Abstract

Feeding the future world population requires increased crop production. Here, we investigate the intensification option of increasing production by increasing cropping intensity and choice of varieties with different crop duration. We developed a model to generate, compare and visualise opportunities for single/double/triple cropping systems consisting of irrigated rice and optionally a vegetable. The model was applied in a case study in the Senegal River valley. Results showed that with appropriate choice of sowing dates, severe cold sterility in rice can be avoided, also in rice-rice crop rotations. At optimal sowing dates, simulated total long term average potential yields of single, double and triple cropping yields were 10.3, 19.0 and 18.9 t/ha respectively (total of 1, 2 and 3 yields). With a hypothetical completely cold tolerant variety, yields could increase to 11.2, 20.2 and 20.9 respectively. Simulated Triple crop yields are hardly any higher than those of a double crop with two medium duration varieties. Delay in sowing due to late availability of resources (machinery, irrigation water allocation within a scheme, credits for pump fuel) is a known problem in the region. Therefore we also simulated how much delay was possible (width of the sowing windows) whilst still allowing for double cropping. We found enough delay was possible to allow for a rice-rice or a rice-vegetable crop. A rice-rice-vegetable triple cropping system would only be possible without delays and with a very short duration vegetable of 2 months. Most promising options to increase production are through shifting the sowing date to facilitate double cropping, adoption of medium duration varieties and breeding for cold tolerant varieties.
1 Introduction

Global demand for agricultural crop production is expected to roughly double by 2050 (Kastner et al., 2012). The challenge of meeting demands of a growing population can be met by increasing yields on existing land, bringing new land into cultivation or imports from other parts of the world (Van Oort et al., 2015b). The options for bringing new land into cultivation may be limited, as often the suitable lands are already in use (Hall and Richards, 2013; Young, 1999). Reliance on imports can be a solution only when pressure on land and water is less in exporting countries. Although the relation between high import dependency and poverty, price fluctuations and food riots or political instability is complex and dependent on many factors (Natalini et al., 2015), a number of studies suggest that such relations do exist (Sternberg, 2012; Weinberg and Bakker, 2015; Wischnath and Buhaug, 2014).

To increase production, most researchers advocate increasing yields on existing land, referred to as intensification. The two main intensification options are: (1) closing the yield gap and (2) increasing the number of days in the year in which the land is used for crop cultivation (Cassman et al., 2003; Foley et al., 2011; Garnett et al., 2013; Pretty et al., 2011; Ramankutty and Rhemtulla, 2012; van Ittersum et al., 2013). Breeding can contribute to this through the development of high yielding and stress tolerant varieties (Evenson and Gollin, 2003) and varieties with “optimal” phenology.

In irrigated areas an important question for breeders is whether they should select for shorter duration varieties which would enable growing two or even three crops per year, or alternatively breed for medium/long duration varieties that yield more per individual crop but possibly restrict options for growing two or three crops per year. The same question is relevant for farmers, who decide on what varieties to include in their crop rotations. The answer to this question on short versus medium duration varieties depends on how many days exist within the year with a favourable climate. At high latitude locations only one crop may be possible per year because of low temperatures and low radiation levels in the colder half of the year. There, extending the length of the growing season of a single crop may have more prospects. Or, when a yield plateau is reached at
a certain crop duration, an intensification option is growing a vegetable crop or cover crop in
autumn, after harvesting a winter cereal in summer. Moving closer to the equator the number of
favourable days increases and so the choice between single/double/triple cereal cropping becomes
more pertinent; all three should be considered. Clearly, when researching options for intensification
we should take into consideration the climate. We should not only look at intensification options for
individual crops but also implications for the viability of crop rotations.

Ideotyping has in the past (Dingkuhn et al., 1991) and more recently again (Rötter et al., 2015) been
proposed as a method in which crop growth models can be used to identify the optimal combination
of morphological and/or physiological traits in a crop, for optimizing performance in a particular
biophysical environment and crop management package. Ideotyping to date has remained very much
focussed on individual crops. There have been no ideotyping studies in which trait optimisation has
been conducted in the crop rotation context. A few models have been proposed for comparing crop
rotations (Dogliotti et al., 2003; Huong et al., 2014) but with these it is difficult to simulate in detail
climatic risks and effects of varietal differences. With other models such as APSIM and DSSAT crop
rotations can be simulated and climatic risks quantified (Jones et al., 2003; Keating et al., 2003)
(Holzworth et al., 2014; Jones et al., 2003), but these models do not allow for easily generating and
comparing very large numbers of cropping calendar options and varietal traits. What is missing is a
model that allows for generating and comparing large numbers of crop rotation x ideotype options
whilst at the same time also simulating climatic risks of crops in these rotations.

In this study, we analyse the scope for intensification at a site in Senegal, near the town of Fanaye,
representing the middle valley of the Senegal River in the Sahel. The study area has three seasons: a
cold dry season (Nov.-Feb.), a hot dry season (Mar.-Jun.) and a warm wet season (Jul.-Oct). The area
is sparsely populated and ample irrigation water is available. Important crops are rice, tomato and
onion. These crops are grown for home consumption and for the market. Scope for rice
intensification in this study area has been extensively studied in the 1990s as reported in the book by
Reflecting on the various contributions to this book, (Matlon, 1997), noted a number of knowledge gaps including the need to look more broadly for other options and not only at rice-rice double cropping. The second gap in the research reported in the book by (Miezan et al., 1997) as noted by (Matlon, 1997) was the lack of adequate consideration of the farmers’ perspective.

Since these critical comments by (Matlon, 1997), there have been more studies on the farmers’ perspective. Causes of yield gaps were identified as poor supply of labour, unavailability of machinery, lack of credits to purchase inputs (fertiliser, herbicides, certified seeds), inappropriate timing of fertiliser application and poor timing of allocation of irrigation water within the irrigation scheme as important constraints (Haefele et al., 2002; Krupnik et al., 2012; Tanaka et al., 2015). The original analysis of scope for rice-rice double cropping by Dingkuhn (1995) was later followed up by (Poussin et al., 2006; Poussin et al., 2005) who considered labour organisation of different operations in rice cropping within an irrigation scheme. Three challenges that have not been taken up are (1) broader systematic exploration of options for intensification including vegetables, (2) link to ideotyping where not only sowing dates of the 2 to 3 crops in the rotation are varied, but also crop traits such as crop duration and tolerance to cold-induced sterility and (3) analysis of flexibility: is double or triple cropping also possible if sowing of crops is delayed, for instance due to lack of machinery, seeds or water allocation? If so, how much delay is possible?

The only previous study which did look in a systematic manner into options for intensification was by Dingkuhn (1995). Dingkuhn compared single and double rice cropping options. Specifically for our study area, he concluded that double cropping is “possible but subject to severe time constraints”. These time constraints were caused by the difficulty of fitting two crops in one year, a required period between the two crops and the need to avoid periods with heat and cold sterility. It is interesting therefore in such a site to investigate if twenty years later the situation has changed and opportunities for double cropping have increased. Since the 1990s, a number of developments have
taken place on the ground that call for new cropping calendar research: (1) double cropping has expanded at this site especially in the last 5 years with government promoting rice production (Diagne et al., 2013) and (2) several additional short duration varieties have been introduced. At the time of Dingkuhn (1995), medium variety Jaya was most popular, with a duration for direct seeded rice ranging from 118-192 days depending on sowing date (Sié et al., 1998). Since then, short duration variety Sahel108 with a duration from sowing to maturity of 96-155 days (direct seeded rice) has become a popular variety among farmers (Tanaka et al., 2015). Also science has advanced since the 1990s. Recently new research on phenology (van Oort et al. (2011)) and sterility (Julia and Dingkuhn (2012, 2013)) has been incorporated into the ORYZA2000 crop growth model (Van Oort et al. (2015a)) which allows for simulating not only sterility risk but also yield. One of the findings of this latest study was that good yields can still be obtained at moderate levels of sterility (say <30%); this is possible only if enough spikelets and biomass have been formed at flowering. For a source limited crop, a limited reduction in the sink size (=fertilised spikelets) has no effect on yield. This finding suggests that the previous selection of “safe” sowing windows by Dingkuhn (1995), based on simulated sterility was perhaps too strict.

Farmers face many constraints and research should consider their objectives and constraints. It is impossible to include all farmers’ perspectives here. And it can also be interesting to move beyond the current situation, to systematically explore what would be possible if farmers’ constraints would be alleviated. We address all the above mentioned issues in the following way in this paper. Firstly, we include in a rudimentary way a vegetable in our analysis of possible crop rotations. Secondly, we consider two different farmers’ objectives: yield maximisation and maximisation of yield per unit time. Thirdly, we investigate not only optimal sowing dates but also sowing windows. These sowing windows tell us how much temporal flexibility there is in the cropping calendar. We developed a model for constructing cropping calendars, which was linked to the ORYZA2000 model for rice. For the vegetable crop, we simply blocked a part of the year. With this part of the year blocked, we used ORYZA2000 to simulate potential yields as a function of sowing dates of the rice crop(s).
The biggest steps in intensification can be made by increasing the number of crops grown per year (cropping intensity). Smaller steps in intensification can be made by growing medium instead of short duration varieties. Both intensifications are considered in this paper. In order from least intensive to most intensive we compared the following crop rotations:

1. Rice only (single)
2. Rice-vegetable (double)
3. Rice-rice (double)
4. Rice-rice-vegetable (triple)
5. Rice-rice-rice (triple)

In relation to ideotyping, we consider two traits relevant for the current study area: crop duration and tolerance to cold sterility. A logical follow-up to the current study would be to also quantify vegetable production, optimise the sowing date for vegetables and add a gross margin calculation. Such was impossible at the time of writing due to lack of data on vegetables and whole farm economics.

2 Materials & Methods

In the following sections we describe the methods for cropping calendar construction, the phenological models, the crop growth model and the weather data. We simulated potential yield. Potential yield is yield of a crop free from weeds, pests and diseases, with ample nutrition and water and with no soil constraints. Therefore no soil data or irrigation data were needed. Although actual yields are often much lower than potential, phenology and response to climatic risks is similar both in actual and potential production. All simulated yields reported in the paper are long term average potential yields, i.e. averaged over simulations of 20 years of weather data.
2.1 Cropping calendar construction

A new cropping calendar construction (CCC) model was developed to investigate intensification options. The CCC model generates input data for a stand-alone crop growth model, in this case the ORYZA2000 model. The input file for ORYZA2000 is the so-called “rerun” file and is commonly used for conducting bulk simulations with the “Wageningen” family of crop growth models (van Ittersum et al., 2003). An earlier test (not shown) confirmed that the same CCC model could also be used to investigate options for potato double cropping simulated with the more widely used WOFOST model.

For this study cropping calendars were constructed from all possible combinations of the following components:

1. Site: Fanaye in Senegal, about 150km inland (16.633 N, 14.917 W) with 20 years of weather data to capture climatic variability (years 1994-2013). This site is representative of the middle valley of the Senegal River in the Sahel.

2. 36 sowing dates: from day 10 to day 360 in steps of 10 days.

3. 5 Varieties with different maturity periods. We defined a baseline variety (Sahel108) and hypothetical varieties that would mature systematically earlier (-20, -10 days) and later (10, 20 days), by adjusting the length of the basic vegetative phase (BVP). Of the different growth stages in rice this phase is known to be the most variable (Vergara and Chang, 1985). As the baseline variety Sahel108 is a short duration variety, the -10/-20 days varieties can be considered ultra-short duration varieties and the +10/+20 days varieties can be considered medium duration varieties.

4. 2 Varieties differing in cold tolerance: normal cold sensitive and newly developed completely cold tolerant. The latter is more “hypothetical” and serves to quantify yield losses due to cold sterility, or alternatively, potential yield gains possible if breeders develop or identify such a suitable cold tolerant variety.

5. Minimum 20 days between harvesting one crop and sowing the next (DURHASOW = 20). With two crops, 2*20 = 40 days are reserved for this, with 3 crops, 3*20=60 days are reserved for the
period in between crops. Note that 20 days is the minimum, actual duration between two crops can be larger. One of the model outputs is the width of the sowing window; a wide sowing window indicates the rotation is possible even with much delay between two crops.

6. Different parts of the year were blocked for vegetable cropping: December-April (5 months) which is a normal duration for onion or tomato, December-January (2 months) and January-February (2 months). We anticipate that a rice-rice-vegetable rotation will not be practically possible with a 5 month vegetable crop. We use the scenarios with 2 month vegetables to explore if triple cropping would be possible if such a short duration vegetable could be found.

For each possible crop rotation two sets of 3600 simulations (36 sowing dates, 5 varieties, 20 years) were conducted: one set for a cold sensitive variety and one for a cold tolerant variety. Thus in total 5*2 = 10 varieties were compared. In total 16 crop rotations were simulated. The CCC model constructs all possible single/double/triple sowing date configurations, taking into account that:

1. Growing periods may not overlap and this should also go well across calendar years.

2. There must be at least DURHASOW days between harvesting one crop and sowing the next crop. This rule is applied both for the rice and the vegetable crop.

3. We considered only closed annual crop rotations, i.e. we fitted two or three crops into one year. The option of growing for example 5 crops in 2 years (e.g. see Huong et al. (2014)) was not considered because of the increased chance that one of these 5 crops would be a rice crop exposed to severe cold sterility in the cold dry season.

After constructing all possible sowing date configurations for a given crop rotation the CCC model automatically sorts the selected sowing date configurations either maximising total yield or maximising total yield per total duration.
To assess the sensitivity of cropping calendar optimisation to uncertainty in phenology models, we compared simulated crop duration, simulated potential yield and optimised cropping calendars constructed with two different phenological models. Direct seeding is most common in our study area; therefore we considered only direct seeding systems. From the study site (Fanaye) plus a second site (Ndiaye), a dataset with sowing date and emergence data was available. This set was used to develop a model to predict the number of days from sowing to emergence (§2.2.1).

Simulations with ORYZA2000 start at emergence. From historical data (2008-2014), n=55 data points were available with data on sowing date, 50% flowering date and maturity date. For this dataset we first estimated the emergence date as in §2.2.1. Limited data were available on duration from panicle initiation to flowering. Based on earlier research by (de Vries et al., 2011) we estimated this duration at 28 days. For the phases from emergence to panicle initiation, panicle initiation to flowering and flowering to maturity, two phenological models were applied, one using the more common temperature sum based approach (§2.2.2) and one with crop duration as an empirical function of sowing date (§2.2.3).

### 2.2.1 Sowing to emergence

ORYZA2000 simulations start at emergence. A simple empirical model was used to predict emergence day as a function of sowing day (Fig. 1a). Pre-germinated seed was direct-seeded (common practice in our study area) and duration to emergence recorded. Total duration from sowing to emergence (DURSOWEM) was predicted as a function of Sowing Day (SOW). For the study site considered in this paper a bilinear-exponential model proved to give the best fit:

\[
DURSOWEM = \begin{cases} 
    d_{urS} + b_{1LS} \times (SOW - doyS), & d_{oyS} < SOW \leq d_{oyL} \\
    d_{urL} + b_{1LE} \times (1 - e^{b_{2LS} \times (SOW - doyL)}) \quad & d_{oyL} < SOW \leq 365 \\
    d_{urL} + b_{1LS} \times (1 - e^{b_{2LS} \times (SOW - doyL + 365)}) \quad & 0 < SOW \leq d_{oyS}
\end{cases}
\]

(1)

Where \(d_{urS}\) and \(d_{urL}\) are the shortest and longest durations from sowing to emergence in days, \(d_{oyS}\) and \(d_{oyL}\) are the sowing days on which the shortest and longest durations occur and parameters...
b1SL, b1LS and b2LS are estimated such that the linear and exponential curves connect at doyS and doyL and the best fit through observed durations is obtained. Parameters used in this model are listed in Table 1.

INSERT ABOUT HERE TABLE 1

2.2.2 TSUM model

Emergence day EMD was calculated as SOW + DURSOWEM. To simulate subsequent phenological phases we used cardinal temperatures as reported by (van Oort et al., 2011) for the baseline variety Sahel 108 (IR 13240-108-2-2-3): TBD = 15°C, TOD=34°C and optimal development at temperatures higher than TOD. Development rates reported by (van Oort et al., 2011) were originally calibrated for transplanted rice in two sites (Ndiaye and Fanaye) and showed interaction with the estimated transplanting shock parameter. To avoid bias, we proceeded with the abovementioned cardinal temperatures and estimated new development rates DVRI, DVRJ, DVRP and DVRR as used in ORYZA2000, such that average predicted duration equalled average observed duration for the different developmental stages in Fanaye. These development rates are defined as follows:

- DVRI and DVRJ are for the phase from emergence to panicle initiation. Since previous analyses showed the baseline variety Sahel 108 is not photoperiod sensitive (van Oort et al., 2011), the same development rate was assumed for the whole period from emergence to panicle initiation (PI), i.e. not making a distinction between development rate for the basic vegetative phase (DVRI) and the development rate for the photoperiod sensitive phase (DVRJ). Development for this combined phase was calculated as DVRI = DVRJ = (0.65-0)/TT_{EMDPI} with 0 for development stage “Emergence”, 0.65 is the development stage at which PI occurs and TT_{EMDPI} is the minimum duration (in days) from emergence day EMD to panicle initiation day PI, which we would theoretically find if the variety were constantly grown at optimal temperature;

- DVRP= (1.0-0.65)/TT_{PIFL} = Development rate for the panicle development phase, which runs from development stage 0.65 to 1.0, starting at panicle initiation (PI) and ending at 50% flowering (FL)
and $TT_{PIFL}$ is, in analogy with the above, the minimum duration of this phase in days, which we would theoretically find if the variety were constantly grown at optimal temperature;

- $DVRR = (2.0-1.0)/TT_{FLM}$ = Development rate for the grain filling (reproductive) phase, which runs from development stage 1.0 to 2.0, starting at flowering (FL) and ending at maturity (M).

This resulted in $DVRI=0.018712$, $DVRL=0.018712$, $DVRP=0.019009$ and $DVRR=0.058208$. Note that these development rates were calculated not with temperature sums (unit oCd) but with normalised thermal time $TT$ (unit d). Both approaches give exactly the same results. Phenology modellers prefer using normalised thermal time $TT$ because it allows for more easily comparing models with different cardinal temperatures (van Oort et al., 2011; Yin et al., 1995). Figure 1b shows observed and simulated duration from emergence to maturity.

Next, to simulate shorter and longer duration varieties, development rates $DVRI$ and $DVRL$ were multiplied with 0.7, 0.85, 1, 1.15 and 1.3 (+/-30% and +/-15%). These percentages were chosen such that with 1.3, the average increase in duration was 20 days, same as with the SOWDOY model below. Only $DVRI$ and $DVRL$ (for the vegetative phase from emergence to panicle initiation) were adjusted, because it is known that this phase shows greatest genetic variation between varieties (Vergara and Chang, 1985).

**2.2.3 SOWDOY model**

A similar model as in equation 1 but with different parameter values, (Table 1) was used to predict the total duration from emergence to maturity ($DUREMMAT_b$) for the baseline variety Sahel 108 as follows:

$$DUREMMAT_b = \begin{cases} 
\text{durS} + b1LS \times (EMD - doyS) & \text{doyS} < EMD \leq doyL \\
\text{durL} + b1LS \times (1 - e^{b2LS \times (EMD - doyL)}) & \text{doyL} < EMD \leq 365 \\
\text{durL} + b1LS \times (1 - e^{b2LE \times (EMD - doyL + 365)}) & 0 < EMD \leq doyS \end{cases}$$

For shorter or longer duration varieties we calculated $DUREMMAT$ as:
\[ DUREMMAT = DUREMMAT_b + DELTADUR \] (3)

Where \( \text{DELTADUR} = [-20, -10, 0, 10, 20] \) generates varieties with 20/10 days shorter duration to 10/20 days longer duration relative to the baseline variety in time steps of 10 days with duration.

\[ \text{DUREMMAT}_b. \] Phenology was modelled as three phases: vegetative (\( \text{DUREPI} \), days from emergence to panicle initiation), reproductive (\( \text{DURPIF} \), days from panicle initiation to flowering) and grain filling (\( \text{DURFLM} \), days from flowering to maturity). According to Vergara and Chang (1985) durations.

\[ \text{DURPIF} \text{ and DURFLM compared with DURSPI are relatively much less sensitive to temperature. We therefore fixed them as constants (DURPIF = 28d, DURFLM = 25d, Table 1). The duration of the vegetative phase was then calculated as:} \]

\[ DUREPI = DUREMMAT - DURPIF - DURFLM \] (4)

Note that in this way, varietal differences in crop duration (eq 3) are only in the duration of the vegetative phase (eq 4).

### 2.3 ORYZA2000

#### 2.3.1 Subversions

Three adapted versions of the ORYZA2000 model were developed, based on model comparisons in [Van Oort et al. (2015a)](https://doi.org/10.1016/j.agee.2015.06.012). Subversion ORYZA2000v2n13s14 (s14 in short) is fully documented in Van Oort et al. (2015a). Subversion s27 was newly developed for this paper. This subversion is identical to subversion s14, with one change, namely the phenological sub-model was replaced by the SOWDOY model (§2.2.3).

Subversion s28 is similar to subversion s27, but with cold sterility equations and parameters set back to the original equations for ORYZA2000. These original equations predict no cold sterility in the Fanaye location (Van Oort et al. (2015a)).

Thus subversions s14 and s27 represent the normal variety and subversion s28 represents a hypothetical completely cold tolerant variety. Whether such a variety can be found in other parts of
the world or bred specifically for the Sahel region is a topic for further research. This study is exploratory in the sense that it shows what yield gains and calendar modifications would be possible if such a variety were found.

2.3.2 Validation
In this paper we validated the s14 and s27 models with the following observed datasets:

1. observed Sahel 108 yield data from (de Vries et al., 2011) with 15 monthly staggered sowing dates in Fanaye in 2006 and 2007
2. observed IR64 yield data from (Stuerz et al., 2014) with 6 bi-monthly sowing dates in Fanaye in 2009/2010. Previously (de Vries et al., 2011) showed that crop duration and yield levels of Sahel108 and IR64 are similar.

2.4 Weather data
Weather data were taken from the AfricaRice weather stations which have over time been operational at the Fanaye site. This weather station dataset showed many gaps. Missing data were filled in with data from the POWER database (http://power.larc.nasa.gov/). The POWER database is known to have systematic errors in its minimum and maximum temperature while radiation values compare well with station data (White et al. (2008); White et al. (2011)). Therefore daily Tmin and Tmax were corrected following the procedure described by (Van Wart et al., 2015). We are not aware of validation studies in which the accuracy of relative humidity in the POWER database was tested. For our study site we found a large difference between long term average mean daily relative humidity in POWER (32%) and our station data (45%), see figure 2b. Therefore, the same method developed by (Van Wart et al., 2015) for correcting Tmin(POWER) and Tmax(POWER) was also applied to correct the dew point temperature Tdew(POWER). The difference between RH(POWER) and station RH is not that strange if we consider that RH(POWER) is a spatial average over a satellite pixel of approximately 110km size, which includes a lot of dry savannah surrounding the Senegal river, whereas the AfricaRice weather station is located close to the river and surrounded by flooded...
paddy fields, from which evaporating water contributes to a higher relative humidity. Annual CO2 concentrations were taken from the Mauna Loa record and effects of CO2 were modelled as described in (Bouman et al., 2001).

### 2.5 Observed sowing dates

This paper is exploratory in the sense of investigating which crop rotations are viable and within these, which sowing dates give highest long term average potential yields. We compared optimised sowing dates with observed sowing dates. A comparison of causes of discrepancies, including climatic and socio-economic drivers, was beyond the scope of this paper. Farmers’ sowing dates for the wet season were extracted from unpublished survey data by M. Diagne (co-author of this paper). Surveys were conducted from 2002 to 2010 among on average 45 farmers per year in our study area, from these we identified annual earliest and average sowing dates per year.

### 3 Results

#### 3.1 Phenology

Figure 1a shows days from sowing to emergence. Duration ranges from 3 to 8 days and is longer in the colder part of the year. Figure 1b shows observed and simulated duration from emergence to maturity. The temperature sum (TSUM) based model predicted duration from emergence to maturity with a root mean square error (RMSE) of 8.3 days and a maximum error of 19 days. For sowing on day 100-150 the TSUM model predicted systematically shorter duration than observed. During day 250-300 the TSUM model predicted systematically longer duration than observed. With the SOWDOY model the duration from emergence to maturity is predicted with a root mean square error (RMSE) of 5.7 days and a maximum absolute error of 16 days. Similar RMSE values were reported before in (van Oort et al., 2011). The effect of biased phenology predictions was reported in (Van Oort et al., 2015a), figure 1b shows both phenology have little to no bias. By reporting long term average potential yields, one may expect cancelling out of errors of overestimation of duration and
underestimation of duration. We therefore consider the accuracy acceptable for the study presented here.

The SOWDOY model predicts duration more accurately than the TSUM model and avoids the systematic errors made by the TSUM model during days 100-150 and 250-300. Predictions by the two phenological models are not identical but are quite similar. Therefore one may expect conclusions on intensification options based on the two models to be similar. To avoid duplication of results we present in the sections below only the results of the most accurate (=SOWDOY) phenology model. In section 4.2 we discuss sensitivity of our results to the choice of the phenological model.

### 3.2 ORYZA2000

Figure 3 shows validation results for simulated yields in specific years. Clearly, model predictions are not perfect. Both the s14 and the s27 models underestimate high yield levels observed by De Vries et al in 2006 for the 20 March and 18 April sowings. There are also large discrepancies within and between the two observed datasets. The very high yield levels observed by de Vries et al. for the March/April 2006 (10.2 and 7.6 t DM ha-1) were not observed in his 18 March/18 April 2007 sowings (6.4 and 5.0 t DM ha-1) and also not by Stuertz (19 April 2010 sowing: 7.7 t DM ha-1). Average predicted yields for these March/April sowing dates were 6.8 and 5.8 t ha-1 with the s27 and s14 models. Mean errors (averaged over all sowing dates) were -0.455 t DM ha-1 and -0.642 t DM ha-1 with the two phenology models (SOWDOY model s27 and TSUM model s14). The higher yields and higher accuracy with model s27 are consistent with the longer and more accurate predicted growing period for sowing in the March-April period (DOY 80 and 110 in Fig 1b.). Although Figure 3 still shows for a number of data points large discrepancies between observation and simulation, one can also note that both models capture three general patterns well, namely the period of severe cold sterility for sowing in October and November, the start and the end of the period in which severe cold sterility occurs (sowing in September and December) and the decrease of yields with sowing date.
from January to September. Therefore, we consider these simulations sufficiently accurate for the
calendar optimisations presented below.

3.3 Simulated heat and cold Sterility

Figure 4 shows that both heat and cold sterility occur throughout the year. Heat sterility ranges from
10 to 30%. Apparently in this environment two adaptations to heat (earlier flowering at higher
temperatures and high transpirational cooling at low RH = high VPD (Julia and Dingkuhn, 2012, 2013;
Van Oort et al., 2015a; van Oort et al., 2014) cancel out the expected increase in heat sterility at
higher air temperatures in the hot dry season (Figure 2). Cold sterility occurs for sowing dates
between day 230 and 70 (August-March). As shown by (Van Oort et al., 2015a), small levels of
sterility do not necessarily cause yield loss. A crop that produces a large number of spikelets would
still be source limited even if the number of fertilised spikelets is reduced a bit due to sterility. The
period with cold sterility (sowing dates 230-70) is therefore 80 days longer than the period with yield
loss (sowing dates 250-10) (Fig. 4c, 4d). Cold sterility causes yield loss for sowing days 250-10 (7 Sept.
–10 Jan., 125 days), with a peak for sowing in days 280-310 (October). The long period is due to inter-
annual variability in temperatures. Figure 4 is for the baseline short duration variety Sahel108. For
medium duration varieties with 20 days longer duration, the sowing dates to be avoided shift to 20
days earlier and for shorter duration varieties sowing dates with highest risk are 20 days later.

3.4 Yield gains from cold tolerant varieties

We can quantify possible yield gains from cold tolerant varieties from Table 2. For example in single
cropping with the baseline short duration variety, long term average potential yields increase from
8.7 to 10.4 t/ha (Table 2, sim. 2,4), a yield gain of +1.7 t/ha or +19%. These yield gains differ
depending on cropping intensity and phenology of the variety. The yield gain is about 1 t/ha (5-8%)
for the medium duration varieties, 1.7 t/ha (10-19%) for the short duration varieties and 2.3 t/ha
in triple cropping. This yield gain occurs because a cold tolerant variety can be sown earlier than the current varieties, exposing it to a cooler climate with a longer growing season. For example comparing the baseline short duration variety (Table 2, sim. 2,4), sowing date would shift from day 10 to day 320 (45 days earlier) and duration would increase from 141 to 175 days (+34 days) and for the medium duration variety sowing date would shift from day 330 to day 320 (10 days earlier) and duration would increase from 186 to 195 days (+9 days).

It should be noted that the yield gains quantified here are the maximum attainable yield gains, because we compared the baseline variety with a hypothetical completely cold tolerant variety. For an intermediately cold tolerant variety, also the yield gain would be less than quantified here.

### 3.5 Trade-off between flexibility and rice yield

Table 2 presents a comparison of all possible crop rotations in order of increasing cropping intensity. To the far right the table shows indicators at the crop rotation level: total rice yield, rice yield per number of days in which rice is growing, total number of days in which crops are growing including the 1, 2 or 3 times 20 days in between crops and in the last column how much “flexibility” is in the system. For example in simulation 5, one rice crop is growing from day 160 to 278 (118 days) and one from day 330 to 131 (166 days). Total duration is 118+166+2*20 = 324 days. Thus there is at most 365-324 = 41 days “flexibility”. Sowing of both crops might be delayed by 20 days per crop and it would still be possible to grow two rice crops in one year.

We visualise this flexibility in sowing windows in figure 5, for selected crop rotations from Table 2. We can see how the sowing window becomes narrower as cropping intensity increases. There is a clear trade-off between flexibility and rice yield. We visualise this trade-off in Fig. 6. The sowing windows in Fig. 5 and the flexibility in the last column of Table 2 show that triple cropping of rice is very difficult if not impossible. Triple rice is only possible with shorter duration varieties than our baseline Sahel108 and even then sowing windows are only 10-40 days wide (Fig. 5e). Rice-rice-vegetable was only possible with a 2 month vegetable and also then, the sowing windows are only
30-40 days wide (Fig. 5f). There is more flexibility in sowing windows for double cropping (Fig. 5a-d). Therefore, rice-rice double cropping options seem most relevant and will be analysed in more detail.

3.6 Optimal sowing dates

Fig. 7 shows a selection of optimised crop rotations. Table 2 shows all optimised crop rotations when maximising rice yields. Table 3 shows all optimised crop rotations when maximising rice yield per unit time. With yield maximisation as the objective a long term average potential rice yield of 10.3 t ha-1 is obtained with sowing on day 330 (26 Nov.) with a medium duration variety (Table 2, sim 1 and sim 5). For the baseline short duration variety optimum sowing date is 45 days later, on day 10 (10 Jan.), and potential yield is 8.7 t ha-1 (Table 2, sim 2 and sim 6). With a completely cold tolerant variety, optimal sowing date shifts to early November (day 320, 16 Nov.) and potential yield is 11.2 or 10.4 t ha-1 for the medium / short duration variety (Table 2, sim 3,4,7,8). Thus crop genetics (duration and cold tolerance) affect optimised sowing date and the associated yields attainable for these sowing dates.

Maximising yield and maximising yield per duration lead to different optimised sowing dates. Maximum yield is obtained with sowing on day 330 to 10 (Fig. 7a, Table 2, sim 1 and sim 5).

Maximum yield per crop duration is obtained with a completely different sowing on day, namely day 140 to 160 (Fig. 7b, Table 3, sim 1 and sim 5). For the medium duration variety maximising yield per duration leads to lower yields (8.8 vs 10.3 t ha-1) and higher yield per duration, 80 vs 62 kg ha-1 d-1, (Table 2 and 3, sim 1). Total duration is less when maximising yield per duration and therefore flexibility is higher (see also the open symbols in Fig. 6, which are shifted upwards, indicating higher
flexibility). Thus the objective of the farmer (what to maximise) affects optimal sowing date and the associated yields.

Figure 4a shows that predicted long term average potential yields for the cold sensitive variety decrease gradually for sowing after day 150. With yield maximisation the model suggests sowing the second crop as early as possible after the cold dry season crop. Optimised sowing dates in the double cropping systems according to our modelling results are around day 160 (early June) which is one to two months before the start of the wet season (Fig. 7). Figure 7 shows for both the rice-rice rotation and the rice-vegetable rotation that there is room for delaying this crop by about 60 days. There is therefore enough time to sow the wet season crop later (= at the start of the wet season) and still sow a cold dry season crop (rice or vegetable) in early December.

3.7 Observed sowing dates

Comparing optimised sowing dates with observed sowing dates for the warm wet season we found our model recommends sowing earlier than farmers do. Earliest farmers sow around day 180 (29 Jun.) which is around the start of the wet season, the majority sows around day 215 (3 August), some time after the start of the wet season. Our model on the contrary recommends sowing around day 140 to 160 i.e. 20 May – 9 June (Tables 2,3, sim 5-10). Farmers sow on average 55 days later than proposed by our model. Even the earliest-sowing farmers sow 20 days later than optimal according to our model. For the medium duration variety the long term average potential yield for the optimal sowing date (DOY 160) in the wet season is 8.7 t ha\(^{-1}\), whereas for farmers’ average sowing date (around day 215) in the wet season it is 7.7 t ha\(^{-1}\), or 12% lower. For the short duration variety, potential yields are 7.7 t ha\(^{-1}\) at DOY 160 and 6.5 t ha\(^{-1}\) for farmers’ average sowing date (16% lower). The only cases in which optimised sowing dates were closer to actual farmers sowing dates was when in the CCC model, a vegetable prevented rice sowing at a date that would give highest yield.
3.8 (Tanaka et al., 2015) Intensification options

Previous sections showed that triple cropping is very difficult to realise because flexibility is small. It was not possible to fit three baseline varieties in one year, but triple cropping was possible with the baseline and two ultra-short duration crops (Table 2, sim 11,12). Long term average total potential yield for triple rice is 18.6 t ha-1 (Table 2 sim 11) and 20.9 t ha-1 for the cold tolerant variety (Table 2 sim 12). A double crop with medium duration varieties gives total yields of 19.0 t ha-1 and 20.1 t ha-1 for the normal and cold tolerant variety (Table 2, sim 5,7). Thus total yield gains of triple rice relative to double rice are small, also with cold tolerant varieties, while flexibility is much lower. Results showed the possibility of triple-cropping rice-rice-vegetable with a 2-month vegetable (Table 2, sim 13-16), but also this crop rotation has very narrow sowing windows (Figure 5) and low overall flexibility (6-45 days, Table 2). More promising are the double cropping systems. Simulated rice potential yields in the double cropping systems are almost twice that of single cropping systems: 8.7-10.3 t ha-1 for the normal cold sensitive varieties in single cropping and 16.4-19.0 t ha-1 for the double crops (Table 2, sim 1,2,5,6). Should breeders succeed at identifying a cold tolerant variety, the cold dry season rice crop could be sown earlier (early November instead of mid-January), resulting in a longer growing season and higher total yields (18.4-20.2 t ha-1, Table 2 sim 7,8). In single rice cropping systems, a shift from short duration varieties to medium duration varieties could increase yields by 19% (Table 2, sim 1 vs 2, 8.7->10.3 t ha-1). For double rice cropping systems, a shift from short duration varieties to medium duration varieties could increase yields by 16% (Table 2, sim 5 vs 6, 16.4->19.0 t ha-1). In double cropping systems, development of a cold tolerant variety would allow yields to increase by 5-10% (Table 2, sim 5 vs 7 and 6 vs 8).

4 Discussion

Twenty years ago Dingkuhn (1995) concluded for our study area that double cropping is possible but subject to severe time constraints. This conclusion was drawn based on simulated sterilities and simulations with a medium duration variety. Since then short duration varieties have been released,
which has increased the viability of double cropping. An important scientific insight has been the finding that, if a rice crop produces a large number of spikelets and source limitation occurs due to a short grain filling period, then a limited increase in sterility (reduced sink size) would not lead to a yield reduction. This was also shown in section 3.3 of this paper, where the period with cold sterility was shown to be 80 days longer than the period with yield loss due to cold. According to the current study sowing is possible in January-February with good yields despite some sterility (Figure 4). This is different from previous simulations by Dingkuhn, which led to the current recommended sowing date of 15 March for the dry season. New results on yields, observed and simulated, suggest that the abovementioned study by Dingkuhn based on minimising sterility was too restrictive for sowing dates in January and February in our study area. The release of short duration varieties and the new insight on the interaction between fertility, source limitation and spikelet number theoretically lead to a more optimistic view on prospects for rice double cropping. But this was to date not quantified. The current analysis fills this gap.

In the book by (Miezan et al., 1997) more analyses were presented on rice double cropping. (Matlon, 1997) noted the need to look more broadly for other options and not only at rice-rice double cropping and the need to include the farmers’ perspective. Twenty years after, we find that while there has been more research on farmers’ constraints and objectives, data collected are still insufficient for whole farm economic analysis and are almost exclusively about rice farming with little to no data collection on other crops (Haefele et al., 2002; Krupnik et al., 2012; Le Gal and Papy, 1998; Poussin et al., 2006; Poussin et al., 2005; Tanaka et al., 2015). With this in mind we included other crops in a rudimentary method, by blocking a part of the year for vegetable cropping. We interviewed some farmers and discussed with them the labour and economic issues in rice-vegetable cropping (§4.4) but readily admit that a more thorough socio-economic analysis is needed.

We quantified flexibility as an important indicator of the viability of crop rotations. How much flexibility is needed will differ between farmers and can change over time if progress is made with
mechanisation and improved access to seeds and credit. This study is an exploratory analysis: we
explore what yield gains are possible should these constraints be alleviated. It shows what yield gains
are theoretically possible by shifting to medium duration varieties, shifting sowing dates, breeding
for cold tolerant varieties and increasing the cropping intensity.

4.1 Main findings
For a site in Senegal, representing the middle valley of the Senegal River in the Sahel, we investigated
options for intensification, by varying sowing dates, variety types and number of crops per year. In
summary, the analyses in this paper provide clear outcomes on options for intensification:

1. Double cropping is possible
2. Triple cropping is almost impossible, except with very tight planning or a rice-rice-vegetable
   rotation with a 2 month vegetable
3. Within single and double cropping systems, intensification is possible by adopting medium
   duration rice varieties instead of short duration varieties

The analysis was exploratory in the sense that potential yields were simulated while we are aware
that in many cases, farmers face many constraints and actual yields are often lower (Tanaka et al.,
2015), while unplanted periods between crops are often larger than the minimum of 20 days
assumed in this paper. Our analysis shows that double cropping (rice-rice or rice-vegetable) is
possible and triple rice-rice-vegetable cropping is only possible where farmers have good control of
the timing of their operations and where a short (2 months) duration vegetable is available. Most
promising options for intensification are therefore to shift from single to double cropping and to
grow medium instead of short duration varieties. Both are available in the Senegal middle valley, e.g.,
popular short duration cv. Sahel108 (used as the baseline variety in this paper) and medium duration
variety Sahel202 (Tanaka et al., 2015). We know that single rice, rice-rice and rice-vegetable rotations
exist and that double cropped area is expanding, but accurate area estimates and dynamics are not
available. The value of the exploratory analysis presented here is that it shows which options for
intensification are and which ones are currently not possible. Whether they can be implemented in practice depends on timely availability of labour, machinery, water, seed and fertiliser.

Methodologically, the approach developed adds something new to previous models for crop rotation optimisation. Compared to models like APSIM and DSSAT (Holzworth et al., 2014; Jones et al., 2003; Keating et al., 2003) (Holzworth et al., 2014; Jones et al., 2003), our model allows for systematic comparison of large numbers of crop rotations, including associated climatic risks. Compared to specialised models for comparing crop rotations (Dogliotti et al., 2003; Huong et al., 2014), our analysis adds a more mechanistic simulation of climatic risks and effects of varietal differences. Compared to ideotyping studies, our analysis is an ideotyping study at the crop rotation level, as opposed to previous studies which only considered single crops. As in (Dingkuhn, 1995) we quantified flexibility, which we visualised here by the width of the bands in figure 5. Such flexibility is very important for farmers who cope with having to divide their labour time over different crops and who often suffer from late availability of machinery and other resources (Connor et al., 2008; Haefele et al., 2002; Tanaka et al., 2015).

4.2 Phenology

Two phenological models were used. The SOWDOY model more accurately predicted phenology for the study site and therefore we used this model to investigate intensification options. Disadvantages of this model are that it is site specific and that it did not simulate interannual variation in phenology. A TSUM model can potentially also be used with the same parameters for other sites, pending successful validation. We investigated the sensitivity of our results to the choice of phenological model. Figure 8 presents the comparison of yields and crop rotations simulated with these two phenological sub-models. The two largest differences in simulated yields (Fig. 8b) are that (i) for sowing dates 10 to 200, the TSUM model predicts 0 to 1 t ha⁻¹ lower yields and (ii) the period with severe yield loss due to cold sterility is shifted 10 to 20 days to the right. Similarities between simulated yields in figure 8b are the dates on which highest yields are simulated, showing peaks at
sowing dates 10 and 150, for which simulated potential yields are very similar for ORYZA2000 subversions with the two different phenological models. As a result of these two similarities, optimised cropping calendars are almost the same for the two models and result in almost the same total days and total yield (Fig. 8c and 8d) for the 20 crop rotations considered in Table 2. Both with the SOWDOY model and with the TSUM model, optimised sowing dates are around sowing dates 10 and 150. Therefore for this specific site we come to the same conclusions on optimal sowing dates, potential yields and options for intensification. More detailed calibrations of a temperature sum based model, for example with specialised calibration models (van Oort et al. (2011), (Archontoulis et al., 2014), (Dingkuhn et al., 2015)) could further increase the accuracy of the analyses presented in this paper, as would more detailed calibration of the crop growth simulation.

4.3 ORYZA2000

Models were used in this paper to answer two questions. Firstly: how many crops (including choice of 5 varietal types with different duration and cold tolerance) can be cultivated successively in one year? And secondly: what are their optimal sowing dates? Calendar construction strictly does not require a crop growth model, it can be done with phenology models alone. We are quite confident on the results the possible number of crops per year, as errors in the phenology model are small and with two different phenological models, we came to similar conclusions. The answer to the second question was based on simulated yields with the ORYZA2000 model. Yields and climatic risks were simulated with adapted subversions s14 and s27 of the ORYZA2000v2n13 model, for which we previously assessed the accuracy in (Van Oort et al., 2015a) and for which we presented an additional validation in Figure 3. The accuracy of the model is not perfect, and simulated yields were also found to be sensitive to phenology simulation, shifting the period with peak yield loss due to cold sterility by 10 to 20 days. Continued work on model improvement and collection of accurate input and validation data is needed. However, approximate accuracy and the absence of distorting bias can be a sufficient condition to answer specific questions. Within the framework of the present hypotheses and factors, a perfect model would not have changed the conclusions.
4.4 Observed vs optimised sowing dates

Our simulations showed yield gains of about 1 t/ha (+12 to +16%) when sowing one to two months earlier than farmers do now. Discrepancies between model optimised sowing dates and actual farmers’ sowing dates indicate the presence of third factors that were not considered, and indicate that the model’s boundaries need to be extended, e.g. through participatory research on farmers’ decision criteria.

During a recent field visit to the study area (van Oort and Sow, 29 April 2016) we spoke with farmers and obtained some cues on why farmers would sow later than optimal according to the model presented here. Farmers told us that in recent years tomato and onion are more profitable than rice, so cultivation of these vegetables gets priority over timely sowing of rice. They told us irrigation is expensive, thus increasing costs and risk when sowing rice before the start of the wet season, as our model suggests. For the same reason, many farmers prefer short duration Sahel 108 over medium duration varieties. According to farmers, the yield gain of medium duration varieties is insufficient to offset the extra costs of irrigation. Our data confirm this perception: in Table 3 simulations 1 and 2 show that going from short to medium duration variety the yield increases from 7.9 to 8.8 t/ha (+10%) while duration increases from 119 to 149 days (+25%). It shows that the marginal cost of increased time (which will be strongly correlated with irrigation water needs) is larger than the marginal yield increase. We found higher marginal costs than marginal yield gains in all comparisons between short and medium duration varieties in Tables 2 and 3. Lastly, farmers also mentioned the already well known constraints of delayed planting due to lack of seed, credit, machinery and constraints of decisions at the scheme level on when to irrigate (Poussin et al., 2006; Poussin et al., 2005; Tanaka et al., 2015). This anecdotal experience highlights the limitations of sowing date optimisation for rice only and highlights the need for broader socio-economic analysis including all crops in the rotation, not only rice.
4.5 Carry-over effects

Our model was selective in the choice of process considered in evaluating cropping calendars. One simplification was the absence of environmental carry-over effects from one crop to the next. Such effects are common in rainfed systems where water uptake of one crop affects initial soil moisture of the following crop. In irrigated systems, this carry-over effect can be ignored as we simply assume that always enough water is available. For this reason, increasing cropping intensity is often more promising in irrigated systems than in rainfed systems. Likewise, we chose to ignore carry-over effects of soil nutrients as we assumed these would be supplemented with fertiliser. In systems where carry-over effects of water and nutrients play an important role it is better to use models specifically designed for that purpose, using models such as APSIM and DSSAT, for example see Balwinder-Singh et al. (2015a); Balwinder-Singh et al. (2015b); (Gaydon et al., 2012a; Gaydon et al., 2012b). A third important carry-over effect is that of the build-up of pests and diseases. Such carry-over effects are less common in continuous irrigated rice systems (Dobermann et al., 2000) in comparison with more vulnerable vegetable systems. In systems where carry-over effects of build-up of pests and diseases play an important role it is better to use models that can simulate these effects, such as ROTAT and PermVeg Dogliotti et al. (2003); (Huong et al., 2014; Van Den Berg and Rossing, 2005; Van Den Berg et al., 2006).

4.6 Limitations and extensions

This paper builds on previous works reported in (Miezan et al., 1997) and knowledge gaps identified by (Matlon, 1997). A previous similar study systematically assessed options for rice single and double cropping Dingkuhn (1995) but did not include vegetable crops, did not include a comparison between ultra-short, short and medium duration varieties and did not explicitly quantify flexibility. These are important factors in farmers’ decision making. Since these works in the mid 1990s, there have been more studies into the farmers’ perspective and causes of yield gaps, and rice models have been improved. The current study builds on that work. Still, there are three important limitations not addressed in this paper which we hope to address in follow-up studies. Firstly, we did not quantify
climate change effects. Secondly, we lacked data on vegetables in the study area. There is a large imbalance between rice and vegetables in terms of available data and models for the study area, probably because there is a rice research institute and not a vegetable research institute present in the study region. The analyses presented in this paper show the potential importance of vegetables in local, intensified, rice-based cropping systems. Thirdly, we did not include an economic evaluation of the intensification options. This, as well as considering implications of climate change for rice-based cropping systems, warrants follow-up studies.

5 Conclusions

A GxExM cropping calendar optimisation model was presented. Optimisation included genetic (G) traits (crop duration and cold tolerance) and management (M) decisions (sowing dates, time between crops) in interaction and in an environment (E) with extreme temperatures. The model optimises cropping calendars of rice single, double and triple crops. Next to rice a second (vegetable) crop was included in a rudimentary manner by blocking part of the year for vegetable cropping. The model also quantified how much flexibility there was in the crop rotations and showed that a clear trade-off exists between flexibility and total yield. The model was applied to the middle valley of the Senegal River. In this site, farmers already practice double cropping. The value of a modelling exercise such as presented here is that it allows for simulating probable yield gains that arise from changes in planting dates, new cold or heat tolerant varieties and choices between duration types. Triple cropping is not practiced and it was unclear to date whether it would be possible. Our analysis showed that it is almost impossible because calendar flexibility would be too small. An expansion of rice cultivated area is expected in the coming decades. For sites newly brought into cultivation in the region, the CCC model developed here can be used to explore which rice-based rotations would be viable.
6 Data and model availability

Data and model can be downloaded from the following website:
http://models.pps.wur.nl/content/cropping-calendar-construction-ccc-model

7 Acknowledgements

Financial support for cold tolerance research at AfricaRice was provided by the project Stress-Tolerant Rice for poor farmers in Africa and South Asia (STRASA) funded by the Bill and Melinda Gates Foundation.

8 References


for response of a rice diversity panel to ten environments in Senegal and Madagascar. 2.


Figure 1

(a) Sowing to Emergence (d) vs. Sowing Date (Julian) Day of Year
- Site 1 = Ndiaye
- Site 2 = Fanaye
- Model

(b) Emergence to Maturity (days) vs. Emergence Date (Julian Day of Year)
- Observed
- TSUM model
- SOWDOY model
Figure 5

- a. short duration (= baseline: Sahel108)
- b. medium duration (= Sahel108 + 20d)
- c. Sowing Date Rice Crop
- d. Sowing Date Rice Crop
- e. Sowing Date Crop 1 / 2 / 3
- f. - Vegetable (J-F)
   - Rice Crop 1
   - Rice Crop 2
Figure 7

Max. Rice Yield

Max. Rice Yield/Duration

Cropping Intensity

Date (Julian Day of Year)

Long-term average rainfall (mm)
Figure 8

(a) Sowing to Maturity (days) vs. Sowing Date (Julian Day of Year)

(b) Yield (kg DM ha⁻¹) vs. Sowing Date (Julian Day of Year)

(c) Total Days (d) with TSUM phenology model vs. Total Days (d) with SOWDOY phenology model

(d) Total Rice Yield (t DM/ha) with TSUM phenology model vs. Total Rice Yield (t DM/ha) with SOWDOY phenology model
### Table 1. Parameters of the phenology model, calibrated for variety Sahel108

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sowing to Emergence (eq 1)</th>
<th>Emergence to maturity (eq 2)</th>
<th>Description</th>
<th>Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>b1LS</td>
<td>-6.14</td>
<td>-57.98</td>
<td>parameter in exponential decline in duration after doyL</td>
<td>((\text{durS} - \text{durL}) / (1 - \text{Exp}(b2LS * (\text{doyS} + 365 - \text{doyL}))))</td>
</tr>
<tr>
<td>b1SL</td>
<td>0.05</td>
<td>0.78</td>
<td>increase in duration (d) per day after doyS</td>
<td>((\text{durL} - \text{durS}) / (\text{doyL} - \text{doyS}))</td>
</tr>
<tr>
<td>b2LS</td>
<td>-0.008027</td>
<td>-0.017196</td>
<td>parameter in exponential decline in duration after doyL</td>
<td>Curve fitting to observed data</td>
</tr>
<tr>
<td>DELTADUR</td>
<td></td>
<td></td>
<td>Absolute change in DUREMMATb for simulating shorter/longer duration varieties</td>
<td>Modeller’s choice</td>
</tr>
<tr>
<td>doyL</td>
<td>366</td>
<td>325</td>
<td>Sowing / emergence day resulting in longest duration</td>
<td>Curve fitting to observed data</td>
</tr>
<tr>
<td>doyS</td>
<td>267</td>
<td>251</td>
<td>day with shortest duration</td>
<td>Curve fitting to observed data</td>
</tr>
<tr>
<td>DURFLM</td>
<td>25</td>
<td></td>
<td>Days from flowering to maturity</td>
<td>Average of data</td>
</tr>
<tr>
<td>durL</td>
<td>8</td>
<td>150</td>
<td>longest duration in days, at doyL</td>
<td>Curve fitting to observed data</td>
</tr>
<tr>
<td>DURPIF</td>
<td>28</td>
<td></td>
<td>Days from panicle initiation to flowering</td>
<td>Average of data</td>
</tr>
<tr>
<td>durS</td>
<td>3</td>
<td>93</td>
<td>shortest duration in days, at doyS</td>
<td>Curve fitting to observed data</td>
</tr>
<tr>
<td>DUREMMATb</td>
<td></td>
<td></td>
<td>Days from emergence to maturity for the baseline variety</td>
<td>Output variable, eq. 2</td>
</tr>
<tr>
<td>DURSOWEM</td>
<td></td>
<td></td>
<td>Days from sowing to emergence</td>
<td>Output variable, eq. 1</td>
</tr>
<tr>
<td>EMD</td>
<td></td>
<td></td>
<td>Emergence Day</td>
<td>SOW + DURSOWEM</td>
</tr>
<tr>
<td>SOW</td>
<td></td>
<td></td>
<td>Sowing Day</td>
<td>Input variable</td>
</tr>
</tbody>
</table>
Table 2. Optimised Cropping calendar options with maximisation of rice yield

<table>
<thead>
<tr>
<th>Sim</th>
<th>Rotation</th>
<th>Variety</th>
<th>ΔDur 1 (d)</th>
<th>ΔDur 2 (d)</th>
<th>ΔDur 3 (d)</th>
<th>SOW 1 (doy)</th>
<th>HAR1 (doy)</th>
<th>DUR1 (d)</th>
<th>Y1 (t/ha)</th>
<th>SOW 2 (doy)</th>
<th>HAR2 (doy)</th>
<th>DUR2 (d)</th>
<th>Y2 (t/ha)</th>
<th>Ytot (t/ha)</th>
<th>Yield / Dur (kg/ha/d)</th>
<th>Total dur. (d)</th>
<th>365-Total dur. (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rice</td>
<td>All</td>
<td>20</td>
<td></td>
<td></td>
<td>330</td>
<td>131</td>
<td>166</td>
<td>10.3</td>
<td>10.3</td>
<td>62</td>
<td>131</td>
<td>166</td>
<td>10.3</td>
<td>186</td>
<td>179</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Rice</td>
<td>Bas.</td>
<td>0</td>
<td></td>
<td></td>
<td>10</td>
<td>131</td>
<td>121</td>
<td>8.7</td>
<td>8.7</td>
<td>72</td>
<td>121</td>
<td>98</td>
<td>7.7</td>
<td>141</td>
<td>224</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Rice</td>
<td>All; ct.</td>
<td>20</td>
<td></td>
<td></td>
<td>320</td>
<td>130</td>
<td>175</td>
<td>11.2</td>
<td>11.2</td>
<td>64</td>
<td>130</td>
<td>175</td>
<td>11.2</td>
<td>195</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Rice</td>
<td>Bas; ct.</td>
<td>0</td>
<td></td>
<td></td>
<td>320</td>
<td>110</td>
<td>155</td>
<td>10.4</td>
<td>10.4</td>
<td>67</td>
<td>110</td>
<td>155</td>
<td>10.4</td>
<td>175</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Rice-Rice</td>
<td>All</td>
<td>20</td>
<td>20</td>
<td></td>
<td>160</td>
<td>278</td>
<td>118</td>
<td>8.7</td>
<td>8.7</td>
<td>67</td>
<td>278</td>
<td>118</td>
<td>8.7</td>
<td>134</td>
<td>121</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Rice-Rice</td>
<td>Bas.</td>
<td>0</td>
<td>0</td>
<td></td>
<td>10</td>
<td>131</td>
<td>121</td>
<td>8.7</td>
<td>8.7</td>
<td>75</td>
<td>121</td>
<td>98</td>
<td>7.7</td>
<td>129</td>
<td>259</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Rice-Rice</td>
<td>All; ct.</td>
<td>20</td>
<td>20</td>
<td></td>
<td>150</td>
<td>269</td>
<td>119</td>
<td>9.0</td>
<td>9.0</td>
<td>69</td>
<td>269</td>
<td>119</td>
<td>9.0</td>
<td>138</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Rice-Rice</td>
<td>Bas; ct.</td>
<td>0</td>
<td>0</td>
<td></td>
<td>130</td>
<td>230</td>
<td>100</td>
<td>7.9</td>
<td>7.9</td>
<td>75</td>
<td>230</td>
<td>100</td>
<td>7.9</td>
<td>145</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Rice-Veg(D-A)</td>
<td>All</td>
<td>20</td>
<td></td>
<td></td>
<td>150</td>
<td>269</td>
<td>119</td>
<td>9.0</td>
<td>9.0</td>
<td>75</td>
<td>269</td>
<td>119</td>
<td>9.0</td>
<td>138</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Rice-Veg(D-A)</td>
<td>Bas.</td>
<td>0</td>
<td></td>
<td></td>
<td>150</td>
<td>249</td>
<td>99</td>
<td>7.9</td>
<td>7.9</td>
<td>80</td>
<td>249</td>
<td>99</td>
<td>7.9</td>
<td>298</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Rice-Rice-Rice</td>
<td>All*</td>
<td>0</td>
<td>-10</td>
<td>-20</td>
<td>150</td>
<td>249</td>
<td>99</td>
<td>7.9</td>
<td>7.9</td>
<td>80</td>
<td>249</td>
<td>99</td>
<td>7.9</td>
<td>298</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Rice-Rice-Rice</td>
<td>All; ct.</td>
<td>-10</td>
<td>0</td>
<td>20</td>
<td>150</td>
<td>249</td>
<td>99</td>
<td>7.9</td>
<td>7.9</td>
<td>80</td>
<td>249</td>
<td>99</td>
<td>7.9</td>
<td>298</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Rice-Rice-Veg(D-J)</td>
<td>All</td>
<td>10</td>
<td>10</td>
<td></td>
<td>60</td>
<td>178</td>
<td>118</td>
<td>8.5</td>
<td>8.5</td>
<td>200</td>
<td>178</td>
<td>118</td>
<td>8.5</td>
<td>346</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Rice-Rice-Veg(D-J)</td>
<td>Bas.</td>
<td>0</td>
<td>0</td>
<td></td>
<td>60</td>
<td>168</td>
<td>108</td>
<td>7.7</td>
<td>7.7</td>
<td>190</td>
<td>168</td>
<td>108</td>
<td>7.7</td>
<td>326</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Rice-Rice-Veg(J-F)</td>
<td>All</td>
<td>20</td>
<td>20</td>
<td></td>
<td>80</td>
<td>205</td>
<td>125</td>
<td>9.4</td>
<td>9.4</td>
<td>230</td>
<td>205</td>
<td>125</td>
<td>9.4</td>
<td>365</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Rice-Rice-Veg(J-F)</td>
<td>Bas.</td>
<td>0</td>
<td>0</td>
<td></td>
<td>80</td>
<td>185</td>
<td>105</td>
<td>7.7</td>
<td>7.7</td>
<td>210</td>
<td>185</td>
<td>105</td>
<td>7.7</td>
<td>320</td>
<td>45</td>
<td></td>
</tr>
</tbody>
</table>

Rotation: Veg(D-A) = Vegetable growing December-April, D-J = December-January, J-F = January-February. Variety: bas. = baseline crop duration, all = all crop duration, ct. = cold tolerant. ΔDur = change in duration (days) relative to baseline duration. SOW = Julian Day of Year in which crop 1/2 is sown. HAR = Harvest Date. DUR = Days from sowing to harvesting. Yield (Y1, Y2, Ytot) (t/ha) = paddy rice at 14% moisture content. Yield / Dur = Total rice yield / Total duration of the rice crops. Total duration = total duration of all harvested crops, including the vegetable and including the minimum period between two crops (DURHASOW) for harvesting and land preparation. Flexibility = 365-Total duration.

* Rice-rice-rice was not possible with the baseline variety.
### Table 3. Optimised Cropping calendar options with maximisation of rice yield per rice crop duration

<table>
<thead>
<tr>
<th>Sim</th>
<th>Rotation</th>
<th>Variety</th>
<th>ΔDur 1 (d)</th>
<th>ΔDur 2 (d)</th>
<th>ΔDur 3 (d)</th>
<th>SOW 1 (doy)</th>
<th>HAR1 (doy)</th>
<th>DUR1 (d)</th>
<th>Y1 (t/ha)</th>
<th>SOW 2 (doy)</th>
<th>HAR2 (doy)</th>
<th>DUR2 (d)</th>
<th>Y2 (t/ha)</th>
<th>Ytot (t/ha)</th>
<th>Yield / Dur (kg/ha/d)</th>
<th>Total dur. (d)</th>
<th>365-Total dur. (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rice</td>
<td>All</td>
<td>20</td>
<td></td>
<td></td>
<td>140</td>
<td>249</td>
<td>109</td>
<td>8.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.8</td>
<td>80</td>
<td>149</td>
</tr>
<tr>
<td>2</td>
<td>Rice</td>
<td>Bas.</td>
<td>0</td>
<td></td>
<td></td>
<td>140</td>
<td>239</td>
<td>99</td>
<td>7.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.9</td>
<td>80</td>
<td>119</td>
</tr>
<tr>
<td>3</td>
<td>Rice</td>
<td>All; ct.</td>
<td>20</td>
<td></td>
<td></td>
<td>140</td>
<td>249</td>
<td>109</td>
<td>8.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.8</td>
<td>80</td>
<td>149</td>
</tr>
<tr>
<td>4</td>
<td>Rice</td>
<td>Bas; ct.</td>
<td>0</td>
<td></td>
<td></td>
<td>140</td>
<td>239</td>
<td>99</td>
<td>7.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.9</td>
<td>80</td>
<td>119</td>
</tr>
<tr>
<td>5</td>
<td>Rice-Rice</td>
<td>All</td>
<td>20</td>
<td>20</td>
<td></td>
<td>20</td>
<td>138</td>
<td>118</td>
<td>8.6</td>
<td>160</td>
<td>258</td>
<td>98</td>
<td>7.7</td>
<td>7.7</td>
<td>16.3</td>
<td>76</td>
<td>276</td>
</tr>
<tr>
<td>6</td>
<td>Rice-Rice</td>
<td>Bas.</td>
<td>0</td>
<td>0</td>
<td></td>
<td>20</td>
<td>138</td>
<td>118</td>
<td>8.6</td>
<td>160</td>
<td>258</td>
<td>98</td>
<td>7.7</td>
<td>7.7</td>
<td>16.3</td>
<td>76</td>
<td>256</td>
</tr>
<tr>
<td>7</td>
<td>Rice-Rice</td>
<td>All; ct.</td>
<td>20</td>
<td>20</td>
<td></td>
<td>140</td>
<td>249</td>
<td>109</td>
<td>8.8</td>
<td>330</td>
<td>91</td>
<td>126</td>
<td>9.1</td>
<td>17.8</td>
<td>76</td>
<td>295</td>
<td>70</td>
</tr>
<tr>
<td>8</td>
<td>Rice-Rice</td>
<td>Bas; ct.</td>
<td>0</td>
<td>0</td>
<td></td>
<td>10</td>
<td>131</td>
<td>121</td>
<td>8.9</td>
<td>160</td>
<td>258</td>
<td>98</td>
<td>7.7</td>
<td>16.6</td>
<td>76</td>
<td>259</td>
<td>106</td>
</tr>
<tr>
<td>9</td>
<td>Rice-Veg(D-A)</td>
<td>All</td>
<td>20</td>
<td></td>
<td></td>
<td>150</td>
<td>249</td>
<td>99</td>
<td>7.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.9</td>
<td>80</td>
<td>289</td>
</tr>
<tr>
<td>10</td>
<td>Rice-Veg(D-A)</td>
<td>Bas.</td>
<td>0</td>
<td>-10</td>
<td>-20</td>
<td>150</td>
<td>249</td>
<td>99</td>
<td>7.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.9</td>
<td>80</td>
<td>269</td>
</tr>
<tr>
<td>11</td>
<td>Rice-Rice-Rice</td>
<td>All</td>
<td>0</td>
<td>-10</td>
<td>0</td>
<td>20</td>
<td>138</td>
<td>118</td>
<td>8.6</td>
<td>160</td>
<td>258</td>
<td>98</td>
<td>7.7</td>
<td>16.6</td>
<td>76</td>
<td>259</td>
<td>106</td>
</tr>
<tr>
<td>12</td>
<td>Rice-Rice-Rice</td>
<td>Bas.*</td>
<td>-10</td>
<td>0</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Rice-Rice-Veg(D-J)</td>
<td>All</td>
<td>10</td>
<td>10</td>
<td></td>
<td>60</td>
<td>168</td>
<td>108</td>
<td>7.7</td>
<td>190</td>
<td>287</td>
<td>97</td>
<td>7.0</td>
<td>14.6</td>
<td>71</td>
<td>326</td>
<td>39</td>
</tr>
<tr>
<td>14</td>
<td>Rice-Rice-Veg(D-J)</td>
<td>Bas.</td>
<td>0</td>
<td>0</td>
<td></td>
<td>60</td>
<td>168</td>
<td>108</td>
<td>7.7</td>
<td>190</td>
<td>287</td>
<td>97</td>
<td>7.0</td>
<td>14.6</td>
<td>71</td>
<td>306</td>
<td>59</td>
</tr>
<tr>
<td>15</td>
<td>Rice-Rice-Veg(J-F)</td>
<td>All</td>
<td>20</td>
<td>20</td>
<td></td>
<td>90</td>
<td>203</td>
<td>113</td>
<td>8.7</td>
<td>230</td>
<td>336</td>
<td>106</td>
<td>7.1</td>
<td>15.8</td>
<td>72</td>
<td>337</td>
<td>28</td>
</tr>
<tr>
<td>16</td>
<td>Rice-Rice-Veg(J-F)</td>
<td>Bas.</td>
<td>0</td>
<td>0</td>
<td></td>
<td>120</td>
<td>220</td>
<td>100</td>
<td>7.9</td>
<td>240</td>
<td>336</td>
<td>96</td>
<td>6.2</td>
<td>14.1</td>
<td>72</td>
<td>294</td>
<td>71</td>
</tr>
</tbody>
</table>

Rotation: Veg(D-A) = Vegetable growing December-April, D-J = December-January, J-F = January-February. Variety: bas. = baseline crop duration, all = all crop duration, ct. = cold tolerant. ΔDur = change in duration (days) relative to baseline duration. SOW = Julian Day of Year in which crop 1/2 is sown. HAR = Harvest Date. DUR = Days from sowing to harvesting. Yield (Y1, Y2, Ytot) (t/ha) = paddy rice at 14% moisture content. Yield / Dur = Total rice yield / Total duration of the rice crops. Total duration = total duration of all harvested crops, including the vegetable and including the minimum period between two crops (DURHASOW) for harvesting and land preparation. Flexibility = 365-Total duration.

* Rice-rice-rice was not possible with the baseline variety