need to take these options into account. The risk of cold-induced spikelet sterility will decrease, and as such will become of lesser importance as a breeding objective; however, heat-tolerance will become of major importance and as such should be a principal breeding target. For other rice-based cropping systems in West Africa, notably when breeding new varieties or developing agronomic options for lowland farmers, this thesis presents relevant insights. I conclude that good options do exist for adaptive management of irrigated rice in the changing environments of the Sahel to sustain production in the 21st century, if action is taken immediately.

Résumé

Compte tenu de l'irrégularité des précipitations dans le Sahel, l'agriculture irriguée revêt une grande importance. L'irrigation fournie par les grands fleuves tels que le Sénégal, le Niger et Volta augmente significativement la sécurité alimentaire et le revenu agricole des populations. Dans la plupart de cette zone la double culture est possible. Cette étude s'intéresse aux systèmes rizicoles irrigués et explore les options de gestion pour garantir une production durable au 21eme siècle. Les approches couplées d'expérimentation et de modélisation ont conduit à une meilleure compréhension du système, à des propositions de gestion adaptées aux conditions sahéliennes, et à des recommandations en termes de perspectives de recherche. L'objectif était de développer des options de gestion pour soutenir la production de riz qui doit faire face à une forte variabilité du climat et de la disponibilité en eau pour l'irrigation. Deux approches couplées ont été mobilisées lors de ces travaux : une approche par expérimentations en plein champ et une approche par simulations au travers de l'utilisation de modèles de cultures. Les expérimentations en plein champ, effectuées dans les stations de recherche de Ndiaye et de Fanaye du Centre du riz en Afrique, représentatives des zones de production agricoles sahélienne, a fourni des données pertinentes et réalistes qui ont été utilisées pour calibrer les modèles de culture existants.

Nous avons étudié les possibilités d'économie d'irrigation pour la production rizicole en conditions sahéliennes sous différents régimes azotés et pour différents niveaux de contrôle des adventices (chapitre 2). Une série d'expérimentation a été conduite comprenant quatre traitements d'irrigation, incluant trois traitements d'économie d'eau construits par alternance d'inondations et de sécheresse (AIS) et un témoin inondé en permanence, combinés à trois niveaux de contrôle des adventices. Une série d'expérimentation a été conduite avec les mêmes traitements d'irrigation combinés à trois traitements azotés. Enfin quatre traitements d'irrigation ont été expérimentés pendant 3 années climatiques. Entre 480 et 1060 mm d'eau d'irrigation ont été utilisés pour les traitements d'économie d'eau, contre 800 à 1490 mm pour le témoin inondé. Les rendements on varié entre 2,3 et 11,8 t ha^{-1} pour les traitements d'économie d'eau et entre 3,7 et 11,7 t ha^{-1} pour le témoin inondés. Pendant la saison humide (SH), le traitement d'économie d'eau soumis à une alternance d'inondation/sécheresse pendant une partie du cycle de culture a conduit au plus haut rendement sur les deux sites. Pendant la saison sèche (SS), le témoin inondé a conduit au meilleur rendement sur le site de Ndiaye mais pas sur le site de Fanaye. À Ndiaye, le contrôle des mauvaises herbes a augmenté les rendements de 2,0 à 7,4 t ha^{-1} en moyenne pendant la SS et de 1,4 à 4,9 t ha^{-1} pendant la SH. L'absence de contrôle des mauvaises herbes, en combinaison avec l'alternance d'inondation et de sec pendant la phase végétative, a réduit les rendements à moins de 1,0 t ha^{-1} pendant les deux saisons. En 2005, lorsque les adventices ont été contrôlés, les rendements obtenus avec un traitement AIS ont été comparables avec les rendements obtenus avec le témoin inondé sur les deux sites. L'efficience de l'azote pour la production de grain (kg grain [kg N par plante] $^{-1}$) a été plus faible à Ndiaye qu'à Fanaye suggérant que les rendements à Ndiaye ont été limités par d'autres facteurs que l'azote. Au travers de cette expérimentation, nous avons démontré qu'il était possible d'économiser de l'eau et d'améliorer l'efficience de l'eau dans les systèmes rizicoles sahéliens. Le maintien d'une AIS nécessite un haut degré de maîtrise de l'eau. Une conduite inondée suivie d'une AIS peut permettre d'économiser de l'eau sans pertes de rendement tout en limitant la pression des adventices et en garantissant une efficacité de l'azote élevée.

Afin d'évaluer l'adaptabilité des génotypes de riz à des environnements variables, nous avons évalué cinq génotypes de riz irrigué : trois nouvelles variétés : WAS161, un NERICA ; IR32307 et ITA344, et deux témoins: IR64 et Sahel108, qui est la variété de riz la plus cultivée dans le région (chapitre 3). Lors d'une expérimentation, le riz a été semé à 15 dates consécutives à intervalles d'un mois à compter de février 2006. Le rendement (0 à 12,2 t ha^{-1}) et la durée du cycle des cultures (de 117 à 190 jours) varient selon la date de semis, le génotype et le site. Le rendement du riz a été très sensible à la date de semis et les régimes de température associés. Une stérilité des épillets a été observée à cause du stress thermique lié aux faibles températures ($T < 22\,^{o}C$) lorsque les cultures ont été semées au mois d'août (Ndiaye), septembre (Ndiaye et Fanaye) et octobre (Ndiaye et Fanaye). Une stérilité des épillets a été observée à cause du stress thermique lié aux fortes températures ($T > 35\,^{o}C$) lorsque les cultures ont été semées en avril (Ndiaye et Fanaye) et mai (Fanaye).

L'équilibre source/puit a été quantifié pour chaque expérimentation. La taille des puits a été plus limitant pour le rendement pour les semis de juillet et octobre. WAS161 a été la variété la moins affectée par les interactions génotype × environnement, entraînant une baisse des valeurs interactive en composantes principales. Une augmentation de la température minimale de 3°C pourrait réduire la stérilité des épillets de 100 à 45%.

Les modèles de cultures sont des outils qui peuvent être utilisés pour calculer le potentiel de rendement lié aux conditions climatiques et analyser les écarts avec les rendements obtenus en plein champs (chapitre 4). Les données expérimentales ont été utilisées pour calibrer les modèles ORYZA2000 et DSSAT4. Le modèle ORYZA_S, basé sur le modèle RIDEV, avait déjà été calibré précédemment. D'après ORYZA2000, 400 degrés jours supplémentaires sont nécessaires à Fanaye pour accomplir le cycle de culture. Le modèle calibré ORYZA2000 simule avec précision la phénologie de la culture mais sous estime le rendement. Après la calibration du modèle DSSAT4, l'utilisation de jeu de paramètres génétiques conduit à des résultats similaires. Les paramètres génétiques reflétant la phénologie conduisent à des rendements légèrement sous-estimés. Les erreurs de simulation d'ORYZA_S et d'ORYZA2000 augmente avec les semis tardifs. L'analyse de sensibilité de l'effet des paramètres génotypiques sur la simulation de la phénologie a montré qu'ORYZA2000 était également sensible à tous les paramètres, et que ORYZA_S était plus sensible à une baisse de la température de base et à une augmentation de la température optimale. Les performances d'ORYZA2000 et ORYZA_S étaient meilleures que DSSAT4. Les effets des changements de paramètres pourraient être mieux quantifiées. Les modèles de culture sont des outils puissants pour prédire les rendements. Toutefois leur utilisation nécessite une phase de calibration afin d'obtenir des résultats pertinents.

Une augmentation des températures moyennes sahéliennes de 1.8 à 4.7 °C est prévue d'ici 2080 (chapitre 5). A certains stades de croissance, le riz est sensible aux faibles températures (<22 °C) ainsi qu'au fortes températures (> 35 °C). Une version calibrée du modèle de simulation ORYZA2000 a été utilisée pour simuler l'effet de l'augmentation de la température sur la stérilité des épis et sur la durée du cycle des cultures. Le modèle calibré a été validé par un ensemble de données indépendantes. Les températures minimales et

maximales prévues ont été comparés à la situation actuelle. Le cycle de culture de la variété IR64, semées sur tous les jours de l'année, a été simulé. Les simulations indiquent une diminution de la durée du cycle de 10-30 jours en fonction de la date de semis. Avec le scénario d'augmentation minimale des températures à Ndiaye (+1.8°C), la stérilité liée aux fortes températures devient plus importante que la stérilité liée aux faibles températures et atteint jusqu'à 69% pour les semis du mois d'août. A Fanaye, à l'exception des semis du mois de septembre et novembre, la stérilité liée aux fortes températures a toujours été supérieure à 56%. Avec le scénario d'augmentation maximale des températures (+4.7 °C), la stérilité augmente à Ndiaye : à l'exception des semis d'octobre, toutes les dates de semis conduisent à une stérilité supérieure à 57%. La même évolution a été simulée à Fanaye. Il en résulte une période de production fortement réduite : la stérilité est inférieure à 40% pour les semis effectués entre septembre et octobre alors qu'elle est supérieure à 90% pour les semis effectués les huit mois restants. Notre étude suggère que compte tenu des projections de changements de température, la période de semis et les conséquences associées en terme de stérilité des épillets sera le principal facteur déterminant les niveaux de rendements du riz le long du fleuve Sénégal. Nous montrons qu'il existe un besoin urgent pour des variétés de riz tolérant à la chaleur. Sans adaptation génétique, les fenêtres de semis vont fortement changer. Dans le pire des scénarios, la double culture annuelle ne sera plus possible et conduira à la réalisation d'un seul cycle de culture au lieu de deux actuellement.

Le même modèle a été utilisé pour étudier les effets combinés de la hausse des températures et la réduction de la consommation d'eau d'irrigation (chapitre 6). Les résultats des simulations ont montré que lorsque la température augmente, l'effet d'un stress hydrique précoce est aggravé et l'accumulation de la biomasse est ralentie. Sous l'effet de l'augmentation de la température, le rendement en grain a été largement affecté par la stérilité induite par les fortes températures. À la suite de stress hydrique, la floraison du riz a été retardée et la durée totale du cycle augmentée. Une augmentation de température combinée aux régimes d'irrigation économes augmentent les risques de pertes de récoltes dues au stress hydrique.

Cette thèse fournit des informations sur les options de gestion techniques de la production rizicole irriguée (régime d'irrigation, gestion de l'azote, contrôle des adventices), qui seront utilisées par les agriculteurs. Le risque de stérilité des épillets induite par le froid diminuera. Un screening pour obtenir des variétés tolérantes aux fortes températures devra être entrepris pour permettre de prendre en compte ces options de gestion. La recherche de variétés tolérances aux fortes températures devra devenir un enjeu principal pour les sélectionneurs. Cette thèse propose des pistes pour l'adaptation aux autres systèmes rizicoles ouest africains. Je conclus que des options existent pour une gestion adaptée et durable du riz irrigué dans les environnements sahéliens au 21eme siècle, à condition que des mesures soient prises immédiatement.

Samenvatting

Door de onregelmatige regenval in de Sahel, is geïrrigeerde landbouw daar van groot belang. De betrouwbare wateraanvoer voor irrigatie vanuit grote rivieren zoals de Senegal, Niger en Volta's vergroot de voedsel- en inkomenszekerheid aanzienlijk. In deze gebieden is het mogelijk om twee keer per jaar rijst te verbouwen. Om de aanpassingsmogelijkheden van rijsttelers in de Sahel aan de continue veranderende omgeving te vergroten, is er in deze studie onderzoek gedaan naar teeltmaatregelen om de rijstproductie in de 21ste eeuw te waarborgen. Gedetailleerde experimenten hebben tot een vergroot inzicht in het productiesysteem geleid, tot voorstellen om de rijstteelt te verbeteren en tot het agenderen van toekomstige onderzoeksthema's. Het doel was om teeltmaatregelen te ontwikkelen die er voor zorgen dat het productieniveau van rijst gehandhaaft blijft, ondanks grote veranderingen van het klimaat en de beschikbaarheid van water. Er is gebruik gemaakt van een combinatie van twee methoden: veldexperimenten en gewasgroeisimulaties. De veldexperimenten, die plaats vonden op de onderzoeksstations van het Africa Rice Center, Ndiaye en Fanaye in Senegal, zorgden voor realistische en betrouwbare data, die werden gebruikt om bestaande simulatiemodellen te calibreren. Beide onderzoeksstations zijn representatief voor grote gebieden met contrasterende omgevingen voor rijstteelt.

Wij hebben onderzoek gedaan naar de mogelijkheden om irrigatiewater te besparen in rijstproductie in de Sahel, in combinatie met verschillende onkruidbestrijdingsbehandelingen en stikstoftrappen (Hoofdstuk 2). Een serie veldexperimenten is uitgevoerd met vier irrigatieregimes, waarvan er drie waterbesparend waren met afwisselend bevloeide en niet-bevloeide omstandigheden (BNB) en één controlebehandeling met constante bevloeiing. Deze werden uitgevoerd in combinatie met behandelingen van onkruidbestrijding. Daaropvolgend werden op dezelfde plaatsen twee experimenten uitgevoerd met dezelfde vier irrigatieregimes in combinatie met drie stikstoftrappen. Op deze manier werden de irrigatieregimes over drie verschillende seizoenen getest. In de waterbesparende regimes werd tussen de 480 en 1060 mm irrigatiewater gebruikt, terwijl in de bevloeide behandeling tussen de 800 en 1490 mm irrigatiewater werd gebruikt.

De rijstopbrengsten liepen uiteen van 2.3 tot 11.8 t ha^{-1} in de waterbesparende regimes en van 3.7 tot 11.8 t ha^{-1} in de bevloeide controlebehandeling. In het natte seizoen (NS), hadden de behandelingen waarin BNB in een gedeelte van het seizoen werd toegepast, de hoogste opbrengsten op beide plaatsen. In het droge seizoen (DS) presteerde de bevloeide controlebehandeling het best, met uitzondering van de behandeling waarin BNB werd toegepast gedurende het hele seizoen in Fanaye. In Ndiaye verhoogde onkruidbeheersing de opbrengst van 2.0 tot 7.4 t ha^{-1} in het DS en van 1.4 tot 4.9 t ha^{-1} in het NS. Geen onkruidbeheersing, in combinatie met BNB in het vegetatieve groeistadium, reduceerde de opbrengst tot onder 1.0 t ha^{-1} in beide seizoenen in Ndiaye. Niettemin waren de opbrengsten op beide plaatsen in het NS van 2005 in de behandelingen waar onkruid werd beheerst, gelijkwaardig bij de verschillende irrigatieregimes. De interne stikstofefficiëntie (kg korrelopbrengst [kg plant N] $^{-1}$) was kleiner in Ndiaye dan in Fanaye, wat suggereert dat de opbrengst door andere factoren dan stikstof werd gelimiteerd. Door deze experimenten hebben we kunnen aantonen dat het mogelijk is om irrigatiewater te besparen en de waterproductiviteit te verhogen in de Sahel. Het volhouden van een waterbesparend irrigatieregime vergt wel een hoge graad van controle over het water. Een irrigatieregime dat begint als bevloeid, met een laag water op het veld, en halverwege verandert naar waterbesparend kan irrigatiewater besparen met minimale oogstverliezen, terwijl het onkruid beheerst wordt en stikstof efficiënt wordt gebruikt.

Om de geschiktheid van rijst voor het veranderlijke weer van de Sahel te beoordelen, hebben we vijf rassen getest, drie nieuwe rassen: WAS161 (een NERICA), IR32307 en ITA344, en twee standaardrassen: IR64 en Sahel108, het meest populaire rijstras in de regio (Hoofstuk 3). In een veldexperiment werden deze rassen op 15 opeenvolgende maanden gezaaid, beginnend in februari 2006. De opbrengst (0-12.2 t ha^{-1}) en groeiduur (117-190 dagen) veranderden onder invloed van de zaaidatum, ras en plaats. De opbrengst was erg gevoelig voor de zaaidatum en de daarmee samenhangende temperatuur-regimes. Steriliteit van de bloemen in de aar, veroorzaakt door lage temperaturen ($<22^{o}C$), werd waargenomen in de proeven die in augustus (Ndiaye), september (Ndiaye en Fanaye) en oktober (Ndiaye en Fanaye) werden gezaaid. Steriliteit door hittestress ($>35^{o}C$) werd waargenomen in proeven gezaaid in april (Ndiaye en Fanaye) en mei (Fanaye). Voor alle proeven is de verhouding 'source sterkte' en 'sink sterkte' bepaald, hieruit kon worden geconcludeerd dat de opbrengst van rijst die tussen juli en oktober was gezaaid, het meest gelimiteerd werd door de 'sink sterkte'. Het ras WAS161 werd het minst door de ras × omgevingsinteracties beïnvloed, wat resulteerde in lagere waarden voor de 'interactive principal component'. Een verhoging van de minimum temperatuur van 3°C zou de steriliteit van 100 tot 45% kunnen verlagen.

Gewasgroeisimulatiemodellen zijn gereedschappen, die kunnen worden gebruikt om potentiële opbrengsten te berekenen en om een analyse van de kloof tussen potentiële en aktuele opbrengsten te maken (Hoofdstuk 4). Experimentele data zijn gebruikt om de modellen DSSAT4 en ORYZA2000 te calibreren; het model ORYZA_S, gebaseerd op het model RIDEV, was in een eerdere studie al gecalibreerd. Volgens ORYZA2000 hadden dezelfde rassen 400 graaddagen meer nodig in Fanaye dan in Ndiaye voor hun volledige groeicyclus. Het gecalibreerde model ORYZA2000 simuleerde de fenologie van de validatie data-set goed, maar de opbrengst werd onderschat. Nadat DSSAT4 was gecalibreerd, gaven verschillende combinaties van genotypische parameters dezelfde resultaten. Genetische coëfficiënten die de geobserveerde fenologie goed weergaven resulteerden in gesimuleerde opbrengsten die lager waren dan de waargenomen opbrengsten. Bij het gebruik van de gecalibreerde modellen ORYZA2000 en ORYZA_S nam de simulatiefout toe met de zaaidata later in het jaar. De prestatie van ORYZA2000 en ORYZA_S was beter dan die van DSSAT4. Gewasgroeisimulatiemodellen vormen een krachtig gereedschap om opbrengsten te voorspellen, maar locale calibratie blijft nodig om bruikbare resultaten te genereren in toekomstige situaties.

In de Sahel worden temperatuursverhogingen van 1.8 tot 4.7°C voorspeld voor het jaar 2080 (Hoofdstuk 5). Tijdens bepaalde groeistadia is rijst gevoelig voor stress door lage (<22°C) of hoge (>35°C) temperaturen. Een door ons aangepaste versie van het model ORYZA2000 is gebruikt om de effecten van temperatuursstijging op de groeiduur en steriliteit van de bloemen in de aar te simuleren. Het gecalibreerde model werd gevalideerd met een onafhankelijke data-set. De modelresultaten bij de minimale en de maximale temperatuurstijging werden vergeleken met de huidige situatie. De groeiduur van het ras IR64, gezaaid op elke dag van het jaar, werd gesimuleerd.

De resultaten lieten een afname zien van de gesimuleerde groeiduur met 10-30 dagen, afhankelijk van de zaaidatum. Op dit moment is de kans op steriliteit een groot probleem. Voor de minimale temperatuurstijging in Ndiaye, werd de steriliteit door hittestress belangrijker dan die veroorzaakt door koudestress, met een maximum van 69% voor rijst gezaaid in augustus. In Fanaye, leidde hittestress altijd tot een steriliteit van meer dan 56%, behalve voor rijst die tussen september en november was gezaaid. Bij de simulatie van de maximale temperatuurstijging steeg de aan hittestress gerelateerde steriliteit in Ndiaye: voor alle zaaidata werd meer dan 57% steriliteit gesimuleerd, behalve als de rijst in oktober werd gezaaid. Een vergelijkbaar patroon werd in Fanaye waargenomen: rijstproductie was alleen mogelijk wanneer er tussen september en december werd gezaaid (met een maximale steriliteit van 40%); in de andere acht maanden werd meer dan 90% steriliteit gesimuleerd. Onze studie suggereert dat door de voorspelde temperatuursstijgingen, de zaaitijd en dientengevolge het risco op steriliteit, de meest bepalende factor voor de rijstopbrengst langs de Senegal rivier zal blijven. Wij laten zien, dat er urgente behoefte is aan hitte-tolerante rassen. Zonder aanpassingen zal het zaaitijdstip moeten veranderen om steriliteit tot een minimum te beperken. In het slechtste geval is het aan te bevelen om van dubbele teelt naar enkele teelt over te gaan.

Het aangepaste ORYZA2000 model is ook gebruikt voor een onderzoek naar het gecombineerde effect van waterbesparende irrigatieregimes en temperatuurstijging (Hoofdstuk 6). De resultaten van de simulaties lieten zien dat als de temperatuur zou stijgen, kleine effecten van vroege droogtestress worden verergerd en dat aangroei van biomassa wordt vertraagd. Bij een stijging van de temperatuur werd de korrelopbrengst beperkt door hitte gerelateerde steriliteit. Door vochttekort werd de bloei vertraagd en de groeiduur verlengd. Een stijging van de temperatuur in combinatie met waterbesparende irrigatieregimes zal het risco op opbrengstderving door vochttekort vergroten.

Dit proefschrift verschaft informatie over verschillende teeltopties (irrigatieregime, onkruid- en stikstofbeheer), die door telers in praktijk kunnen worden gebracht. In de veredeling zal tijdens de selectie van genotypes voor tolerantie tegen waterbesparende irrigatieregimes met deze opties rekening gehouden moeten worden. Het risco van steriliteit door koudestress zal verminderen en dus van minder belang worden als selectiedoel, maar hittestress zal toenemen en dus binnen de veredeling een zeer belangrijk selectiedoel vormen. Voor andere rijstteeltsystemen in West Afrika, zeker voor de veredeling en ontwikkeling van teeltmaatregelen, zijn in dit proefschrift relevante inzichten te vinden. Ik concludeer dat er goede opties zijn voor aangepaste teelt van geïrrigeerde rijst in de veranderlijke omgeving van de Sahel waarmee de productie in de 21ste eeuw kan worden gehandhaaft, mits er nu actie wordt ondernomen.

Curriculum vitae

Michiel Erik de Vries was born on July 22, 1978 in Groningen, The Netherlands. There, he attended the Preadinius Gymnasium, from which he graduated in 1997. In the summers between 1995 and 2002, he gained practical farm experience at a cereal and potato breeding station. In 1997-1998, he spent 11 months working and travelling in Australia and Indonesia. From 1998 to 2004 Michiel studied at Wageningen University. His first encounters with rice were at a six-month internship at IRRI, the Philippines in 2001. There he witnessed the importance of water-saving in rice, resulting in a minor thesis on modelling aerobic rice. For his Master thesis he undertook on-farm research on fertilizer efficiency in maize at different farms in the Kakamega area in Kenya. After his graduation from Wageningen, he was offered a position as irrigated rice agronomist at the Sahel station of the Africa Rice Center in St Louis, Senegal. Between 2004 and 2007, he performed the experiments that resulted in this thesis. Besides the experimental work, proposal writing, interactions with research and development partners and running a research team were among his duties. In 2007 he returned to the Plant Production Systems group at Wageningen University to continue writing the thesis and to assist in teaching. Early 2009 he joined Joordens Zaden, part of the French seed company RAGT, as a cruciferous green manures breeder.

Acknowledgements

Between 2004 and 2011, many people have helped me to bring this project across the finish line. Here, I'll try to acknowledge all of them. Ken, from thesis supervisor in 2003 to promoter in 2011, you've supervised me for most of the past decade. For me, it has been a rich and learning journey. Your enthusiasm to always find the positive side has been of great motivation. Your moral support to back me and other students has been a great source of inspiration. But, most importantly, it has been fun! Peter, our supervision-relation goes back to 2001, when I started with an internship at IRRI, and continued with a minor thesis in 2002. After ten years of rice, water and modeling, systems analysis has become my mode of thinking from which I benefit every day. Your attitude of questioning numbers, methods and never taking information for granted, has taught me how to think as a genuine researcher. Your trip with Ken to Senegal was one of my personal highlights. Your hawk's eye for my sloppiness has greatly improved this thesis.

The experimental work of this thesis was carried out at the Sahel Station of Africa Rice, there, a number of people were of great help. Vincent Bado, as head of the station and fellow coffee-lover, I've enjoyed our conversations that started with rice science but ended anywhere. Thanks a lot for motivating me to continue, and for supporting this project. The management and organizational skills that I learnt from you are benefiting me up to now. As fellow APO, and then co-supervisor, Jonne Rodenburg, you helped me to introduce me to the skill of scientific writing. Your critical review of my experiments and introduction into basic steps of science has without doubt been of critical value during my time at Africa Rice. J'aimerais remercier tout le personnel de la station Sahel: Abdoulaye Sow, ton expérience, diligence et conseils grand-fraternels ont amélioré la qualité de cette thèse et ma vie énormément, Djibi Sagna et Ana qui ont fait les analyses au labo, Mandiagne Daigne et Maïmouna Ndour qui étaient des bons compagnons aux plusieurs missions, Soulaymane Gaye qui m'a introduit dans le monde de sélection du riz, Mandieye Top pour gérer l'équipe aux champs, Ngouda pour la gestion de l'eau et les autres travailleurs braves aux champs, Abdoulaye Gueye, Ndiémé Ba, Gnagna Lo, Ahram Gaye, Babacar Wade, Ndiack Mall, Djibi Mbodj, Diame, El hadji Gueye, Sérigne Modou. L'équipe de la station de Fanaye: Malick Sarr avec sa rigueur de travail et discipline exemplaire, Bocar Diack, Babacar Sall. Votre attitude général de coopération, disponibilité et hospitalité vis-à-vis moi, ma femme, et toute ma famille étaient réconfortant, donc de fond de cœur de nous tous : Dieuredieuf waii !

Malick Ndiaye, chef d'Agritech et compagnon dans les rizières, ton enthousiasme était contagieux. Pendant ce temps à St Louis il y a eu plusieurs autres personnes qui méritent à être remercié : Penda Ndiaye et Fara Ngom et leurs familles pour assister à la gestion de la maison, Wim, Jos en Aby, Arie, Mariama en de boys, Patrice et Julie, Saliou Mbodj et sa famille à Kaolack : je n'ai jamais vu un plus grand exemple de l'hospitalité Sénégalais. Salif Diack et la casquette policier. In Dakar waren deze personen van groot belang op cruciale momenten: Wim Mulier voor het onderdak, Annemarie voor het eerste thuis van Stan en Lotte voor het 'thuis' in Dakar: altijd een groot plezier om langs te komen.

At Africa Rice, many colleagues have helped me to shape the ideas for this thesis and/or have made me feel at home: Mohamed Kebbeh, Karim Traoré, Baboucarr Manneh, Semon Mande, Moussa Sie, Sitapha Diatta, Lance Narteh, Raman & Savitri, Marie-Noëlle Ndjondjop, Koichi Futakuchi, Yacouba Séré, Paul van Mele, Daniel Tia Dro among others. Paul Kiepe thanks for the motivation, advice and sharing the same wavelength. Marcel en Esther thanks for facilitating our honeymoon and the good times in Cotonou. In Senegal three students came, and helped me a lot: Solenn Guillaume, Daniel van Vugt and Christopher Preciado, without whom I wouldn't have been able to conduct on-farm trials. Solenn, also thanks for the excellent French translation of the summary. In Wageningen, Remi Duflot analysed some experimental data. The field and office staffs of the SAED and ISRA-St Louis were very helpful to cooperate at farmers' fields

I owe much to my co-authors: Pepijn, who created an extremely elegant model that provided the necessary insights to write to final chapter. Naomie, c'est très rare de trouver quelqu'une avec du courage comme toi, je suis très heureux et honoré qu'on a parcouru cette route ensemble, de la boue des rizières Sénégalais jusqu'au Wageningen. Merci pour ton compagnie. Statistical assistance for chapter 2 was provided by Romain Glele Kakaï and for chapter 3 by Jac Thissen of Biometris.

In Wageningen, I spent 18 months at the Haarweg, where I enjoyed the coffee and lunch breaks with its inhabitants. I thank my office mates, Myriam, Sander de Vries and Maja for their nice company and support. Lammert, thanks for assisting with the first article. Xinyou, thank you for sharing your enormous knowledge on rice phenology and modelling. It was stimulating to work among you and share good times at and after work: Sander van D., Sander J., Lenny, Pytrik, Glaciela, Bert R., Bert J. Eelco, Marcel, Joost, Marjolein, Pablo, Tjeerd-jan, Gon, Jan, Jochem, Rik, Kenneth, Peter E., Senthil, Peter G., Frank, Nico, Mark, Gerrie, Martin, Herman and Mariana, Erwin and family.

Recently, I continued my career at Joordens Zaden (RAGT), where I would like to thank Paul Joordens for his confidence in me, despite my inexperience and my present colleagues for putting up with me for the last stretch.

Furthermore, I want to thank my family, Pap, Mam and Mark for their encouragements and support. A special thanks to Wiljo, for giving me those extra days that were very much needed to reach the end.

At last there's the one person who's most important in my life, which was celebrated at our marriage in St Louis. Sara, thank you for pushing me forward and pulling me backwards when needed: you always kept me in balance. Thank you for coming to Senegal, and for sacrificing your time. You were the best companion one could wish on this long, winding, but finally ending journey.

Stan Yero en Tobias Nico, dankzij jullie kon ik dit volbrengen: papa is klaar, voetballen maar!

List of publications

De Vries, M. E., P. A. J. van Oort & P. A. Leffelaar. 2011. Exploring impacts of temperature increase in Sahelian rice-based cropping systems. *Submitted.*

Van Oort, P. A. J., Tinayi Zhang, M. E. de Vries, A. B. Heinemann & H. Meinke. 2011. Correlation between phenology error and temperature in rice (*Oryza sativa* L.). Agricultural and Forest Meteorology doi:10.1016/j.agrformet.2011.06.012.

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PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)

- Constraints and opportunities for rice production in West-Africa

Writing of project proposal (4.5 ECTS)

- Rice in Sahel and Savannah zones of West-Africa: how to increase production efficiency at different spatial and temporal scales?

Post-graduate courses (7 ECTS)

- Decision support systems for agrotechnology transfer; ICRISAT and AfNet (2005)
- The art of modeling; PE&RC (2008)
- Rhizosphere signalling; EPS (2010)

Laboratory training and working visits (0.5 ECTS)

- 1st RCM on "Selection and evaluation of food (cereal and legume) crop genotypes tolerant to low nitrogen and phosphorus soils through the use of isotopic and nuclear-related techniques"; IAEA (2006)

Invited review of (unpublished) journal manuscripts (3 ECTS)

- African Journal of Agricultural Research: analysis of maize water requirements in diverse agroecological zones (2008)
- African Journal of Agricultural Research: influence of legumes on N fertilizer for succeeding sorghum (2008)
- Agricultural Water Management: water supplied by sprinkler irrigation system for upland rice seed production (2011)

Competence strengthening / skills courses (1.6 ECTS)

- Scientific writing; Language Centre (2008)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)

- PE&RC Weekend (2007)
- PE&RC Day (2007)

Discussion groups / local seminars / other scientific meetings (10.5 ECTS)

- WARDA 's annual research program days; with presentation; Cotonou, Benin (2004)
- WARDA 's annual research days; with presentation; Cotonou, Benin (2005)
- WARDA 's annual research days; Cotonou, Benin (2006)
- Lowland development trajectories Project Workshop WARDA-GTZ; with presentation; Cotonou, Benin (2006)
- Invited presentation at Hohenheim University, chair group of Prof. Folkard Asch (2009)

International symposia, workshops and conferences (5.7 ECTS)

- Biological Systems Simulation Group meeting; Phoenix, USA (2005)
- Frontis workshop Gene-plant-crop interactions; with poster; Wageningen, the Netherlands (2006)
- Africa Rice Conference; With plenary presentation; Dar-es-Salaam, Tanzania (2006)

Lecturing / supervision of practicals / tutorials; 12 days (3.6 ECTS)

- Models in forest and nature conservation (2008)

Supervision of 3 MSc students; 70 days

- Water saving irrigation in rice production in the Senegal River Valley and Delta; Solenne Guillaume
- Assessing the adoption potential of water saving techniques in irrigated rice schemes in the Senegal River Valley; Daniel van Vugt
- Rice adaptation to alternating wetting and drying regimes in West African conditions; Remi Duflot

Funding

Research described in this thesis was financially supported by the following organisations, their contributions are gratefully acknowledged:

Ministry of foreign affairs of the kingdom of the Netherlands, directorate general of international cooperation (DGIS). From 2004 to 2007, I benefited from an APO appointment, providing financial assistance to carry out research at the Sahel Station of Africa Rice.

Between 2004 and 2007, additional funding for essential experimental work was provided by the Africa Rice Center, member of the CGIAR group.

Cover design: Edward Houting, Groningen

Cover photography: Michiel de Vries (front and back centre) & Bart de Vries (back left and right)