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Feet in the water and hands on the keyboard: A critical retrospective of crop modelling at AfricaRice

P.A.J. van Oort[a],*, M. Dingkuhn[b]

[a] Wageningen Plant Research, Agrosystems Research, P.O. Box 16, 6700 AA, Wageningen, the Netherlands
[b] CIRAD, UMR AGAP, F-34398, Montpellier, France

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ABSTRACT

Rice is cultivated throughout Africa in a vast array of environments. Crop growth modelling at AfricaRice seeks to develop an understanding of genotype, management and environment interactions to inform research and development. This paper reviews progress made over thirty years of modelling, as well as the knowledge gaps remaining. Major advances were made in modelling phenology and heat- and cold-induced sterility. This crucially took into account the crop-generated microclimate *via* transpirational cooling in irrigated rice. On this basis, the RIDEV model and its successors provided effective support to applied breeding, genetics, agronomy and cropping systems research. As a major learning, rice very effectively avoids heat stress if it can transpire water abundantly. For water-limited systems, ORYZA2000 based yield gap, climate-change impact and drought mapping projects gave direction to AfricaRice's applied research agenda. But large gaps remain in modelling capabilities and underlying knowledge, particularly regarding biotic stresses, inland valley hydrology, and rice-based cropping sequences, e.g. including vegetable crops. In terms of understanding the physiology, more research is needed to accurately model spikelet number, thermal acclimation, photosynthesis response to extreme temperatures, and variation in rooting depth. This will require enhanced collaboration between AfricaRice and advanced research centers to resolve the scientific and technical bottlenecks in crop modelling.

1. Introduction

1.1. *The need for crop modelling in support for rice crop research for Africa*

Crop modelling is not an end in itself. In the context of applied research for the development of the rice sector in Africa, pertinent agricultural technologies and knowledge must be generated and transferred to stakeholders involved in rice production, extension, research or policy. Modelling thereby formalizes important processes and factor interactions to raise them to the level of genericity needed to answer "what-if" and "why/how" questions within the relevant extrapolation domain – which can be the plant, plot or possibly a whole region such as the Sahel.

A small regional commodity research center such as Africa Rice Centre (previously WARDA/ADRAO, hereafter called AfricaRice) inevitably faces the problem of having to serve a vast mandate with very limited human and technical resources, even if extended through national and international. Here, crop modelling can assist in (i) setting research priorities according to the prevalence of specific constraints and potential paths to overcome them; (ii) understanding crop genotype, environment and management interactions; (iii) targeting technologies from their development or testing sites to other places, including scenarios of environment or system change; and (iv) predicting the potential beneficial impact of the technologies' adoption. Transferring models to stakeholders is also important at AfricaRice as the center can only generate regional impact via a network of partners.

1.2. *History: intermittent modelling heights, interrupted by periods of political unrest*

The extraordinary diversity of rice systems and environments in West Africa ranges from irrigated intensified, via rainfed-lowland, to traditional upland (dryland) cultivation; and from arid near-desert to equatorial forest environments, generally in geographically scattered and frequently poorly accessible locations (Andriesse and Fresco, 1991). Located in Liberia after its inception in 1971, and until its relocation to Ivory Coast in 1988 due to civil war, AfricaRice also conducted research

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* Corresponding author.
E-mail address: pepijn.vanoort@wur.nl (P.A.J. van Oort).

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on the coastal mangrove rice ecosystem and deep-water rice in the inland flood plains. AfricaRice first only operated in West Africa. East African countries gradually joined AfricaRice, including Madagascar in 2010. This development added the cool highlands of East Africa to the already large diversity of rice agroecologies on which the center works.

When crop modelling first started in 1990, the center's research was focused on (1) the mostly rainfed "upland-inland-valley continuum" systems in the humid zones and (2) the river-fed irrigated rice systems in the Sahel. Crop modelling chiefly addressed the latter. Our first section (§2) "RIDEV" reviews advances in rice crop modelling activities on Sahel irrigated rice during the 1990s, as well as more recent research that directly emanated from it. The second section (§3) addresses crop modelling conducted at AfricaRice since 2005, when the center temporarily moved to Cotonou in Bénin – again due to civil unrest that started in Ivory Coast in 2002. AfricaRice moved back to Ivory Coast in 2016/2017. During the 2010s the center's modelling research was broadened to include rainfed environments in addition to irrigated systems, addressing new research challenges e.g. related to climate change and abiotic stress mapping at the regional scale. We terminate this review paper with a discussion of the lessons learnt for future crop modelling research at AfricaRice and similar research centers.

Celebrating the 50th anniversary of AfricaRice, we observe that over the past five decades many forms of modelling have been practiced at the institute. Notable are various forms of spatial modelling (a.o. Zwart et al., 2014; Duku et al., 2016; van Oort, 2018; Busetto et al., 2019), modelling of yield losses due to weeds, and modelling of economics and technology adoption (a.o. Diagne, 2006; Fiamohe et al., 2013; Ogwuike et al., 2014; Rodenburg et al., 2016; N'Cho et al., 2019). Much work was done on soil fertility modelling (Haefele et al., 2000, 2003; Segda et al., 2005; Saito et al., 2015) and turning this work into freely available decision support tools (www.riceadvice.info). These various forms of modelling are covered in other articles in this special issue. The current article is specifically focused on crop growth modelling at AfricaRice.

2. RIDEV: a simple crop model assisting rice breeders and agronomists in the Sahel

2.1. A breeder-physiologist team seeking crop adaptation to the Sahelian climate

Crop Modelling expertise first came to AfricaRice in late 1990 as a new breeder-ecophysiologist team (Kouame Miezan and Michael Dingkuhn) were posted to the Sahel irrigated rice program based near Saint Louis, Senegal. Its initial tasks were a characterization exercise, namely to take stock of the regionally available rice germplasm, the biophysical constraints to yield and production, and the most promising solutions that could be conceived on the basis of existing and emerging rice-based cropping systems. In parallel the team developed a new rice research laboratory and irrigated experimental farm at the Ndiaye site in the Senegal river delta.

Two abiotic constraint foci were retained early on, i) seasonal thermal stresses and their possible avoidance *via* adequate combinations of cropping calendars (Dingkuhn, 1995) and varietal choice (Dingkuhn and Miezan, 1995); and ii) salinity (either coastal or inland, in the latter case associated with alkalinity) (Asch et al., 2000; Van Asten et al., 2004). A major focus of AfricaRice and the national research institutes (NARS) was also on genotypic and climatic yield potential in conjunction with intensification, in line with objectives of investors and policy and decision-makers across the region. This focus was justified by the high cost of irrigated rice production (1990s ex-ante assessment: (Fisher et al., 2001); a recent perspective: (Manikowski and Strapasson, 2016). Irrigated rice in the Sahel is generally based on large investments in irrigation infrastructure along major rivers (Senegal, Niger, Shari, Logone, Kou/Sourou/Volta river systems), mostly relying on pumping. This, and national priorities to achieve rice self-sufficiency (only achieved by Mali today; van Oort et al., 2015b), resulted in rice-rice double cropping as a major goal across the region - which eventually contributed little to Mali's success story.

The rice cropping seasons in the Sahel are the wet season (WS) in summer (the traditional rice season), followed by a cool-dry season (CDS) in winter and a hot-dry season (HDS) in spring. The timing of two consecutive rice crops on this basis is delicate as both cold and heat stress can occur. The Sahel team of AfricaRice developed as one of its major research tools the "rice garden" experiment, originally conceived at the international Rice Research Institute (IRRI) in the Philippines as a continuous cropping system with monthly or bi-weekly sowings around the year (Alocilja et al., 1981). As a cropping system it had failed because it increases pest pressure, but as a tool to understand climatic stresses, crop phenology and genotypic adaptation, and on this basis to parameterize crop models, it proved very useful. Multiannual rice garden experiments were thus implemented at AfricaRice and NARS sites across the Sahel region, forming a successful, multi-disciplinary research network (funded by BMZ, German Federal Ministry for Cooperation). Luckily, pest pressure remained low.

Although rice crop data were scarce and had to be generated from scratch to support crop modelling, climate data were in good supply. The inter-governmental CILSS (Comité inter-État de lutte contre la sécheresse au Sahel) with its center AGRHYMET in Niamey (Niger Rep.; http://ccr-agrhymet.cilss.int/) kept a well-curated and up-to-date database of daily weather records for synoptic weather stations all over the Sahel region (Morel, 1992; Traore et al., 2014) reaching back to the 1950s and used since the 1990s for real-time drought forecasting for dryland crops with the SARRA/DHC crop water balance model (Abdallah, 1999; Baron et al., 1999). As this network covered the locations of major irrigation schemes, rice crop modelling for the Sahel, in contrast to the humid zones, could rely on an exceptional weather data resource.

2.2. Modelling of phenology, thermal stresses and crop-generated microclimate

The rice garden trials, conducted on 30-m^2 elemental (genotype) plots for intensive sampling on key genotypes and on 1-m^2 microplots in "mini rice gardens" to phenotype larger populations enabled developing the RIDEV rice model. It simulated phenology and heat- and cold-induced spikelet sterility, yield-relevant traits that were found to be most affected by climatic stresses. In addition to these traits, floodwater and canopy-top air temperature were continuously monitored, and full growth and yield component analyses were performed for key genotypes. All rice garden trials had an adjacent electronic weather station. We will summarize only key results here, as the rice garden trials and associated modelling were reported in detail by (Dingkuhn, 1995; Dingkuhn and Miezan, 1995; Dingkuhn et al., 1995b; Dingkuhn and Sow, 1997).

Typical sowing date effects on phenology and thermal spikelet sterility for the local cv. Sahel 108 at AfricaRice's research station in Ndiaye (Senegal) are shown in Fig. 1. For the simulations, the RIDEV V2 model was used, as described further down.

Observed spikelet sterility was low for the wet season (sowing in July) (Fig. 1, center) and crop duration was also shortest (top), as observed on the research station of Ndiaye in Senegal. Sowing in September or October, however, frequently resulted in near-total sterility and yield loss. The authors had often observed such crop failure in farmers' fields, attributed by locals to "variety" or "disease" but now hypothesized to be due to late sowing or early onset of the cool season. Sterility tended to be higher (but was never catastrophic) or more variable for the hot dry season (sowing in February), associated with intense heat around the flowering period, whereby crop duration was longer due to photoperiodism and early-season low temperatures. Strong seasonal and genotypic variation in crop duration, modulated by sowing date, influenced the thermal conditions the crops were exposed to during the critical phases of reproductive development and flowering.

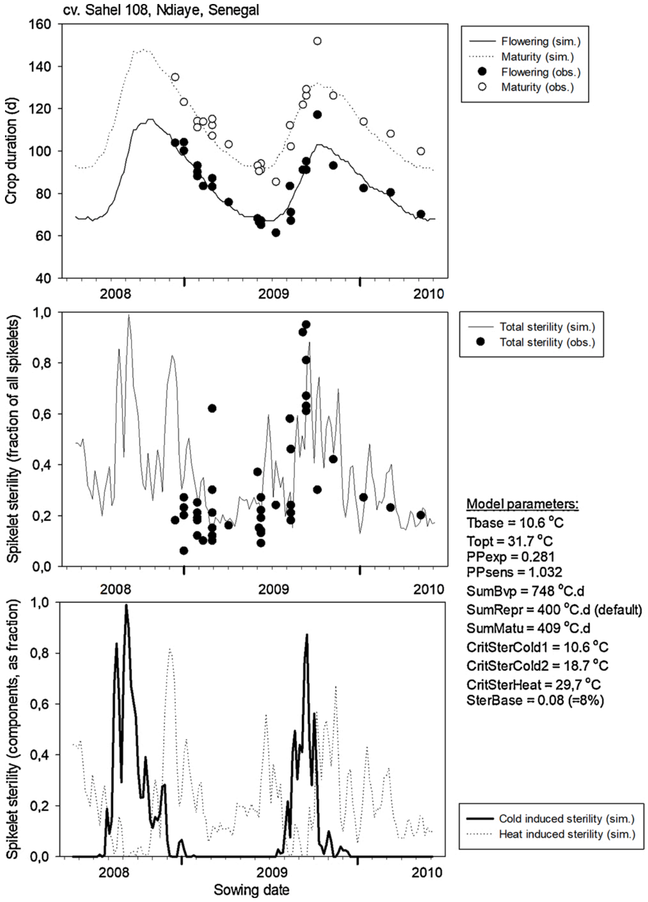


Fig. 1. Comparisons of simulations with the calibrated RIDEV V2 model with observations on crop duration (top) and spikelet sterility (center), and separation of simulated chilling and heat effects on sterility (bottom); for Sahel 108 rice planted at different dates at Ndiaye, Senegal. Field data courtesy of ORYTAGE project (Cirad) and the Ph.D. thesis of Dr. Sabine Stürz (Hohenheim University). Model parameters: Tbase, base temperature; Topt, optimum temperature; PPexp / PPsens, exponentiality and sensitivity of day length response; SUMbvb / SUMrepr / SUMmatu, thermal duration of basic vegetative, reproductive and maturation phases, respectively; CritSterCold1 / CritSterCold2, thermal interval of sterility response to cold; CritSterHeat, critical panicle temperature for heat sterility; SterBase, baseline unexplained spikelet sterility.

The most vulnerable growth stages were microspore stage for chilling, coinciding with booting stage (Dingkuhn et al., 1995b; Imin et al., 2004); and anthesis for heat (Jagadish et al., 2007), both causing male sterility through different physiological mechanisms. Chilling at seedling stage also caused delay in crop establishment and sometimes mortality, and chilling during grain filling caused heterogenous grain filling (Fig. 2A) and reduced mean kernel weight (Fig. 2B) (Dingkuhn and Sow, 1997). High temperatures, frequently exceeding 40 °C, had only small effects on growth and yield when occurring outside the anthesis period, enabling top yields during the hot dry season (Dingkuhn and Sow, 1997).

The first crop model developed at AfricaRice focusing on thermal sterility and phenology, later called RIDEV (Dingkuhn et al., 1995a; Wopereis et al., 2003), integrated several system features:

- Flowering response to temperature, based on thermal time and the genotypic cardinal temperatures Tbase and Topt (base temperature and optimum temperature),
- Flowering response to day length, based on a photoperiod-sensitive phase,
- Temperature-dependent extension of the basic vegetative phase due to transplanting shock (Dingkuhn et al., 1990) if the crop was not direct seeded,
- Sterility response to chilling, assumed to be induced at microspore stage,
- Sterility response to heat assumed to occur at anthesis, and
- Floodwater temperature (setting shoot apex temperature while still submerged), in turn affected by shading by the canopy, influencing development rate and sterility response to chilling (Dingkuhn et al., 1995b).

Rice sterility was shown to be extremely sensitive to the daily minimum temperature (Tmin) of the apex, responding when Tmin dropped below 18 °C, to 100 % sterility at Tmin < 15 °C during microspore stage (Dingkuhn et al., 1995b).

RIDEV was initially programmed in GW-Basic and made use of a multi-parameter and multi-environment fitting procedure to estimate thermal-time budgets, cardinal temperatures and photoperiod sensitivity for individual genotypes from rice garden crop and weather data. Much later, Julia (2012) and Julia and Dingkuhn (2012, 2013) also studied the variation of time of day of anthesis and panicle temperature dynamics in multiple field environments in Senegal, the Philippines and France. Major conclusions were as follows:

- Transpirational cooling of the canopy and the panicle itself can reduce panicle temperature to 10 °C below air

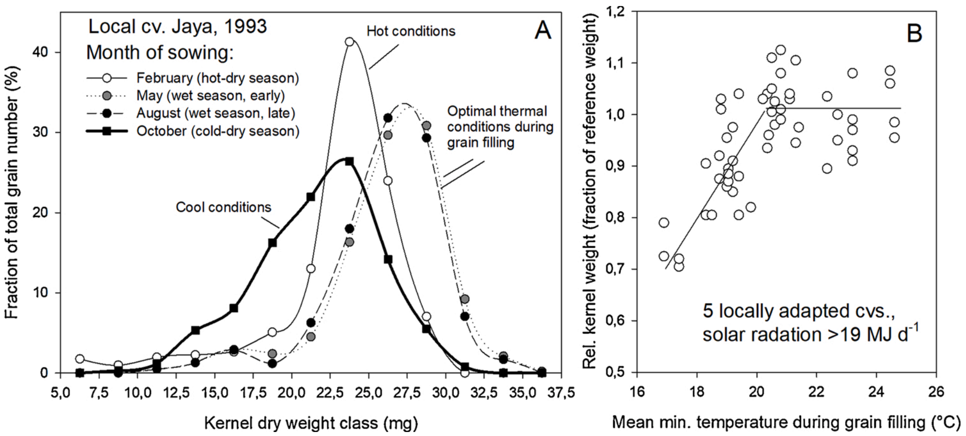


Fig. 2. A: Variation of filled grain weight distribution of Jaya rice based on 500 randomly taken grains, as affected by sowing date. Hot conditions reduced grain weight homogenously whereas chilling caused heterogeneous grain filling. B: Relationship between relative kernel weight (fraction of reference weight under stress free conditions) and mean minimum air temperature during grain filling, for 5 cvs. incl. Jaya. Data were used to simulate kernel weight in ORYZAS according to a broken-stick model (straight lines). Ndiaye, Senegal rice garden trial 1993. Reprinted/adapted by permission from Springer Nature: Kluwer Academic Publishers, Applications of Systems Approaches at the Field Level, Potential yield of irrigated rice in African arid environments, by Dingkuhn and Sow © 1997.

temperature at 2 m, chiefly depending on air humidity. Air humidity or vapor pressure deficit (VPD) at flowering are thus essential parameters to estimate heat-induced sterility.
- Night temperature and humidity influence the time of day of anthesis, usually between morning and midday, and can contribute to temporal escape from heat-induced sterility. A given spikelet undergoes anthesis only on one day, for about two hours.
- As a combined result, heat sterility risks are particularly high in warm-humid environments but surprisingly low under extreme heat paired with low humidity.

These observations were the rationale for developing in 2012 a new RIDEV V2 model in 2012, simulating, in addition to the variables already simulated in RIDEV, diurnal dynamics of panicle temperature and the time of day of anthesis. The model documentation and source code are accessible on the site https://umr-agap.cirad.fr/en/research/scientific-teams2/ridev).

We briefly review the underlying field data of panicle and leaf temperature because this extensive but little known resource can be of great value for future modelling of climate change impacts. It was published as part of a Ph.D. thesis (Julia, 2012). Over 3000 datasets for panicle and top leaf (flag or the leaf below it) temperature, based on IR imagery and micrometeorological records, were obtained at around flowering stage for four genotypes, different times of day and in three environments: Cold-dry season (CDS) and Hot-dry season (HDS) in Senegal, as well as the dry season in the Philippines (Fig. 3: only local cv. Sahel 108 is shown). The air temperature at 2 m varied between 20 and 40 °C.

The panicle-air temperature difference (Tp-Ta) varied between -12 and +3 °C and was lowest (most negative) at low air relative humidity (RH), indicating transpirational cooling (Fig. 3A). The humidity effect thereby varied among the environments. However, Tp-Ta followed a common linear function ($R^2 = 0.69$) of vapor pressure deficit (VPD) at 2 m, presumably because VPD considers both RH and air temperature (Fig. 3B). The leaf-air temperature difference responded similarly but transpirational cooling was by one to three degrees stronger, and R^2 was higher (0.82). These results were derived from a large dataset collected in AfricaRice Senegal study. A similar study using published data from humid to semi-arid environments across the world found a very similar transpirational cooling *vs.* humidity relation (van Oort et al., 2014c). The data indicated that under hot and dry air conditions, and unlimited water availability to the plant, transpirational cooling is a powerful heat avoidance mechanism (Julia and Dingkuhn, 2013; van Oort et al., 2014c).

For Julia's dataset, covering air temperature ranges of 17−40 °C and VPD ranges of 0.5–6.0 MPa across the environments, the correlation was VPD(MPa)=-11.1 + 0.421*T (°C), with $R^2 = 0.79$. Applying the correlation for Tp-Ta vs. vapor pressure deficit (VPD) in Fig. 3B to the data results in a nearly constant panicle temperature (largely within 25−30 °C) for the much larger range of air temperatures encountered (Fig. 4). This is important because the common assumption in modelling is that panicle temperature follows changes in ambient temperature.

In RIDEV V2, Tp-Ta is calculated with the following empirical equation that takes into account air temperature and relative humidity, solar radiation and two canopy parameters:

$$\mathrm{Tp\text{-}Ta} = 0.782 + 0.422 * \mathrm{Ta\_2\ m} - 0.0443 * \mathrm{RH\_2\ m} - 0.00287 * \mathrm{Rs} - 8.05 * Z - 6.59 * \mathrm{LTR}$$

Whereby:

Ta_2 m = T(air) at 2 m
RH_2 m = rel. air humidity at 2 m
Rs = solar radiation (W/m^2)
Z = mean panicle position relative to canopy height (fraction, 0.7…1)

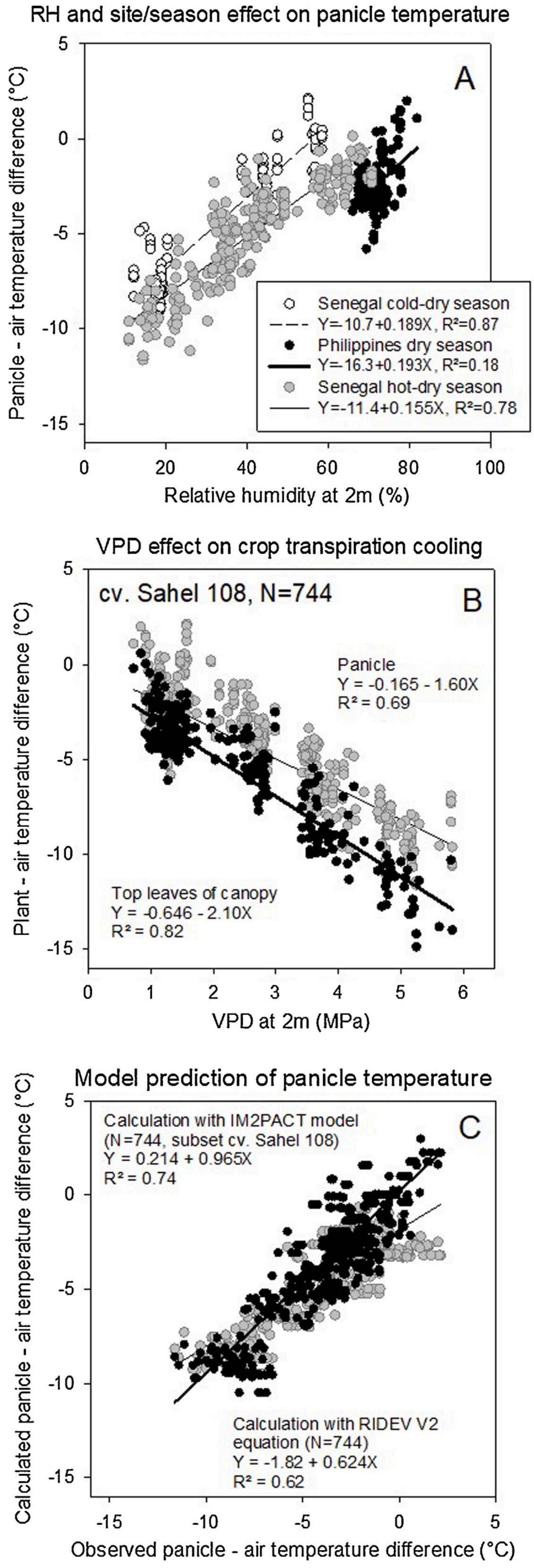
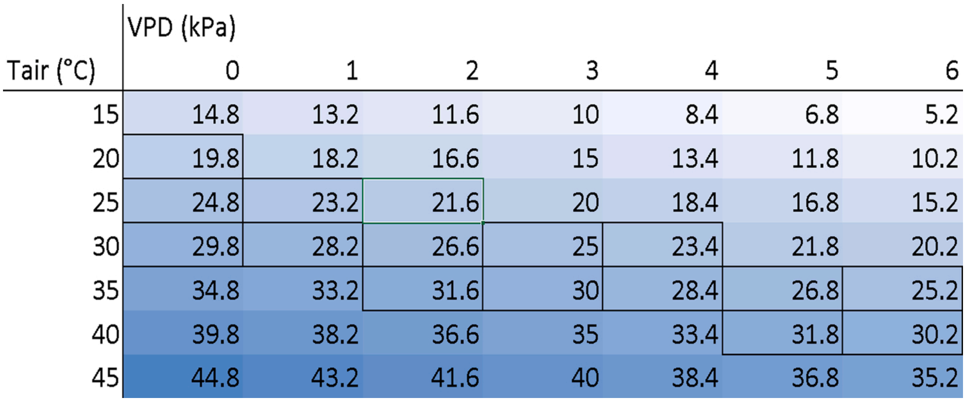


Fig. 3. A: Relationship between panicle-air temperature difference (Tp-Ta) and relative air humidity for Sahel 108 rice in 3 environments. B: Relationship between plant-air temperature difference and air vapor pressure difference (VPD) across the environments (grey symbols, panicles; black symbols, leaves). C: Comparison of RIDEV V2 and IM2PACT model predictions of Tp-Ta.



Tair (°C)	VPD (kPa) 0	1	2	3	4	5	6
15	14.8	13.2	11.6	10	8.4	6.8	5.2
20	19.8	18.2	16.6	15	13.4	11.8	10.2
25	24.8	23.2	21.6	20	18.4	16.8	15.2
30	29.8	28.2	26.6	25	23.4	21.8	20.2
35	34.8	33.2	31.6	30	28.4	26.8	25.2
40	39.8	38.2	36.6	35	33.4	31.8	30.2
45	44.8	43.2	41.6	40	38.4	36.8	35.2

Fig. 4. Predicted panicle temperature under varied air temperature and vapor pressure deficit (VPD) condition as calculated from the equation in Fig. 3B. The boxed values indicate the observed range of conditions observed in Senegal and the Philippines by Julia (2013, thesis data).

LTR = canopy light transmission ratio (0…1 theoretically, but mostly 1)

The panicle temperature is calculated for the time of day at which anthesis is expected to happen, using another empirical function that causes earlier anthesis after warm and humid nights (Julia and Dingkuhn, 2012). RIDEV V2 thus simulates two heat avoidance responses of rice panicles, one through transpirational cooling and the other through temporal escape of anthesis from the midday heat. In retrospective, however, this model leaves room for further improvement. In Fig. 3C we compared Ridev V2 calculations of Tp-Ta with those of IM2PACT, a heat balance based canopy and panicle temperature model developed for rice, based on FACE experiments in Japan (Yoshimoto et al., 2011). We apply it here to the same dataset. The IM2PACT model gave better predictions than the empirical equation of RIDEV V2, with slope and R^2 values nearer to 1 when regressed against observed Tp-Ta. Specifically, RIDEV V2 overestimated transpirational cooling at low vapor pressure deficit. It should thus be considered to implement a physics-based model such as IM2PACT in future versions of crop models that simulate heat stress effects on crops.

Both RIDEV V2 and the original RIDEV consider floodwater temperature effects on crop phenology. However, in RIDEV V2 the simple linear response model of flowering response to day length was replaced with the Impatience model (Dingkuhn et al., 2008) developed for sorghum, able to predict the extreme photoperiodism of traditional cereal cultivars.

RIDEV V2, implemented at hourly time steps to capture variation of time of day of anthesis, has been used to perform model-assisted phenotyping (Dingkuhn et al., 2015a, c) and genome-wide analyses (Dingkuhn et al., 2017a, b) on a rice diversity panel for phenology and thermal sterility traits. It was also incorporated in the ORYZAS growth model described further down, and in simplified form in SAMARA, a crop model simulating the phenotypic plasticity of rice (Kumar et al., 2016, 2017). The original RIDEV, however, is still in use at West African NARS because of its robustness and small input data requirements. In the next sections describing model applications, we will refer to RIDEV (original version) or RIDEV V2 depending on which model was used.

2.3. Regional mapping of thermal sterility risks and potential rice crop calendars

RIDEV was applied to map phenological variation and thermal sterility risks for key rice cultivars and crop calendars across irrigated rice environments in the Sahel, based on 10 years (1970–79) of weather records (Dingkuhn, 1995). Although similar thermal constraints occur all over the Sahel region, the feasible calendar options for rice-rice double cropping varied geographically and required different genotypic crop duration in some cases. These differences were related to the N–S climatic gradient and the longer cool period in zones under maritime influence (Senegal, Mauritania). An important criterion for the feasibility of rice double cropping, aside from sterility risks, was the time available between two crops for harvest and subsequent land preparation which require some calendar flexibility (timely availability of machinery, inputs, labor etc.). On this basis, double cropping was found to be feasible for most environments when using short-duration cultivars.

In hindsight, rice double cropping was a priority for policy and decision-makers in the Sahelbut not necessarily farmers, who frequently split their labor and investment among several agricultural activities, including irrigated vegetable crops and dryland coarse cereals in nearby uplands (Le Gal and Papy, 1998; Krupnik et al., 2012; Brosseau, 2018). Possibly for that reason, rice double cropping has not been adopted widely in the Sahel even today (Busetto et al., 2019). Nevertheless, irrigated rice production has in increased substantially in Mali and Senegal due to increased yields (http://ricepedia.org/maliand/senegal) and expansion of irrigated production area (Manikowski and Strapasson, 2016; Busetto et al., 2019). Information on rice vs. non-rice activities in the Sahel is scarce (Van Oort et al., 2016). The Cropping Calendar Construction (CCC) model presented further down was developed to model such systems.

The 1990s modelling studies, which were conducted on the basis of historical climate dating even further back, would give different results today as global warming has taken place and might affect crop calendar options. According to farmer surveys on current sowing dates and perceptions of thermal constraints in the Senegal river valley (Tanaka et al., 2015), the wet season crop is now frequently sown as late as September, a date that would previously have incurred severe risks of cold sterility. Preliminary analyses of inter-annual thermal trends and simulations with RIDEV confirmed a diminishing risk of cold sterility, and farmers reported that an early onset of the cold “as in the past” has become rare. The farmers’ shift to later sowing dates may have been enabled by warming but it was mostly motivated by socio-economic considerations. Even more recently, the Senegalese irrigation authorities SAED reported verbally (A. Thiam, SAED: Dingkuhn, pers. com. 2019; see also Busetto, 2019) a major shift of sowing in the Senegal river delta from the wet season to the hot dry season for the main crop, in part to avoid bottlenecks in availability of shared agricultural machinery (SAED, pers. com.) and to benefit from the high climatic yield potential in the hot dry season arising from high incoming radiation (Dingkuhn and Sow, 1997).

The probable effects of climate change on the evolution of irrigated rice based systems in the Sahel merit a systematic modelling and survey study. They could make an interesting case study on adaptive change in agriculture under global warming, underpinned by trends towards further intensification, large scale commercial rice production and competition for water between urban and agricultural demand, namely in the dry season (A. Thiam, SAED, pers. com. 2019).

2.4. RIDEV applications in support of farmers' tactical decisions

RIDEV was widely shared with partners and has been used as a participatory tool to improve crop calendars in the Senegal valley (Poussin et al., 2005, 2006). RIDEV was incorporated into a decision-aid system called CalCul and used with farmers to optimize planting and irrigation schedules at community level. The authors reported large yield and production gains through collective management at the irrigation scheme scale without using additional technologies or inputs. The results seem to indicate that improved, model-assisted coordination among farmers can increase the technical efficiency of rice production in Sahel irrigation schemes. RIDEV was published by (Wopereis et al., 2003) as a decision aid tool for rice systems in West Africa.

2.5. Modelling in support for breeding and genetics

The development of RIDEV in the early 1990s stood in the context of rice breeding for improved adaptation to the Sahelian climate. RIDEV-assisted characterization of promising genetic lines in the "mini rice garden" trials described above was at the time a pioneering attempt in crop model-assisted, multi-environment phenotyping (Dingkuhn and Miezan, 1995). An initial set of 49 cultivars was phenotyped based on monthly sowing and phenology and spikelet sterility measurements. Other populations were later phenotyped with this method by breeders but we do not have further information on it. These were small populations compared to model-assisted phenotyping approaches today and they were not yet linked to genomic mapping or selection objectives (Cooper et al., 2016).

The model-assisted phenotyping used parameter optimization procedures to estimate cardinal temperatures, thermal-time budgets for development phases, photoperiod sensitivity and thermal response of spikelet sterility. The information was then used to predict genotypic response to variable environments and to select adapted cultivars or parental materials for further breeding. The study explained superior adaptation of cultivars that had already been successful in the Sahel (e.g., low base temperature and photoperiod sensitivity) and helped selecting Sahel 108, the short-duration cultivar that was then adopted in Senegal where it replaced virtually all previously released irrigated rice cultivars.

The more recent RIDEV V2 was used to phenotype the phenology (Dingkuhn et al., 2015c, a) and thermal sterility traits (Dingkuhn et al., 2015b, b) of an indica-rice diversity panel with 200 accessions. The datasets were generated in a mini rice-garden trial at AfricaRice in Senegal and at different altitudes in Madagascar. RIDEV parameter estimation was then conducted across environments and genome-wide association studies (GWAS) were performed on the estimated genotypic crop parameters of the model (Dingkuhn et al., 2017ab).

A major result of these genetic studies was that thermal response of phenology and sterility for many cultivars was not the same in all environments. To account for this, an additional model parameter was introduced in RIDEV V2 to simulate hypothetical acclimation effects, e.g. in cases where plants exposed to chilling during reproductive stage had been previously exposed to chilling at juvenile stage. This model modification strongly improved phenotype prediction across environments. Moreover, the acclimation parameters for phenology and cold-induced sterility gave strong GWAS signals. The QTLs co-localized with genes putatively controlling epigenetic responses, such as DNA methyltransferases and histone-like transcription factors (Dingkuhn et al., 2017b). A base temperature QTL co-localized with HD3a, a florigen known to be important for thermal adaptation (Gómez-Ariza et al., 2015; Dingkuhn et al., 2017a).

The RIDEV V2 model-assisted genetic study should now be followed up by the identification and validation of molecular markers, in order to enable marker-assisted selection (MAS) or other forms of molecular breeding for improved adaptation to thermally adverse climates.

2.6. RIDEV applications within rice growth and yield models

RIDEV was incorporated into ORYZA1, a commonly used rice growth model during the 1990s, and along with some other modifications (e.g., transplanting/direct-seeding options and transplanting shock). The result was called ORYZAS (S for Sahel). ORYZAS also simulated thermal effects on kernel weight (Fig. 2B) and leaf/stem assimilate partitioning (Dingkuhn and Sow, 1997).

ORYZAS was then calibrated on rice garden data and used to simulate climate, sowing date, location and cultivar dependent yield potential (Dingkuhn and Sow, 1997). Typical patterns of sowing-date dependent phenology and yield are shown in Fig. 5. Yield potential was greatest at about 10 t ha^{-1} in the hot dry season which has the longest days, but also in the wet season when sowing was done late but not too late to risk cold-induced sterility. The high hot dry season yields were possible despite heat causing partial spikelet sterility, as well as slightly reduced kernel weight and assimilate partitioning to leaves in favor of stems – constraints that were offset by the longer crop duration.

ORYZAS was also used in rice salt tolerance studied in the 1990s in Senegal. It was observed that under moderate salinity, tolerant cultivars were greener than non-stressed controls, but produced much less leaf area and biomass, both above and below ground. In an apparent contradiction to this, leaf photosynthetic rates of the stressed plants were higher than those of controls. Dark respiration rates of leaves could not explain this discrepancy. It was hypothesized that the salt-stressed but greener plants did not use a large fraction of their assimilates for biomass growth. ORYZAS was used to simulate the observed growth and leaf area in saline and control plots, whereby the photosynthetic rates were adjusted to reproduce the observed growth. On the basis of the parameter adjustments, it was estimated that under salt stress 8 to 49 % of carbon assimilation did not contribute to biomass growth, depending on genotype. According to Asch et al. (2000), the likely explanation was the high metabolic cost of osmoregulation and sodium exclusion in the root system. Higher leaf chlorophyll content in stressed plants was explained by the lesser degree of growth-driven nitrogen dilution in the salt stressed plants, which had received the same N inputs as the controls.

This result points at the importance the carbon costs associated with plant stress defenses, generally not simulated by crop growth models.

2.7. Lessons learnt from RIDEV-based modelling in the 1990s

Given its narrow focus on phenology and thermal sterility, RIDEV helped addressing a surprisingly broad range of research questions, including the optimizing of rice crop calendars, regional mapping of thermal stress risks, decision aid at production level, breeding support and phenotyping for genetic studies. Two factors contributed to this success. First, the large variation of crop duration and spikelet fertility of rice in the Sahel, as irrigation enables multiple calendar options independent of rains. These systems cannot build on traditional knowledge. Farmers, agronomists and breeders alike are in need of guidance. In fact, RIDEV has also been applied in regions prone to extreme climates outside Africa, such as Nepal (Shrestha et al., 2011). Second, RIDEV is a simple model that can easily be adapted to different applications or incorporated into other modelling systems.

The more detailed RIDEV V2 (Dingkuhn et al., 2017ab) has greater capabilities to simulate thermal acclimation, crop-generated microclimate and genotypic response of spikelet sterility to heat. Because of its greater data requirements, but also because it did not address principally new research questions, RIDEV V2 achieved less adoption than the original RIDEV. Thus, a major lesson was that a simple tool tailored to address a regionally dominant agricultural constraint can generate large positive impact. Another lesson is that focused and sustained collaboration between complementary disciplines (e.g., physiology/modelling and breeding) can enable effective research.

The narrow focus of RIDEV in terms of traits and factors meant that

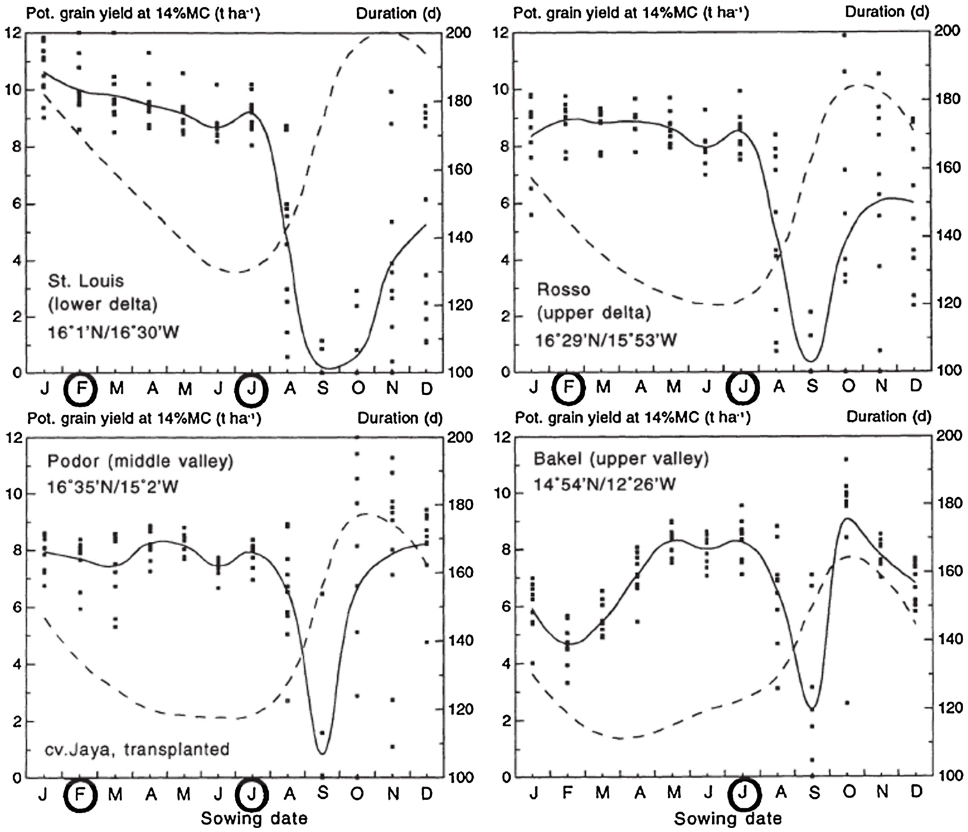


Fig. 5. Simulated potential yield (solid lines for means of 10 years and points for individual years, 1970-1979) and seed-to-seed crop duration (broken lines) as a function of sowing date for rice cv. Jaya on a climatic gradient (four sites) along the Senegal river, using ORYZAS model. Locally recommended months of sowing are enhanced with circles. Reprinted/adapted by permission from Springer Nature: Kluwer Academic Publishers, Applications of Systems Approaches at the Field Level, Potential yield of irrigated rice in African arid environments, by Dingkuhn and Sow © 1997.

other important stresses and traits were not considered, limiting the model's extrapolation domain. ORYZAS, implementing RIDEV as a module, filled some of these gaps. But as AfricaRice's modelling research broadened thematically in the 2010s, other tools were needed.

3. Cropping systems, rainfed rice, yield gaps and climate change

By 2010, crop growth modelling could build on a range of existing models (Fig. 6), including RIDEV, RIDEV V2, ORYZAS and ORYZA2000 (Bouman et al., 2001). During the 2010s, some models were combined, but at the same time they grew apart. For example, ORYZA2000 contains a plant and a soil component. Its plant part was integrated in the broadly used decision support system APSIM, allowing for analyzing cropping systems with multiple crops (Gaydon et al., 2012, 2017). At IRRI, ORYZAv3 succeeded ORYZA2000 (Li et al., 2017), featuring new scientific and user interface functions. Elements of RIDEV V2 were integrated into an 'AfricaRice' successor of ORYZA2000 (van Oort et al., 2014a; van Oort et al., 2015a; van Oort and Zwart, 2018), often referred

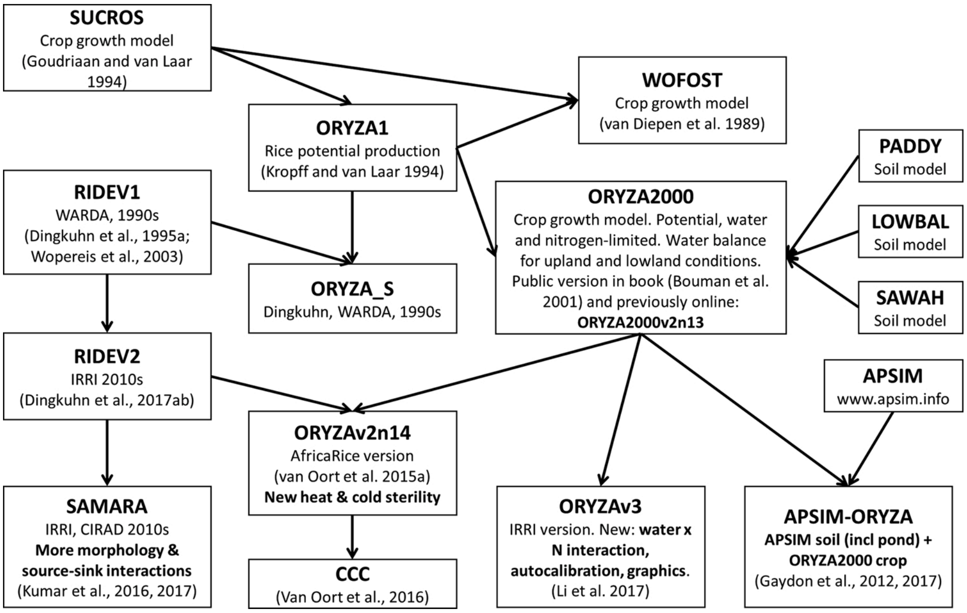


Fig. 6. Brief history of rice models.

to as ORYZA2000v2n14 (see van Oort et al., 2015a for version numbering). The new Cropping Calendar Construction (CCC) model linked to ORYZA2000 aimed at optimizing cropping intensity, sowing dates and variety traits in cropping systems with multiple rice crops.

In 2012, AfricaRice joined the global yield gap atlas (GYGA) project (www.yieldgap.org). It entailed simulating potential yields across the whole of Africa, from the cold highlands of Rwanda and Madagascar, warm and humid West Africa environments and the hot and dry Sahel where RIDEV originated. This wide array of environments provided an ideal testing ground for crop models, with the aim to achieve reasonable simulations across all environments. The ORYZA2000 model was chosen as reference model, for a number of reasons. RIDEV V2 does not simulate grain yield, needed for the yield gaps. ORYZAS cannot simulate water limited yields, whereas approximately 74 % of the cultivated rice area in Africa is rainfed (Diagne et al., 2013). SAMARA can simulate rainfed conditions and deficit irrigation but due to its focus on phenotypic plasticity, it is unnecessarily complex for large-scale yield gap studies (Kumar et al., 2016, 2017). Cropping systems models like DSSAT and APSIM simulate like ORYZA2000 both potential and water-limited yield. However, limited access to their source code in the early 2010s would have made modifications difficult. Testing across diverse environments brought to light weaknesses in ORYZA2000, stimulating further research and concurrent model improvements.

3.1. *Irrigated rice*

3.1.1. *Testing and improving ORYZA2000 in Senegal: Phenology and thermal sterility*

ORYZA2000 was developed in the 1990s by the international Rice Research Institute (IRRI) and AB-DLO (later incorporated into Wageningen University and Research, WUR). The scientific basis and code is well documented (Bouman et al., 2001). The calibration program DRATES (provided along with the ORYZA2000 model) uses default cardinal temperatures of 8, 30 and 42 °C. Zhang et al. (2008) questioned the validity of these values, notably with respect to climate change. van Oort et al. (2011) used a large dataset from Senegal (de Vries et al., 2011) to develop the calibration program pheno_opt_rice and applied it to optimize cardinal temperatures that were compatible with the ORYZA2000 phenology sub-model. As in previous studies (Dingkuhn, 1995; Dingkuhn and Miezan, 1995; Dingkuhn et al., 1995b; Yin et al., 1995), cardinal temperatures differed among rice cultivars. Two important differences compared to the default ORYZA2000 parameters were (1) a higher base temperature and (2) no delay in development above the optimum temperature.

Starting with the original ORYZA2000v2n13 model (Bouman et al., 2001), van Oort et al. (2015a) improved ORYZA2000 in a stepwise process:

- Different default cardinal temperatures (from 8, 30, 42 °C to 15, 30 °C and no delay in development above optimum temperature; based on (van Oort et al., 2011));
- Enhanced leaf death due to shading (without this function, ORYZA2000 produced unrealistically high leaf area index (LAI) with values up to 22 in the cold dry season, due to a long vegetative phase and high radiation levels);
- New heat sterility equations, copied from RIDEV2 based on (Julia and Dingkuhn, 2012, 2013). The original ORYZA2000v2n13 model predicted complete crop failure due to heat sterility in hot seasons, while actually heat was rarely a problem;
- New cold sterility equations, copied from RIDEV2 based on (Julia and Dingkuhn, 2012, 2013). Without these the original ORYZA2000v2n13 model predicted no cold stress at all, while in reality when planted in October, complete crop failure occurred due to cold sterility.

These improvements were confirmed later with an independent dataset from the same site (Stuerz et al., 2014b), resulting in similar model accuracies (van Oort et al., 2016).

While ORYZA2000 improvements significantly increased model accuracy, substantial uncertainties remained for the simulation of spikelet number per hectare, which can strongly affect yield. Simulations with observed phenology and spikelet number showed model efficiencies of up to 0.70, while with both traits simulated the model efficiencies decreased to 0.50. It is not clear whether uncertainties in the spikelet number simulations are due to uncertainty in observed data, in the model or both. To date there has been no large-scale systematic testing of models' capabilities to simulate spikelet number. Further research is needed. Rice garden trials conducted on a wide array of environments with consistent data collection protocols and check varieties would allow for filling this knowledge gap.

3.1.2. *ORYZA2000 in East African highlands*

While for the Sahel zone there was a longstanding history of modelling and rice garden experiments we could build on in the early 2010s, this was not the case for the East African highland sites. Since then, several experiments were initiated. Initial simulations with ORYZA2000 for sites in Tanzania, Ethiopa, Rwanda and Uganda showed the following results (van Oort et al., 2014b; van Oort and Saito, 2015):

- the original ORYZA2000 version (Bouman et al., 2001) predicted almost no cold sterility
- the 'AfricaRice' ORYZA2000 version, ORYZA2000v2n14 (van Oort et al., 2015a) improved for the Senegal site (see above), predicted almost complete cold sterility

Neither of these results made sense. We knew from national partners and ongoing research in Rwanda, Ethiopia and Madagascar that cold is a serious problem in East Africa. However, if cold sterility problems were prohibitive, farmers wouldn't be growing rice. Dingkuhn et al. (2015b) reported for the same rice genotype at the same temperature during the critical stages, cold sterility was much greater in Senegal than in Madagascar highlands. For lack of a better solution, a switch function was implemented in the 'AfricaRice' ORYZA2000 version (ORYZA2000v2n14), using the Senegal parameters as representative for West Africa and using the Madagascar cold sterility parameters for East Africa. This approach was used for subsequent simulations for the GYGA project (van Oort et al., 2015b; van Ittersum et al., 2016; van Oort et al., 2017), climate change studies (van Oort and Zwart, 2018) and abiotic stress mapping (van Oort, 2018). The switch function was practical but is scientifically unsatisfactory, as crop parameters should vary with genotype and not environment.

Some light was shed on the problem by multi-environment phenotyping work (Dingkuhn et al., 2015b & 2017b). A major difference between thermal patterns in the Sahel and East African highlands is that cold stress affects the crop during one specific stage in the Sahel (either crop establishment or reproductive stage) but during several development phases in the highlands. (Dingkuhn et al., 2017b) experimentally equipped RIDEV V2 with a "hardening" or acclimation function which explained the conflicting observations. In fact, as detailed in section 2.5, genome-wide association studies identified putative epigenetic loci controlling the hypothesized cold acclimation, the acclimation alleles occurring mainly in highland-adapted genotypes. To date, however, the epigenetic acclimation hypothesis is insufficiently validated to justify its incorporation in ORYZA2000v2n14. More research will be necessary to do so.

3.1.3. Cropping calendar construction

The Cropping Calendar Construction (CCC) model (van Oort et al., 2016) was designed to update and broaden the RIDEV cropping calendar study (Dingkuhn, 1995; Section 2.3) with improved simulation models based on ORYZA2000v2n14 (Fig. 6). While the older RIDEV-based study considered only irrigated rice monoculture (single or double cropped) with rice phenology-based time frames and thermal sterility risks as sole evaluation criteria for scenarios, the Cropping Calendar Construction (CCC) model provided additional information on potential rice yields and the inclusion of vegetable crops in the crop calendars.

A model was needed that can optimize crop succession scenarios drawing from phenologically different varieties while imposing specific constraints such as breaks between crops and periods reserved for non-rice crops. This can also be done with cropping systems models like APSIM or DSSAT. However, for high numbers of combinations of varieties, years and sowing dates, computational speed would become an issue, and a customized interface would be required for mass simulations and scenario extraction/optimization. In CCC, three modules were implemented to perform the following tasks (van Oort et al., 2016):

1 Simulation of a virtual rice-garden trial: Year-round, multiannual simulation with ORYZA2000 of rice potential yield for sowings at 10-day intervals (36/year) at a given site for 5 'synthetic' varieties based on a local check cv. but differing in crop duration.
2 Extract feasible cropping calendar scenarios, based on appropriate break periods between crops: Single rice, rice-vegetable, rice-rice, rice-rice-vegetable and rice-rice-rice.
3 Generate a table of all possible cropping calendars and associated yield data permitting extraction of best (or most stably) performing crop calendars, based on a user-friendly interface.

The CCC model was used to optimize sowing dates and traits in the Fanaye site of Senegal (van Oort et al., 2016). It showed that triple cropping (rice-rice-rice or rice-rice-vegetable) is virtually impossible and that in rice-rice and rice-vegetable systems, rice yields can be increased by implementing earlier sowing and switching from short to medium duration varieties. Researchers and extension service staff were trained in using the CCC tool in Senegal and Madagascar. Results are site specific but the tool is generic within the extrapolation domain (irrigated rice-based systems in which thermal constraints are important). Most users opted for constrained optimizations, first blocking part of the year for vegetables and then fitting rice into the remainder of the year. Farmers along the Senegal river prefer short-duration varieties to escape cold stress when planting of rice is late, which frequently happens due to late availability of credit, seed, irrigation, fertilizer or machinery (Tanaka et al., 2015; van Oort et al., 2016). Breeding accommodated these preferences, exemplified by the success of Sahel 108. However, if organizational constraints can be mitigated, adoption of medium-duration varieties can increase production (van Oort et al., 2016). The CCC model was also used to simulate climate change adaptation options (section 3.4).

3.2. Rainfed rice

3.2.1. Simulating rainfed situations with ORYZA2000

In rainfed rice, water is the defining resource. Rainfed lowlands such as valley bottoms generally have high groundwater levels, temporary storage of ponded water that can be enhanced with bunding, and low percolation rates. Rainfed uplands have free draining soils, higher percolation rates, and in most cases inaccessibly deep groundwater, whereby water storage is limited to topsoil water holding capacity. Intermediate situations in the form of a continuum are common. Previous modelling studies showed rainfed rice attainable yields depend strongly on hardpan presence, groundwater depth and percolation losses (Bouman et al., 1994; Wopereis et al., 1994; Boling et al., 2007; Bouman et al., 2007). The drought stress part of ORYZA2000 (Bouman et al., 2001) was not modified in the ORYZA2000v2n14 'AfricaRice' version.

Rainfed rice yields simulated by ORYZA2000 are like potential yields (assuming ample nutrients, no weeds, pests and diseases) but with yield reductions due to drought. ORYZA2000 can simulate effects of soil water holding capacity (which depends on soil texture), bunding and groundwater level. A hardpan is simulated by assigning a low hydraulic conductivity to the respective soil layer, reducing percolation. In turn, this causes more run-off (if there are no bunds) or higher pond water levels (if bunds are present). Being a 'point based' model, ORYZA2000 does not simulate lateral flow. It thus can simulate water run-off but not run-on, nor can it simulate below-ground lateral flow. Previous studies showed ORYZA2000 can accurately simulate field level water dynamics if fed with accurate data on irrigation, groundwater, bunding and soil parameters (Wopereis et al., 1994; Belder et al., 2005a, b; Belder et al., 2007; Gaydon et al., 2012). For the rainfed lowland, this implies providing a forcing function of daily observed groundwater depths and percolation rates, as lateral inflow is not simulated. In ORYZA2000, there is no effect of hardpan presence on rooting depth, but one can limit the maximal rooting depth to that of the hardpan. Setting these two model parameters should be guided by observations, as root penetration on the hardpan depends on its compaction and on cultivar (Clark et al., 2002; Samson et al., 2002).

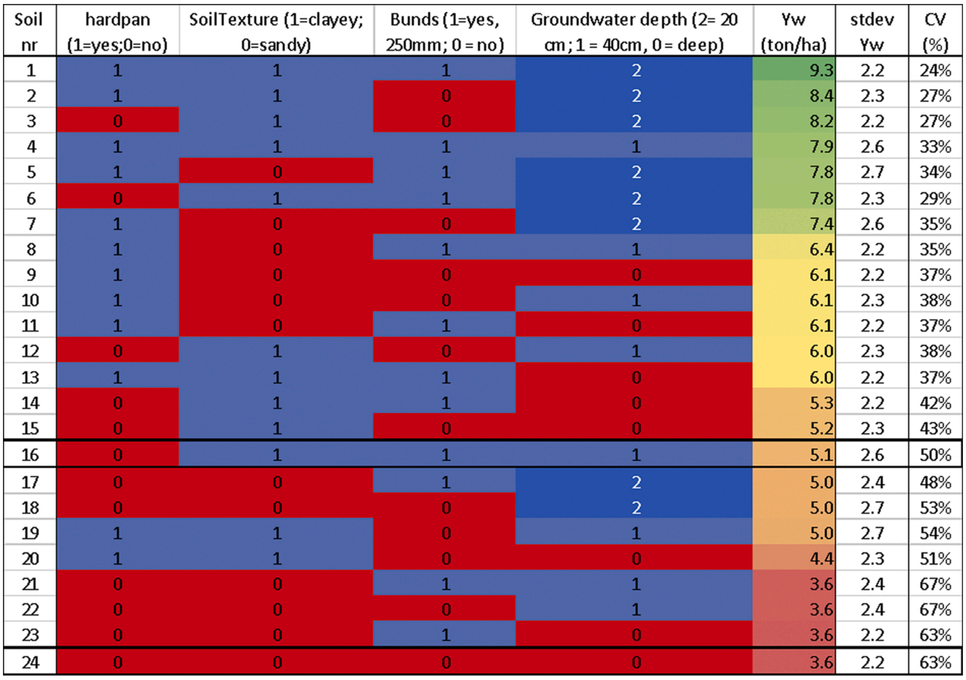
3.2.2. Sensitivity analysis on soil parameters

With the frequent lack of 'forcing' data on lateral flow, groundwater, hardpan, bund height and soil texture, accuracy of model simulations will be limited. A sensitivity analysis was conducted with the ORYZA2000v2n14 model to identify the most influential soil parameters on yield (van Oort et al., 2014b; van Oort and Saito, 2015). An array of prototypic scenarios composed of percolation slowed by hardpan (present/absent), soil texture (clayey vs. sandy soil, differing in water holding capacity and hydraulic conductivity), bunding (present/absent) and groundwater (20 cm, 40 cm or deep) was implemented for a multi-annual climate series of 29 sites in Africa, using local sowing dates for the main season (Fig. 7: only mean yields are presented). See supporting material for the set of soil parameters used.

Simulated mean yield across sites and years varied between 3.6 t ha^{-1} (no hardpan, sandy; soils 21–24 in Fig. 7) and 9.4 t ha^{-1} (hardpan, clayey, bunded, shallow groundwater; soil 1 in Fig. 7). Factor interactions were modelled. For example presence of bunds can have a positive effect especially in combination with high ground water or in combination with a hardpan and high rainfall. However in low rainfall environments and in rapidly draining sandy soils, bunds can be ineffective. Where water-limited yields (Yw) were low, yield variability was greater, ranging from a coefficient of variation of 24 % for soil 1 with Yw = 9.4 t/ha to CV = 63 % for soil 24 with Yw = 3.6 t/ha. Overall, the proximity of groundwater was the most influential factor for high mean yield and small yield variance. Where groundwater was inaccessible to the plant, presence of a hardpan and high soil water holding capacity (clay) was important. Unsurprisingly, yield variance tended to be greater on sandy soil. Although the results confirmed well-known factor contributions to rainfed rice yield variation, capturing such combined effects and interactions with crop and climate with a crop model is useful. In particular, it allows mapping and classifying environments according to drought risks and types of mitigating management solutions research should focus on. This sensitivity-analysis based modelling approach can also be applied to large-scale predictions of climate change impacts.

3.2.3. Large area simulations

Simulations were conducted with ORYZA2000v2n14 for yield gap analyses (van Oort et al., 2015b; van Ittersum et al., 2016; van Oort et al., 2017), drought risk analysis (van Oort, 2018) and climate change impact (van Oort and Zwart, 2018). In all rainfed rice simulations, lack of soil data was a problem. Soil texture data are globally available at high (250 m) spatial resolution (Hengl et al., 2015) and it is possible to



Soil nr	hardpan (1=yes;0=no)	SoilTexture (1=clayey; 0=sandy)	Bunds (1=yes, 250mm; 0 = no)	Groundwater depth (2= 20 cm; 1 = 40cm, 0= deep)	Yw (ton/ha)	stdev Yw	CV (%)
1	1	1	1	2	9.3	2.2	24%
2	1	1	0	2	8.4	2.3	27%
3	0	1	0	2	8.2	2.2	27%
4	1	1	1	1	7.9	2.6	33%
5	1	0	1	2	7.8	2.7	34%
6	0	1	1	2	7.8	2.3	29%
7	1	0	0	2	7.4	2.6	35%
8	1	0	1	1	6.4	2.2	35%
9	1	0	0	0	6.1	2.2	37%
10	1	0	0	1	6.1	2.3	38%
11	1	0	1	0	6.1	2.2	37%
12	0	1	0	1	6.0	2.3	38%
13	1	1	1	0	6.0	2.2	37%
14	0	1	1	0	5.3	2.2	42%
15	0	1	0	0	5.2	2.3	43%
16	0	1	1	1	5.1	2.6	50%
17	0	0	1	2	5.0	2.4	48%
18	0	0	0	2	5.0	2.7	53%
19	1	1	0	1	5.0	2.7	54%
20	1	1	0	0	4.4	2.3	51%
21	0	0	1	1	3.6	2.4	67%
22	0	0	0	1	3.6	2.4	67%
23	0	0	1	0	3.6	2.2	63%
24	0	0	0	0	3.6	2.2	63%

Fig. 7. Results of a sensitivity analysis on combinations of soil parameters on simulated rice yields. Yw is the water-limited rough rice yield at 14 % moisture content, averaged over simulations in multiple years in 29 stations across Africa. Table S1 in the supporting material provides details on the soil parameters used.

derive from these model input parameters using pedotransfer functions. However, no data are widely available for other important soil parameters, and estimates have to rely on expert opinion. Most African rice soils lack a hardpan. Bunds are common practice in lowland but not upland rice, consistent with the observation that without a hardpan bunding is less effective. Simple assumptions were made and used in the rainfed rice simulations, constituting two prototypic situations: (1) an upland soil with deep groundwater, sandy texture and no bunds (soil 24 in Fig. 7) and (2) a lowland soil with shallow groundwater, a clayey texture and bunds (soil 16 in Fig. 7). Fig. 7 shows average water-limited yield of 5.1 t/ha for a typical lowland soil (16) and 3.6 t/ha for a typical upland soil (24). The lowland/upland yield ratio, 5.1/3.6 = 1.45, is of a similar order of magnitude as that reported by Diagne (Diagne et al., 2013) for actual yields: yield (lowland) = 1.89, yield (upland) = 1.23 t/ha, giving a ratio of 1.54.

Drought risks were compared between these two soils and among climatic zones by van Oort (2018). Results showed lower yield levels and greater variation in yields (i.e. risk) for the upland. The study showed that soil related yield differences (comparing lowland vs upland within any climatic zone) are much larger than climate related yield differences (drought risk is generally smaller in lowland than in upland for all climatic zones). For any specific local prediction, however, data on relevant soil and hydrology properties are needed, beyond soil texture. This modelling exercise influenced AfricaRice's experimental characterization of inland valleys (Schmitter et al., 2015; Danvi et al., 2016).

Rainfed rice simulations assumed constant groundwater level throughout the season, which is the simplest assumption as data were absent. In reality it fluctuates. Rainfed lowland rice is grown in the wet season when run-on and water tables are high, possibly justifying the assumption. If the crop duration is shorter than the wet season, flexibility for cropping calendars and varietal duration types may be elements to improve productivity. Terminal drought, or in bimodal rainfall environments also midseason drought, are risk factors that can be evaluated by multiannual analyses. A model like ORYZA2000 can be used to simulate yield gains and risks related to calendar and variety options as a baseline for regional research priorities. However, for any location specific studies, simulations would require high quality input data on all soil parameters and local dynamics of soil hydrology.

3.3. *Yield gap analyses*

In yield gap analysis, differences between 'actual' and 'potential' yields are quantified. Often potential yields are determined through modelling but in some cases farmers' maximum yields are used. For irrigated lands potential yields are simulated, for rainfed rice water-limited yields are simulated. Actual yields are those attained by the majority of farmers. AfricaRice has a long history of yield gap analyses. The first published yield gap analyses were those by (Wopereis et al., 1999) and (Becker and Johnson, 1999) for sites in Ivory Coast, followed by a more extensive analysis across climatic zones in West Africa (Becker et al., 2003). In the 2010s AfricaRice participated in the Global Yield Gap Analysis (GYGA) project focused on quantifying yield gaps and aggregating them nationally.

At AfricaRice, much work was conducted to inform stakeholders on how to close yield gaps. Yield gap studies were combined with surveys on farmers practices to identify causes of yield gaps (Becker and Johnson, 1999; Becker et al., 2003; Tanaka et al., 2013; Nhamo et al., 2014; Tanaka et al., 2015; Niang et al., 2017; Tanaka et al., 2017; Dossou-Yovo et al., 2020; Senthilkumar et al., 2020). Many factors contributing to yield gaps are the same now as 20 years ago: weeds (particularly in rainfed systems), low inputs, bird damage and poor technical efficiency of irrigation systems. Knowledge on causes can guide tailored interventions. Yield gap information was used in analyses of national self-sufficiency. Two recent studies showed that yield gap closure alone would be insufficient to keep pace with population growth and achieve national self-sufficiency (van Oort et al., 2015b; van Ittersum et al., 2016). Massive crop area expansion would be required, even with accelerated yield increases. Rice area expansion in turn raises new research issues:

- Mapping of areas with high biodiversity value that may need protection (need for this also noted by Rodenburg et al., 2014).
- Identifying suitable areas for expansion. Windmeijer and Andriesse (1993) observed a great number of unused inland valleys in West Africa suited for rice cultivation. Recently, potential sites for inland valley development were investigated (Djagba et al., 2014;

Rodenburg et al., 2014; Danvi et al., 2016; Djagba et al., 2018; Akpoti et al., 2019, 2020).
- While national self-sufficiency may not always be achievable or economical, continued reliance on imports makes African countries more vulnerable to shocks in the international market (Puma et al., 2015; d'Amour et al., 2016; Marchand et al., 2016), as observed during the rice-price crisis of 2007/2008 (Dawe, 2010). Establishing coping scenarios will require crop simulations as input.

A method was proposed for R&D prioritization based on outcomes of yield gap analyses (van Oort et al., 2017). Highest expected return of investment for R&D interventions was hypothesized for crops and sites having moderate yield gaps and small climatic risk. In Africa, rice was shown to have a high return on R&D investment compared with sorghum or maize, although the latter are more important for food security due to the greater area cultivated. While sorghum and millet are main staples in areas that are too dry for rice and maize, rice and maize are particularly important for urban consumers. Rice is a main rural staple mainly in West Africa's coastal countries. Most food security or self-sufficiency studies do not make this rural/urban or coastal/inland distinction. Future food security studies involving modelled crop scenarios might thus be linked to within country vulnerability of different population groups.

3.4. Modelling of climate change impacts on rice

3.4.1. Impacts, causes and uncertainties

After extensive model testing and improving weather data bases, ORYZA2000v2n14 was used for a climate change impact study on rice in Africa. van Oort and Zwart (2018) showed that without varietal adaptation, yields would decrease due to shortening of crop duration. With varietal adaptation (longer duration varieties) yields might increase by +4 to +8% depending on the climate change scenario. The single exception was the hot dry season in the non-coastal Sahel zone, which was the hottest climate considered. In the current climate, daily Tmax frequently exceeds 40 °C and occasionally attains >45 °C. According to 2050 scenarios (van Oort and Zwart, 2018), daily Tmax will increase further by 3.6 °C compared to the year 2000. For this scenario, simulations predicted yields dropping by 60–80 % due to a collapse in photosynthesis due to heat. A model experiment with the "photosynthesis collapse" disabled showed hardly any yield decline.

The study identified a need for further research on photosynthesis at extreme temperatures. The ORYZA2000v2n14 version used accounted for effects of transpirational cooling on sterility but not on photosynthesis. The origin of the photosynthesis x temperature response function in ORYZA2000 (also used in ORYZA2000v2n14) is not documented in (Bouman et al., 2001) or (Matthews et al., 1995, 1997). We lack on data on rice photosynthesis at extreme temperatures. Field photosynthesis measurements in the hot dry season in Senegal (Stuerz et al., 2014a) were just below the temperature threshold at which, ORYZA2000v2n14 predicts a collapse in photosynthesis.

Does rice leaf net photosynthesis "collapse" under extreme heat? (Scafaro et al., 2016) reported a 40 % reduction in photosynthetic rate in one indica and one japonica cultivar, four hours after plant exposure to 45 °C treatment, with leaf temperature at about 41 °C. This reduction was explained by concomitant Rubisco deactivation, caused by inhibition of rice Rubisco activase (RCA) at temperatures above 36 °C. By contrast, RCA of heat tolerant *Oryza australiensis* was only inhibited above 42 °C and photosynthetic rates were not affected by 41 °C leaf temperature (Scafaro et al., 2016). It appears that rice photosynthesis gradually declines above 36 °C leaf temperature, as opposed to "collapsing".

Do rice leaf temperatures attain such >36 or >45 °C values in the field? Julia and Dingkuhn (2013) observed flag leaf and panicle temperatures in the field for four rice cvs. around flowering in different seasons and at different times of day in Senegal and the Philippines by IR thermal imagery. We re-analyzed the over 3000 observations, which ranged between 17 and 40 °C air temperature at 2 m (Fig. 8). Air relative humidity was between 10 % and 80 % (Fig. 3A) and was generally low when air temperature was high. Potential transpirational cooling thus increases with rising air temperature. As air temperature increased from 30 to 40 °C, leaf temperature only ranged from 23 to 31 °C (Fig. 8, top) depending on humidity, windspeed and radiation. Leaf temperature never exceeded 32 °C even at 40 °C air temperature. Panicle temperature behaved similarly, but at a level of several °C warmer (Fig. 8, bottom).

By extension, the data suggest that for the leaf to attain the critical temperature of 36 °C for photosynthesis, air temperature must exceed 46 °C (if we suppose that the observed cooling effect at 40 °C in Fig. 3 (top) constituted was the physiological maximum), or even much higher (if we suppose that transpirational cooling will further increase). In conclusion, the leaf temperature of irrigated rice is unlikely to inhibit leaf photosynthesis in any current climate, and even the conceivable scenarios for global warming are unlikely to have major effects on it. Crop models that accurately simulate leaf temperature can thus probably ignore heat stress effects on photosynthesis, under the condition that water deficit does not occur, which would affect the leaf and panicle cooling capacity. Likewise, transpirational cooling is reduced under increased atmospheric CO_2 concentration due to stomatal response as observed in rice Free-Air Carbon dioxide Enrichment (FACE)experiments (Oue et al., 2005), which in turn shifts anthesis to times of day (Kobayasi et al., 2019). This should be considered when simulating the impact of future climate scenarios.

In the light of these findings, the ORYZA2000 study on climate change impacts in Africa (van Oort and Zwart, 2018) certainly overestimated heat stress effects on irrigated rice photosynthesis in the Sahelian inland dry season. Predictions for other parts of Africa were below the "collapse" temperature and therefore deemed more accurate. The more realistic scenario in (van Oort and Zwart, 2018) which removed the heat stress effects on photosynthesis showed for Sahelian

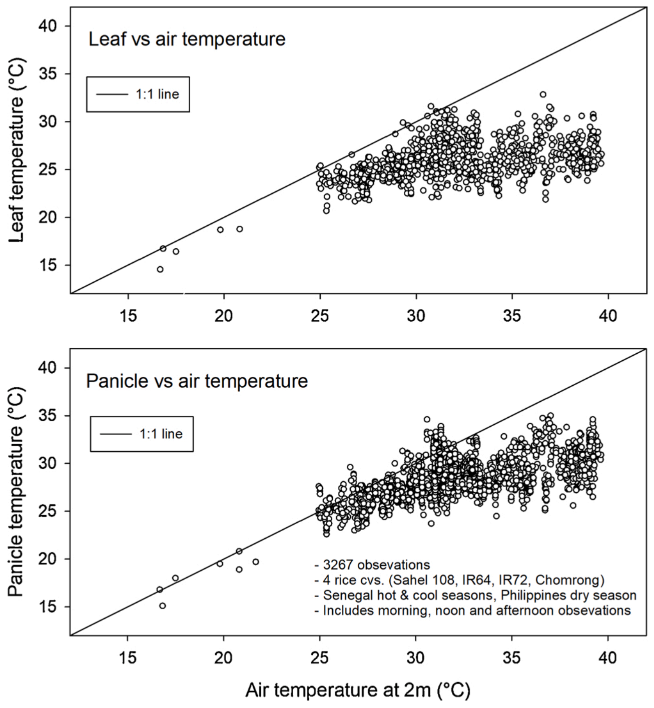


Fig. 8. Relationship between flag leaf (top) and panicle (bottom) temperature vs. air temperature at 2 m for irrigated rice during flowering, confounding different sites, seasons, times of day and genotypes. Underlying study was published by Julia and Dingkuhn (2012 & 2013). IR imagery data were re-analysed from Ph.D. thesis by C. Julia, Montpellier, France 2013.

inland dry season irrigated rice much less yield reduction, as we will also show in the following section. For further research, a model version is needed that considers transpirational cooling of leaves and models photosynthesis as a function of leaf rather than air temperature. To develop improved models, the data resource generated by (Julia and Dingkuhn, 2013) will be helpful. Additional experiments exploring the effect of even more extreme heat conditions (45 °C and above) on photosynthesis, growth, phenology and spikelet sterility will be necessary. They should also cover water limited conditions. Such experiments are technically difficult because leaf porometers and phytotrons reach physical limits under extreme heat and/or humidity, and extrapolation to field conditions remains fraught with uncertainty. For field experiments, the hottest rice environments in Africa also tend to be poorly accessible. Developing an accurate rice crop model for extremely hot climates may thus require dedicated research equipment and access to proxy field sites outside the Sahel.

3.4.2. Adaptation options

In their study on climate change impact on irrigated rice (van Oort and Zwart, 2018) analyzed only one adaptation option, i.e. longer duration varieties to compensate for shorter growth duration caused by climate change. In a follow-up study (van Oort et al., 2019) used the CCC model to explore three possible adaptation options to climate change: (1) change in variety, with different phenology (2) change in sowing dates and (3) change in number of crops per year. In Fig. 9 we present new results without photosynthesis collapse. We compare the current situation (a) with three adaptation options (b,c,d) for the worst case climate change scenario (RCP8.5, 2050): (b) case without adaptation, (c) adoption of longer duration varieties and (d) current variety with sowing dates shifted to maximize aggregate annual potential yield. Without adaptation (Fig. 9a,b), aggregate annual potential yields drop from 17.1 to 14.9 t ha-^{1}. With varietal change towards longer duration varieties potential yields may increase from 17.1 to 19.0 t ha^{-1}. Big shifts in sowing dates with the current popular variety could increase aggregate potential yield from 17.1 to 17.9 t ha^{-1} (Fig. 9a,d). Varietal adaptation (Fig. 9a,c) gives larger yield gains than shifting sowing dates with the current variety (Fig. 9a,d). We observe that Fig. 9 (without photosynthesis collapse) shows very different outcomes from those reported in (van Oort et al., 2019) (with photosynthesis collapse at extreme temperatures). For example for the scenario without adaptation, future yields would be 2.4 + 7.8 = 10.2 t/ha with collapse (van Oort et al., 2019) and 6.7 + 8.2 = 14.9 t/ha without collapse (Fig. 9b). Note especially the large difference in simulated future yield in the hot dry season (2.4 vs 6.7 t/ha). It shows once again how sensitive model outcomes can be to our understanding of how transpirational cooling affects not only sterility, but also photosynthesis.

These analyses show the potential of models to explore adaptation options to climate change for irrigated rice in the Sahel. Adaptation options should be validated experimentally and their local acceptability evaluated with farmer participation. They may conflict with calendars for other activities (e.g., labor demand for dryland or vegetable crops), the rapid succession of two rice crops proposed here may be impractical, and interannual variation timing/intensity of cold spells may affect the cold-dry season rice crop. Our example illustrates how crop modelling can stimulate participatory on-farm research towards technological innovations.

4. Lessons learnt

4.1. Scientific

Given the large diversity of African rice environments and systems, the limited crop and environment data, the limited availability of suitable modelling tools and the presence of only one modeler at AfricaRice in the 1990s and 2010s, hard choices had to be made – both in terms of priorities and simplifications/assumptions with respect to the systems' complexity. In an applied research context expected to generate impact in a reasonable time, the choices are further constrained.

The main modelling foci implemented were (1) thermal constraints in irrigated rice vs. genotype and cropping calendars and (2) mapping potential and water-limited yields across environment typologies, regions and scenarios of climate change. The two foci used fundamentally different approaches: experiments and custom-made models for (1), application of existing models and expert assumptions to collated, large-scale data resources for (2). Biotic stresses were generally not modelled. Approach (1) concretely impacted varietal development and adoption and also generated new physiological and genetic knowledge. A major scientific learning was the role of leaf and panicle transpirational cooling as a very effective heat avoidance mechanism. Approach (2) probably influenced the institute's and also NARS' research agenda (through the regional Task Force network: www.africarice.org/africa-wide-rice-task-forces), but in the first place it exposed massive data and knowledge gaps particularly on soil- and hydrology-based yield limitations in rainfed systems, raising a humbling host of research questions. Both approaches were complementary, e.g. in stimulating attempts to scale up plot-level stress simulations to regional or cropping systems scales.

Among the emerging research questions we want to highlight a few:

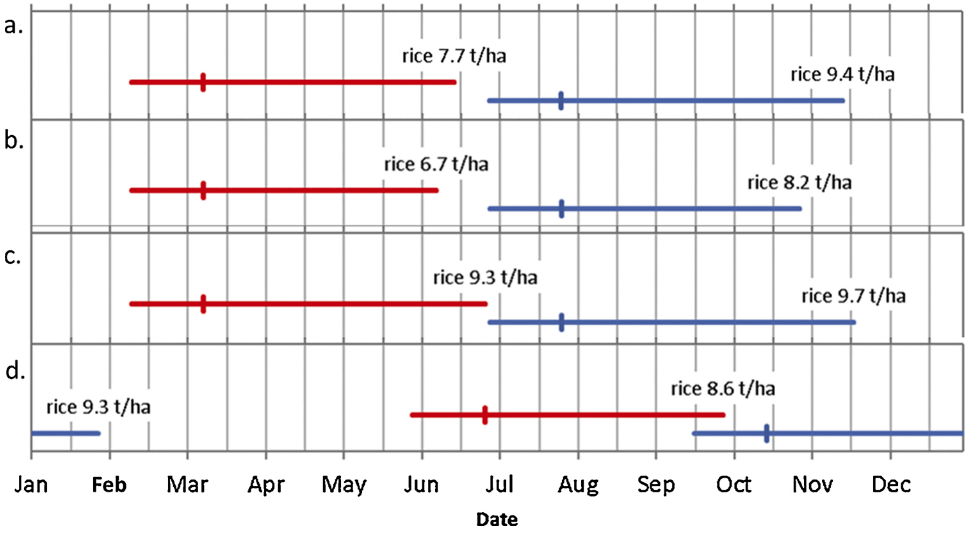


Fig. 9. Simulated cropping calendars and potential yields in Niono, Mali. Four cropping calendar scenarios are shown: (a) current cropping calendars & variety, climate around year 2000 and simulated future yields (b,c,d) with the RCP8.5 scenario for the year 2050 and the ORYZA2000v2n14 version without photosynthesis collapse:(b) no adaptation: current cropping calendars & variety, future climate; (c) varietal adaptation: a longer duration variety; (d) sowing date adaptation: current variety with sowing dates maximizing aggregate rice yield in the future climate. Small vertical lines are transplanting dates, thus in 8d, the nursery of the blue crop starts before harvesting of the red crop; the crop blue is transplanted 17 days after harvesting of the red crop. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

- Given the importance of transpirational cooling, are there present or future environments in which day-time heat stress would cause major yield reductions through spikelet sterility and/or photosynthetic inhibition? How would this play out under water limitation, and what are the trade-offs between transpirational cooling and water-saving? Is there genetic diversity for transpirational cooling and how can it be phenotyped affordably?
- How can crop models get a better handle on drought risks in rainfed valley bottoms and fringes (water run-on and run-off, groundwater dynamics and surface storage, crop submergence) without resorting to extreme model complexity and input data requirements?
- Water-limited crop performance depends on rooting depth. How variable is it under the variable soil texture, compaction, (an)aerobiosis and fertility in submersible valley bottoms and fringes? How can rice crop models be improved to predict it?
- As a general problem encountered, physiological crop parameters tend to lack robustness across diverse environments although they are supposed to be “genetic”. Sterility response to chilling was mentioned as an example, possibly requiring the simulation of acclimation as remedy. Another example is photoperiod response of flowering, which can be easily parameterized for different sowing dates or latitudes, but not always both (Dingkuhn, pers. observation). Multi-environment predictions of spikelet load per panicle or field area also tend to be poor and require more investigation.

Models are not magic bullets that will tell us what to do. In an applied research context models should be tailored to address the specific issues breeders, agronomists, policy researchers and others are working on. When necessary, models can be further elaborated or new models can be developed. Awareness of the application domain and uncertainties of models is necessary to avoid promising more than one can deliver. For example, given the paucity of soil data we have always refrained from providing sowing date advice for rainfed rice. Optimal dates depend on the frequently unknown local soil and hydrological conditions. Predictions of “safe” sowing dates would be very useful given the importance of drought in African rice (van Oort, 2018), but this will require sufficiently accurate data and well validated models.

4.2. *Organizational*

There is obviously an institutional trade-off between investment in applied, technology developing research (e.g., breeding or agronomy) and strategic research support (e.g., crop modelling). We hope to have demonstrated the synergies, but as a dollar can be spent only once, achieving critical mass for both can be difficult. Crop modelling also requires dedicated experimental work that binds research capacity in other disciplines.

This review paper shows how AfricaRice modelling efforts have been linked to local issues and integrated in breeding and agronomy work. It is important for the modeler to be present on site, develop a good understanding of the issues breeders, agronomists, extension workers and policy researchers are working on. Continuous presence is impossible as a researcher is often based in one station whilst running projects all over the continent. Site visits, frequent interactions with scientists in other stations and interactions with national researchers are critical. The advent of the internet over the past decades has greatly facilitated online collaboration but should never replace being present on the ground (feet in the muddy waters). We suggest that modes of collaboration with “detached” modelers acting as simple service providers are rarely effective.

At a small, impact-oriented institute like AfricaRice, sustaining a multi-disciplinary research agenda in which breeding, agronomy and other disciplines collaborate with crop modelers can be challenging. Too often we have seen these disciplines work in isolation, while as we have shown in this paper, much is to be gained from collaboration. Critical are (1) a consensual thematic focus, grouping complementary research objectives around a core plan to generate impact; (2) nesting the modeler in a multi-disciplinary team that understands the practical benefits of a systems approach, whatever its scale and scope may be; and (3) team-wide responsiveness to new research questions that will inevitably emerge.

Declaration of Competing Interest

The authors report no declarations of interest.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2021.108074.

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