Sowing rules for estimating rainfed yield potential of sorghum and maize in Burkina Faso

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Abstract

To reduce the dependence on local expert knowledge, which is important for large-scale crop modelling studies, we analysed sowing dates and rules for maize (*Zea Mays* L.) and sorghum (*Sorghum bicolor* (L.)) at three locations in Burkina Faso with strongly decreasing rainfall amounts from south to north. We tested in total 22 methods to derive optimal sowing dates that result in highest water-limited yields and lowest yield variation in a reproducible and objective way. The WOFOST crop growth simulation model was used.

We found that sowing dates that are based on local expert knowledge, may work quite well for Burkina Faso and for West Africa in general. However, when no a priori information is available, maize should be sown between Julian days 160 and 200, with application of the following criteria: a) cumulative rainfall in the sowing window is ≥ 3 cm or available soil moisture content is > 2 cm in the moderately dry central part of Burkina Faso, b) cumulative

rainfall in this period is ≥ 2 cm or available soil moisture content is > 1 cm in the more humid regions in the southern part of Burkina Faso. Sorghum should also be sown between Julian days 160 and 200 with application of the following criteria: a) in the dry northern part of Burkina Faso the long duration sorghum variety should be sown when cumulative rainfall is ≥ 2 cm in the sowing window, and the short duration sorghum variety should be sown later when cumulative rainfall is ≥ 3 cm, b) in central Burkina Faso sowing should start when cumulative rainfall in this period is ≥ 2 cm or when available soil moisture content is > 1 cm.

Sowing date rules are shown to be generally crop and location specific and are not generic for West Africa. However, the required precision of the sowing rules appears to rapidly decrease with increasing duration and intensity of the rainy season. Sowing delay as a result of, for example, labour constraints, has a disastrous effect on rainfed maize and sorghum yields, particularly in the northern part of West Africa with low rainfall.

Optimization of sowing dates can also be done by simulating crop yields in a time window of two months around a predefined sowing date. Using these optimized dates appears to result in a good estimate of the maximal mean rainfed yield level.

Key words Crop modelling Maize Sorghum Sowing WOFOST Yield potential

1. Introduction

For many African countries it is unclear if the future food demand of the rapidly growing population can be met by increasing domestic food production (Alexandratos & Bruinsma, 2012; Nelson et al., 2010). Especially, in the semi-arid regions of Africa where agriculture is based on small-scale, climatically vulnerable systems (Challinor et al., 2007), increasing food

production will be a challenge. Rainfall in West Africa shows high spatial and temporal variability (Graef & Haigis, 2001). Both the start and length of the rainy season, as well as the rainfall distribution over time strongly vary from year to year (Sivakumar, 1990). Consequently, rainfed agricultural production is highly variable and optimal timing of farm operations is very important. Based on their experience, farmers should adapt the periods for land preparation and sowing to the start of the rainy season, trying to avoid dry spells after the first rainfall events (Marteau et al., 2011; Wang et al., 2008). On the other hand, they can also not wait too long with land preparation to avoid drought periods at the end of the crop's growth period.

Approaches have been developed and crop models have been applied for optimizing sowing dates for maize in Burkina Faso (Waongo et al., 2014) and Nigeria (Kamara et al., 2009), and millet in Niger (Soler et al., 2008; Sultan et al., 2005). Also, analyses of dry spell occurrence after different sowing dates (Sivakumar, 1992) and evaluation of different methods to determine the onset of the growing season (Ati et al., 2002; Stern et al., 1981; Marteau et al., 2011) at different locations in West Africa have been performed. The implementation of such approaches could indicate the high risk periods for sowing and could help to attain higher yields and to reduce risk of severe yield reduction or complete crop failure due to drought stress at the beginning or end of the crop's growth period. Crop modelling studies have also been used to estimate climate change impacts on cropping systems and yields and yield variations over Africa (Challinor et al., 2007; Thornton et al., 2011) and at the global scale (Rosenzweig et al., 2014; Parry et al., 2004), and to assess the adaptive capacity of farming systems (e.g. through optimization of sowing dates) to future conditions. Challenges of such impact and adaptation studies were reviewed by Challinor et al. (2009).

Simulated yield levels of rainfed grain crops in semi-arid regions strongly depend on the sowing date (Soler et al., 2008; Kamara et al., 2009). For crop growth simulations of maize

and sorghum in West Africa, often sowing dates were based on local expert knowledge of farmer's practices (e.g. the approach used in the Global yield gap atlas project, see <http://www.yieldgap.org/web/guest/methods-overview>) or on the generic crop calendar data from FAO (see <http://www.fao.org/agriculture/seed/cropcalendar/welcome.do>). Such approaches have some limitations, such as: a) the same sowing date is used for each year independent of the inter-annual variation in rainfall pattern, b) the same sowing date is used for short and long duration varieties, and c) the compiled sowing dates for all region - crop combinations per country are rather subjective, as they are dependent on the local expert knowledge of farmer's practices. Particularly for large-scale modelling studies on, for example, yield potential and yield gaps of the main grain crops, food security and climate change impacts on yields and food production over Africa, good estimates of the mean sowing date per crop per region or climate zone are essential, but are not available with sufficient precision from the two approaches mentioned above.

The main objective of this study which is related to the type of modelling analyses mentioned in the previous paragraph, is to solve this sowing date-problem for large-scale studies. Therefore we tested methods for deriving optimal sowing dates that result in highest water-limited yields and lowest yield variation for the main grain crop–region combinations in Burkina Faso (as an example for the range of environmental conditions over West Africa). These methods are reproducible and objective, and reduce the dependence on local expert knowledge. We performed model analyses for different sowing dates and rules for both maize (*Zea Mays L.*) and sorghum (*Sorghum bicolor (L.)*) at three locations in Burkina Faso with a strongly decreasing rainfall gradient from south to north.

2. Materials and methods

Yield levels for the two main grain crops in Burkina Faso, i.e. sorghum and maize, were modelled using management information per climate zone (Van Wart et al., 2013) and per crop variety. In the following sections we discuss in more detail how this information was obtained and to what purpose it was used.

2.1 WOFOST model and the simulated yields

We used WOFOST version 7.1.3 (release March 2011) to simulate the rainfed crop yields for maize and sorghum (Supit et al., 1994, 2012; Wolf et al., 2011; Boogaard et al., 2013; see for further information <http://www.wageningenur.nl/en/Expertise-Services/Research-Institutes/alterra/Facilities-Products/Software-and-models/WOFOST.htm>). The basic processes simulated by WOFOST are phenological development, biomass growth, its partitioning over plant organs, and root growth, as determined by the defined crop's characteristics, and the soil water balance and its main components (e.g. influx from rainfall, soil evaporation and crop transpiration). The most important external drivers are daily weather data such as solar radiation, temperature, and rainfall. Yield estimates are established for water limited (i.e. rainfed) growing conditions, assuming optimal nutrient availability and optimal crop management. This means that crop growth is not hampered by nutrient shortage and yield losses due to pests and diseases do not occur. Consequently, the simulated water limited yields are much higher (3-4 times) than occur in reality. However, since the nutrient levels have a very limited effect on the quest for the optimal sowing dates to attain highest yields, these simulated water limited yields provide a useful indicator for the sowing date analysis.

Simulated crop emergence occurs after a certain temperature threshold in degree days is reached after sowing. Yield failures that occurred in our study, were mainly caused by

drought stress, either during crop development directly after emergence or during grain filling.

2.2 Model calibration and Input data

Model calibration

We used the standard crop parameter sets of WOFOST for maize and sorghum as compiled by Van Heemst (1988) and Boons-Prins et al. (1993) as base to start from. Next, we compiled data from literature and local experts concerning the crop characteristics for short and long duration maize and sorghum varieties commonly grown in Burkina Faso (Table 1). These characteristics can be considered representative for optimal (i.e. no water and no nutrient limitation and optimal crop management and protection) growing conditions in Burkina Faso. Table 2 presents the optimal crop calendars for both short- and long-duration sorghum and maize varieties at three locations in Burkina Faso. Based on these calendars we calculated the temperature sums that each variety needed to reach anthesis and maturity. We assumed a base temperature of 10°C for both maize and sorghum. Subsequently, we calibrated the model parameters and tested whether the WOFOST outcomes such as total biomass, leaf area index, and yield levels were in accordance with the collected information. Apart from the temperature sums to model phenological development we adapted: (a) maximal rooting depth, which is set to 100 cm for both maize and sorghum due to the poor soil structure and the moderate rainfall excess in West Africa; (b) life span of leaves (SPAN) for sorghum and maize was set to 42 days; (c) the correction factor for evapo-transpiration (CFET) which has been increased from 1.0 to 1.1 for both maize and sorghum because of the semi-arid conditions.

Input data and initialization of simulation runs

Maximally available soil water fraction (i.e. the difference between soil water fractions at field capacity and wilting point) was set to a mean value of 10% of the soil volume, which represented well the main soil types in Burkina Faso according to the ISRIC-WISE database (see Batjes, 2012 and <http://www.isric.org/data/isric-wise-international-soil-profile-dataset>).

Sorghum and maize are grown as single cropping systems in Burkina Faso. The simulated water balance was generally started 30 days before the optimal sowing date (see Table 2). This starting date for the water balance was set earlier in those cases that the possible sowing period was very long. At this start date the total amount of available soil water was set to 3.3 cm (i.e. one third of the maximal soil water holding capacity).

The precipitation fraction that is lost by surface runoff during the growing season, strongly depends on terrain slope angle and the soil permeability (Rockström et al., 1999), which in turn depends on soil type and the land and soil management (Hoogmoed & Stroosnijder, 1984; Hoogmoed et al., 1991). The surface runoff fraction was set to a mean value of 10% which assumes good land management, possibly mulching and use of not too steep land areas. We tested two other loss fractions as well: 0% and 20%. These fractions represent a range from good to poor soil and land management (i.e. from tied ridging to zero tillage) and/or from flat to hilly land and/or from permeable to impermeable soils, and were used to investigate their consequences for the optimal sowing dates and the yield levels. Note that actual runoff fractions in arable cropping systems of Burkina Faso can sometimes be higher than 20% due to poor land management and the too steep land areas in use.

Weather data from a representative meteorological station per climate zone was used as input for crop modelling. The historical weather data sets used for the crop growth simulations covered 15 years (1990-2004 and were collected from the Direction de la Météorologie du Burkina Faso. Linear interpolation was applied to fill missing weather data. We focused on

three locations, Dori in the north, Ouagadougou in the centre and Bobo Dioulasso in the south of Burkina Faso. The mean annual rainfall amount strongly increases from Dori (476 mm on average over period 1990-2007, with CV= 0.243), to Ouagadougou (714 mm on average over period 1990-2007, with CV= 0.124) and to Bobo Dioulasso (1028 mm on average over period 1990-2004, with CV= 0.147), covering the main range of climatic conditions in Sahelian West Africa.

2.3 Sowing date and sowing rule analyses

Simulation runs were performed for 10 crop variety-location combinations (see Table 2) over a 15 year period (1990-2004) using three runoff loss fractions (see end of Section 2.2), resulting in **30 runs**. We tested the effects of various sowing rules on yields and their variability. Some of these rules are based on the cumulative rainfall. However, rain has to infiltrate in the soil before it comes available to the crop, depending on the soil properties, runoff and interception. In fact, there is a small delay and not all rainfall is coming available. To account for these effects, we also tested rules that are based on the amount of available soil water. Furthermore, we investigated the sowing data provided by the local expert. Based on this information various windows of opportunity were defined in which sowing could take place. In total **22 variants** (i.e. sowing date and sowing rule variants) were simulated for the 30 runs. The main differences between these variants are given in Table 3. Some variants were left out because of overlap with the other presented variants. Variant **Fix** applied the **fixed optimal** sowing date (see Table 2 with the optimal dates for the different crop-location combinations as based on local expert knowledge; note that the local expert estimates that the farmers in Burkina Faso do the sowings over a period of one month around these optimal sowing dates) to each of the 15 years (1990-2004), for which crop growth simulations were

done. Variant *Opt* represented a modelling optimization approach and used eight different sowing dates (i.e. fixed optimal sowing date -30 to +40 days), of which only the results for the '*optimized*' sowing date (as given in Table 2) with the highest mean grain yield over the 15 year period were presented. Variant *Fix+30* applied the fixed optimal sowing date plus 30 days in each year (see Section 2.4). Next, we applied a number of sowing rules in the simulation runs which consisted of a) minimally required amount of cumulative rainfall (MCRAIN, respectively, ≥ 2.0 , 3.0 and 4.0 cm), b). minimally required amount of available soil water (WAVMN, i.e. water content above wilting point) in the maximal rooting zone of 100 cm depth (respectively, > 1.0 , 2.0 and 3.0 cm), c) allowed window for sowing (i.e., periods were set around the optimal date for sowing, IDSOW (see Table 2 with IDSOW per location as based on local expert knowledge), and were respectively, between Julian day 136 and 212, between Julian day 160 and 200 or between IDSOW - 10 days and IDSOW + 10 days), and d) a combination of MCRAIN and the minimally required amount of initially available soil water in the initial rooting zone (IAVMN > 0.8 cm in topsoil of 10 cm depth).

2.4 Non-mechanized versus mechanized farming

To attain the simulated water-limited yield level, land and soil management should be improved compared to the actual situation of nil to limited tillage. This would require more labour input and oxen use for at least plowing or earthing up and possibly even tied ridging, to prevent the considerable precipitation losses by surface runoff, to improve the soil structure and to increase the yields (Palé et al., 2009; Chiroma et al., 2008; Klaij & Hoogmoed, 1993; Nicou et al., 1993). With mechanized farming operations sowing can be done at the fixed optimal date (i.e. variant Fix). However, without mechanization much more time is needed for farm operations at the beginning of the rainy season and the date of sowing is delayed. To mimic the influence of non-mechanized farming on crop yields, variant Fix+30 applies the

fixed optimal sowing date plus 30 days in each year. We assume here that sowing was done over a time period of 60 days after the optimal sowing date, as a consequence of labour shortage for performing tillage, sowing, weeding, mulching and other crop management operations on all fields and the need for possibly re-sowing of some fields, which results in a mean time delay by 30 days.

3. Results

An overview of all simulation results for a short duration sorghum variety in Dori is given in Appendix A. Note that these results are obtained for a situation with ample nutrient supply and optimal crop protection and management, and thus without yield losses by pests and diseases. Hence, under actual farming conditions in Burkina Faso, the attained farmer's yields may be a factor 3-4 lower. The runs were done for all different sowing date and sowing rule *variants* (Table 3) using a runoff loss fraction of 10%. Similar results for all other crop variety – location combinations (Table 2) were used as the basis for the figures discussed in the following sections. The following acronym-combinations were used to indicate the different sowing date and sowing rule variants: **Fix**= fixed optimal sowing date; **Opt**= optimized sowing date; sowing periods were long (e.g. day 136 to 212), medium or short, as indicated with respectively, **Lp**, **Mp** and **Sp**; rules based on MCRAIN of respectively, ≥ 2.0 , 3.0 and 4.0 cm were indicated by **Ra1**, **Ra2** and **Ra3**; rules based on WAVMN of respectively, >1.0 , 2.0 and 3.0 cm were indicated by **Av1**, **Av2** and **Av3**; and rule based on IAVMN of >0.8 cm was indicated by **II**. For more detailed information about these variants, we refer to Table 3. For example using these acronym-combinations, the fifth variant in Table 3 was described as LpAv2.

3.1 Two sorghum varieties in Dori

For the short sorghum variety the simulated mean yield over 15 years was 2730 kg dry matter (DM) per ha for the optimal sowing date with a very large SD equal to 1800 kg DM ha⁻¹ (variant Fix in Fig. 1 left). Variant Opt that tested a range of possible sowing dates to attain the highest grain yield, resulted in the same sowing date and thus the same mean and SD of grain yields. Almost equally high grain yields were derived from variants MpRa2, MpRa3, SpAv2, SpAv3, SpRa1, SpRa2, SpRa3, and MpIIRa2 (Table 3). This shows that the sowing rules could only derive well the optimal sowing date for attaining a highest possible yield level in cases that the time window for sowing was not too large (i.e. windows Sp and Mp).

All variants LpAv and LpRa gave the relatively lowest yields over time which can be explained from the sowing dates being too early in those cases that the time window for sowing was relatively large (see e.g. variants LpAv2 and LpRa2 in Fig. 1 left). Further, the use of MCRAIN (variants MpRa1-MpRa3) as sowing criterion appeared to be more effective (resulting in higher simulated yields in Fig. 1 left) than the use of WAVMN (variants MpAv1 - MpAv3) in case the time window for sowing was between Julian day 160 and 200. If the possible time period for sowing was limited to only 20 days around IDSOW (i.e. optimal sowing date), almost all sowing criteria (i.e. variants SpAv2, SpAv3, SpRa1, SpRa2, and SpRa3) appeared to be effective (resulting in highest yields in Fig. 1 left).

In Dori, as a result of a highly variable rainfall pattern in space as well in time, the simulated yield variation over the period of 15 years was very large. In some years as a result of heat and water stress the crops died shortly after emergence. In other years the crops could develop, however, severe drought during the grain filling stage resulted in low to zero yields too. In those years where the rainfall was well distributed over the growing season and was sufficient for crop growth, high yields were simulated.

Figure 1

For the long variety of sorghum grown in Dori the mean yield over 15 years was 2420 kg DM ha⁻¹ for the optimal sowing date with a very large SD equal to 1470 kg DM ha⁻¹ (variant Fix in Fig. 1 right). Variant Opt used a 10 day earlier sowing date than variant Fix, which resulted in a higher grain yield (i.e. 2940 kg DM ha⁻¹, see Fig. 1 right). Almost equally high grain yields were derived from the variants MpRa1, SpAv1 and SpAv2, which were all caused by the relatively early (but not too early as in all variants LpAv, LpRa and MpAv1) sowing dates. This shows that the best sowing date for a short and a long variety at the same location may differ. The long variety required an earlier sowing date to limit the negative yield effects of drought stress at the end of the growing season. For the same reason, variant MpRa1 (with MCRAIN ≥ 2.0) which derived an earlier sowing date than variants MpRa2 and MpRa3, resulted in a higher grain yield (Fig. 1 right). Again all variants LpAv and LpRa and also variant MpAv1 with the lowest WAVMN criterion (Table 3) gave relatively lowest mean yields (Fig. 1 right) which can be explained from the sowing dates being too early in case the time window for sowing was relatively large.

3.2 Maize and sorghum in Ouagadougou

Mean maize yield (long variety) for the optimal sowing date, was 5190 kg DM ha⁻¹ with a large SD equal to 2340 kg DM ha⁻¹ (variant Fix in Fig. 2 left). Variant Opt used a 10 day later sowing day than variant Fix, which resulted in a higher grain yield (i.e. 6220 kg DM ha⁻¹). Almost equally high grain yields were derived from variants MpAv3, MpRa1, MpRa2, MpRa3, SpAv3, SpRa1, SpRa2, SpRa3, and MpI1Ra2 (Fig. 2 left). In case the time window for sowing was relatively large (i.e. between Julian day 160 and 200), variants MpAv3, MpRa1, MpRa2, MpRa3, and MpI1Ra2 were best in deriving a sowing date that resulted in a relatively high yield level. If the time window for sowing was limited to only 20 days around IDSOW, almost all sowing criteria (i.e. variants SpAv3, SpRa1, SpRa2, and SpRa3) appeared to be precise enough to derive a good sowing date. However, if the time window for sowing was large (like for all variants LpAv and LpRa, see Table 3), all sowing criteria resulted in too early sowing dates and thus low yields.

Figure 2

For sorghum (long variety) the mean yield was 5640 kg DM ha⁻¹ for the optimal sowing date with a moderately large SD equal to 1440 kg DM ha⁻¹ (variant Fix in Fig. 2 right). Variant Opt derived the same sowing date which resulted in the same simulated grain yield. Almost equally high or slightly higher grain yields were derived from variants MpAv1, MpAv2, MpAv3, MpRa1, SpAv1, SpAv2, SpAv3, and SpRa1 (Fig. 2 right). These results are partly

the same as those for maize, but also show that higher yields for sorghum were mainly modelled for lower sowing criteria (see lower requirements for WAVMN and MCRAIN in variants MpAv1, MpAv2, MpRa1, SpAv1 and SpAv2 in Table 3) and thus earlier sowing dates, whereas higher yields for maize were mainly modelled for higher sowing criteria (see higher requirements for variants MpRa2, MpRa3, SpRa2 and SpRa3 in Table 3). Grain filling in sorghum occurs at the end of the growing period (Stoop, 1987; Buah et al., 2012), making its yield more sensitive to drought stress at the end of the rainy season than that of maize. Early sowing is therefore more profitable for sorghum than for maize.

3.3 Maize and sorghum in Bobo Dioulasso

The mean maize yield (long variety) was 9070 kg DM ha⁻¹ for the optimal sowing date with a small SD equal to 680 kg DM ha⁻¹ (variant Fix in Fig. 3 left). Variant Opt derived the same sowing date which resulted in the same simulated grain yield. Equally high grain yields and small SD values were derived from variants MpAv1, MpAv2, MpAv3, MpRa1, MpRa2, MpRa3, SpAv3, SpRa1, SpRa2, SpRa3, and Mp11Ra2 (Fig. 3 left). Clearly, the sowing criterion becomes less critical at a relatively high rainfall location such as Bobo Dioulasso. However, if the time window for sowing was large (like for all variants LpAv and LpRa, see Table 3), none of the sowing criteria was sufficiently precise. This always resulted in sowing too early and thus in low yields and large SD values.

Figure 3

For sorghum (long variety) the mean yield was 7060 kg DM ha⁻¹ for the optimal sowing date with a very small SD equal to 280 kg DM ha⁻¹ (variant Fix in Fig. 3 right). Variant Opt derived a 10 day earlier sowing date which resulted in a slightly higher grain yield (i.e. 7270 kg DM ha⁻¹). Equally high grain yields and very small SD values were derived from all other variants (Fig. 3 right) at this high rainfall location. Only for all variants LpAv the SD values were much larger. This can be explained from the large time window for sowing (Table 3), which resulted in sowing too early.

3.4 Effect of precipitation losses by surface runoff on sorghum yields in Dori

The precipitation fraction that may be lost on average by surface runoff, was set to 10% for Burkina Faso, but might vary depending on soil type, terrain slope angle, soil and land management (Section 2.2). Simulation runs were performed for sorghum (short variety) in Dori with both a runoff fraction (**RF**) equal to 0% (Fig. 4 left) and RF equal to 20% (Fig. 4 right). The results show that mean yields for the optimal sowing date were 340 kg DM ha⁻¹ higher with RF equal to 0% (variant Fix in Fig. 4 left) and 530 kg DM ha⁻¹ lower with RF equal to 20% (variant Fix in Fig. 4 right), compared to those with RF equal to 10% (Fig. 1 left). SD values were about the same for the three RF values and variant Fix. Almost identical mean grain yields and SD values were derived for variants MpRa2, MpRa3, SpAv3, SpRa1, SpRa2, SpRa3, and MpIIRa2 in comparison to those for variant Fix, both in case RF was equal to 0% (Fig. 4 left) and in case RF was equal to 20% (Fig. 4 right).

Figure 4

3.5 Effects on yields of non-mechanized versus mechanized farming

To mimic the influence of non-mechanized farming on crop yields, we delayed the sowing date by 30 days on average (variant Fix+30). In at least half of the years maize yields (long variety) in Ouagadougou were then considerably reduced (Fig. 5 left). In Bobo Dioulasso in most years, maize yields were reduced to a limited extent by the sowing delay. The sorghum yields (long variety) in Dori that were already low and highly variable between years, became nil, when sowing was delayed by one month (Fig. 5 right). In Ouagadougou the sorghum yields were strongly reduced in all years by the sowing delay and became almost nil in one third of the years. These crop failures were mainly caused by extensive drought stress during crop development directly after emergence or during grain filling. In Bobo Dioulasso the sorghum yields were reduced to a moderate extent when sowing was delayed.

Figure 5

3.6 Effectivity of applying a combined sowing criterion

We tested if the cumulative rainfall sowing rule ($MCRAIN \geq 3.0$ cm; i.e., variants MpRa2 and SpRa2 in Table 3) could be improved by combining it with a minimally required amount of available soil water in the simulated initial rooting depth of 10 cm (i.e. $IAVMN > 0.8$ cm, see variant MpI1Ra2 in Table 3). For variant MpI1Ra2, sorghum and maize yields at the three locations in Burkina Faso were similar or slightly lower than the yields for the comparable variants MpRa2 and SpRa2 (Fig. 1, 2, and 3). This was due to the additional criterion that mostly resulted in the same or slightly later sowing date.

4. Discussion

We compared the simulated yields obtained with expert knowledge-based sowing dates (variant Fix, see Table 2 with the dates for the different crop-location combinations) to the yields simulated with other sowing dates or rules. This should indicate if another, more generic, better reproducible and less expert knowledge-dependent approach should be used for large-scale crop modelling studies for West Africa.

4.1 Interaction between the best sowing date and rule variants and the location

We found a clear interaction between the climate zone and the precision required for the sowing dates or rule. For Bobo Dioulasso with high rainfall most sowing dates gave about the same maize and sorghum yields per year on average (Fig. 3 and Fig. 6 bottom).

In Ouagadougou the rainfall amount was lower and more variable, which resulted in a considerable maize and sorghum yield variation among the years. For sorghum, rules that resulted in an early sowing date (like variants LpAv2 and LpRa2 with a long possible sowing period, see Table 3), gave sometimes the highest yield but often very low yields or crop failure in years with a delayed start of the rainy season as a result of drought stress during crop development directly after emergence. Rules that gave a late sowing date, resulted in drought stress during the grain filling period and reduced yields in many years for the long sorghum variety (Fig. 2 right). Other sowing rules (e.g. variants MpAv2 and SpAv2, in addition to variants Fix and Opt with resp. fixed optimal and optimized sowing dates) and the best sowing dates between Julian days 164 and 174 (Fig. 6 middle) gave on average highest yields (Fig. 2 right), which still showed a large year to year variation.

In Dori, the average amount of rainfall was lowest (476 mm per year) and showed a strong inter-annual variation. This resulted in a low average yield and a strong yield variation from year to year (Fig. 1), and also for the best sowing rules (e.g. variant SpAv2 in addition to variants Fix and Opt) and for the best sowing date (Julian day 172 in Fig. 6 top). Certain sowing criteria gave often a too early sowing date (e.g. variant LpAv2) or a too late sowing date (e.g. variant SpRa3) which resulted in a low mean yield (Fig. 1 right) and quite often in crop failure as a result of drought during crop development directly after emergence or during the grain filling. The window of opportunity for sowing (around Julian day 172) is very small in Dori (Fig. 6 top).

Note that strong yield variation, as in Dori, results in a high risk of years with production costs that exceed the crop's gross benefits, and in situations where intensification of arable cropping systems and yield increases are financially impossible.

Figure 6

4.2 Use of optimized sowing date

In variant Opt the sowing date was changed in ten-day steps over 80 days in total around an estimated optimal sowing date, in order to find the optimized sowing date (i.e., the sowing date that gives the highest mean yield with the lowest SD). Note that the fixed optimal sowing dates as used in this study, are based on local expert knowledge (sowing dates for variants Fix

and Opt are both given in Table 2), but that for other large-scale studies where local expert knowledge is not available, optimal sowing dates should generally be derived from broad crop calendars of e.g. FAO (see Table 2, columns to the right). This optimized sowing date we found, was subsequently used for the crop growth simulations for all years, and it was not adapted to the yearly rainfall pattern. This approach gave the highest mean yields for almost all crop-location combinations in Burkina Faso (Fig. 1, 2 and 3).

For large scale modelling studies to investigate, for example, the effects of climate change on the yield potential (e.g. Supit et al., 2012), such an approach is useful, however, for farmers especially subsistence farmers it is not. The fixed sowing date in combination with a strong inter-annual variation rainfall pattern may lead to high yields in some years whereas in other years low yields may occur.

Besides, the use of the optimized sowing date assumes a sort of clairvoyance of the farmer, which is impossible in reality. The resulting yield overestimation in certain years is probably nullified by underestimated yields in other years due to the fixed sowing date and the inter-annual variation in rainfall pattern. Hence, we can assume that the simulations for 10 or more years according to variant Opt gave good estimates of the maximal mean water-limited yield level for each crop-location combination, but that the simulated yields per individual year may differ from the really attainable yield level.

4.3 Comparing the results from different sowing rule variants

Results from all variants LpAv and LpRa showed that a large time window for sowing led generally to low mean yields and high SD values (see Fig. 1 and 2) due to many years with too early starts of the growth period followed by severe drought periods. Hence, the sowing window should be at most 40 days and should be set around the optimal sowing date (see the

information in Section 4.2 how these optimal dates were derived in this study and might be collected for other large-scale studies). If the rainfall was relatively high (>100 cm per year as in Bobo Dioulasso), all variants with a time window for sowing of at most 40 days (i.e. all variants MpAv, MpRa, SpAv, SpRa and MpIIRa2) resulted in the highest possible yield level (Fig. 3).

In the drier regions as around Ouagadougou, the same variants gave high maize yields except for variants MpAv1, MpAv2, SpAv1 and SpAv2 (Fig. 2 left), for which early sowing dates resulted in drought stress and low leaf area index (LAI) values during the vegetative period and thus in low yields. However for sorghum in Ouagadougou, the early sowing dates (variants MpAv1, MpAv2, SpAv1 and SpAv2) resulted in the highest yields (Fig. 2 right). Sorghum has a longer vegetative period than maize and hence, early sowing and drought stress during initial growth had less effect on LAI and biomass production. Note that sorghum has a shorter grain filling period than maize and consequently, its yields were more sensitive to drought at the end of the growth period than those of maize. Hence, rules which resulted in late sowing dates (i.e. variants MpRa2, MpRa3, SpRa2, SpRa3, and MpIIRa2), gave relatively low yields for sorghum. This shows that the best sowing rule is crop type dependent.

In a dry Sahelian region as around Dori, sowing rules that gave a relatively late sowing date, reduced the drought risk at the beginning of the growth period (i.e. variants MpRa2, MpRa3, SpAv3, all SpRa and MpIIRa2) and resulted in the highest yields for the short sorghum variety. For the long sorghum variety grown in this region, the sowing rules that resulted in intermediate sowing dates, reduced best the drought risks at both the start and the end of the growth period (i.e. variants MpAv3, MpRa1, SpAv1 and SpAv2) and resulted in the highest yields. This shows that the best sowing rule also depends on the crop variety, and particularly on its growth duration in comparison to the length of the rainy season. Note that it is most

interesting for large-scale crop model analyses (to reduce the dependence on local expert knowledge), if the sowing criterion can be applied within a relatively large time window for sowing (i.e. M_p and L_p).

4.4 Comparing the results from different sowing rule variants with those for the fixed optimal sowing date

The best sowing rule should be able to calculate sowing dates that are better adapted to the year specific rainfall pattern than the fixed optimal sowing date (variant Fix) per crop-location combination as based on local expert knowledge (Table 2). That would mean that the crop growth simulations performed for the best sowing rule result in higher mean yields and lower SD values than those for variant Fix. The modelling results show that for maize and sorghum in Bobo Dioulasso fixed optimal sowing date and best sowing rule gave the same mean and SD of the yields (Fig. 3), and that for maize and sorghum in Ouagadougou the best sowing rule gave slightly higher yields than those for the fixed optimal sowing date (Fig. 2). However, the best sowing rules for sorghum and for maize in Ouagadougou were clearly different (as described above). In Dori for the short sorghum variety the fixed optimal sowing date and the best sowing rule gave the same mean and SD of the yields (Fig. 1 left), and for the long sorghum variety, the best sowing rule gave moderately higher yields than those for the fixed optimal sowing date (Fig. 1 right), however, with a higher SD. The best sowing rules clearly differed between the short and long sorghum varieties, as a result of fitting the growth period to the short rainy season in Dori.

4.5 Effects of surface runoff

In the Sahelian region of West Africa due to limited tillage, low soil organic matter contents and topsoil sealing, the precipitation losses through surface runoff can be considerable. We tested the effects of surface runoff on sowing rule selection by setting the runoff fraction to respectively, 0%, 10% and 20% for a short sorghum variety in Dori. The results (Fig. 4 left versus right) showed lower mean yields, if a larger part of the precipitation was lost by surface runoff. However, the yield differences among the sowing variants remained the same for the three runoff fractions. This means that the selection of the best sowing criteria and thus the conclusions from this study are not affected by the chosen runoff fraction. Note that the actual surface runoff fractions in arable cropping systems of Burkina Faso are sometimes much higher than the mean runoff fraction of 10% used in this study. The reason for this difference is that we assumed good land management, possibly mulching and use of not too steep land areas.

4.6 Effects of delayed sowing date

If farm operations are mechanized, sowing in western Africa can be done at the optimal date (Table 2). However, if tillage and other farm operations are done with oxen-plough and hand labour, these time consuming and labour intensive operations can only start at the beginning of the rainy season. We investigated the consequences, if sowing was delayed by 30 days on average in comparison to the optimal sowing date. Modelling results for maize showed that the yields in Ouagadougou were considerably reduced in at least half of the years, if the sowing date was delayed by one month. In Bobo Dioulasso the yields were also reduced in most years but to a more limited extent (Fig. 5). In Dori the sorghum yields that were already low and highly variable, became nil if the sowing was delayed by one month, and in Ouagadougou the sorghum yields were strongly reduced in all years and became almost nil in

one third of the years. These zero yields were caused by the occurrence of excessive drought stress during crop development directly after emergence and particularly during the grainfilling. In Bobo Dioulasso, however, the sorghum yields were reduced to a moderate extent. This shows that sowing delay due to labour constraints strongly increased terminal drought stress effects on crop growth and hence, had a disastrous effect on the water limited maize and sorghum yields, particularly in the more northern Sahelian regions with low rainfall (e.g. Ouagadougou and Dori).

5. Conclusions

Sowing dates which are based on local expert knowledge and that are used in large-scale cropping studies, have some limitations (e.g. one sowing date is used in different years and for different crop varieties; the sowing date is subjective as it depends on the local expert; it is difficult to get reliable sowing dates for all crop–region combinations in large-scale model analyses), but the dates that we obtained, worked quite well for Burkina Faso.

Sowing rules for Burkina Faso, and thus also for West Africa, should have a time window for sowing that is at most 40 days around the roughly estimated best date for sowing (as for example based on the FAO crop calendars per country; however, Table 2 shows the limitations of the FAO crop calendars, such as data missing for a certain crop or strange calendars). Results for this studied region show that maize could be sown best between Julian days 160 and 200, with application of the following criteria: a) cumulative rainfall in the sowing window is ≥ 3 cm or available soil moisture content is > 2 cm in the moderately dry, central part of Burkina Faso, b) cumulative rainfall in this period is ≥ 2 cm or available soil moisture content is > 1 cm in the more humid regions in the southern part of Burkina Faso.

550 Sorghum should also be sown between Julian days 160 and 200 with application of the
551 following criteria: a) in northern Burkina Faso the long duration sorghum variety should be
552 sown when cumulated rainfall in the sowing window is ≥ 2 cm and the short duration should
553 be sown later when cumulative rainfall is ≥ 3 cm, b) in central Burkina Faso sowing should
554 start when cumulative rainfall in this period is ≥ 2 cm or when available soil moisture content
555 is > 1 cm. Sowing outside this window, for example directly after the first rains, may lead to
556 initial growth followed by drought that may result in low yields or complete crop failure. This
557 indicates that sowing rules for Sahelian West Africa cannot be constructed without broad
558 knowledge about the optimal sowing period per climate zone or region.

559 Best sowing dates for attaining the highest water limited grain yields can also be derived by
560 performing simulation runs for a period of about two months around the assumed optimal
561 sowing date (as for example based on the FAO crop calendars per country or based on broad
562 expert knowledge); next, the derived, optimized sowing dates were used in the crop growth
563 simulations for Burkina Faso. Simulations over about 10 years for this optimized sowing date
564 gave a good estimate of the maximal mean water-limited yield level for each crop-location
565 combination; however, the simulated yields for individual years may differ from the really
566 attainable yield level.

567 Optimal rules for deriving the best sowing date to attain the highest water limited grain yield
568 are crop, variety, growth duration and region dependent. The correspondence of the growth
569 period with the start and length of the rainy season and the rainfall distribution appears to play
570 an important role. This means that sowing rules applied within crop growth simulations for
571 Burkina Faso, as an example for the range of climatic conditions over West Africa, are crop
572 and location specific, which makes such rules less generic and less useful.

The required precision of the sowing rules is shown to rapidly decrease with increases in the duration of the rainy season and in the total rainfall amount, when moving from north to south in Sahelian West Africa.

Modelled mean rainfed yields strongly decrease if precipitation losses due to surface runoff increase, however, the sowing rule selection is not affected by the degree of runoff losses.

Sowing date delay due to, for example, labour constraints has a disastrous effect on the simulated rainfed maize and sorghum yields, particularly in regions with low rainfall such as the northern Sahel.

Acknowledgement

This research was executed in the context of the Global Yield Gap Atlas (GYGA) project (<http://yieldgap.org/web/guest/home>) supported by the Bill & Melinda Gates foundation (Seattle, USA), the Robert B. Daugherty Water for Food Institute at the University of Nebraska (Lincoln, USA), and Wageningen University (Wageningen, The Netherlands). We would like to thank Martin van Ittersum and Lenny van Bussel for their useful comments on earlier drafts of the manuscript.

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Tables

Table 1 Main crop characteristics for grain maize and sorghum in Burkina Faso used to calibrate the WOFOST model parameters; these characteristics are representative for high-yield varieties growing under optimal conditions with respect to water and nutrient supply and optimal management¹

Crop, Zones in Burkina Faso	Period from emergence to maturity (days)	Period fractions from emergence to flowering and from flowering to maturity (%)	LAI-max (m ² m ⁻²)	Total biomass above-ground ² (kg dry matter ha ⁻¹)	Yield ² (kg dry matter ha ⁻¹)	Harvest index ³
Grain maize, all zones	80 - 120	50% - 50%	3 to 7	10000 to 20000	5000 to 10000	0.45 to 0.55
Sorghum, all zones	75 - 120	55% - 45%	3 to 7	8000 to 18000	3200 to 7200	0.35 to 0.45

¹ Crop characteristics are based on crop data, expert knowledge and experimental information for Burkina Faso, as reported by Stoop (1987), Mando et al. (2005), Ouedraogo et al. (2007), Muleba (1999), Olaoye et al. (2009), and are based on experimental information from Ghana (i.e. Kpongpor, 2007; Morris et al., 1999; Adjei-Nsiah, 2012; DTMaize bulletin, 2013 and MacCarthy et al., 2009) for total biomass production and crop yields

² The growth duration may vary strongly between short- and long-duration varieties which causes the considerable variation in total amount of above-ground biomass and in yield

³ Yield / Total biomass above ground

Table 2 Crop calendars for short and long duration varieties of maize and sorghum for which growth simulations at three locations in Burkina Faso were performed; these calendars are based on local expert knowledge; the temperature sums for the modelled crop phenological development from crop emergence until flowering (TSUM1) and from flowering to maturity (TSUM2) were derived for the

location-specific climate conditions; optimized sowing dates and FAO sowing calendar dates for Burkina Faso were been added for comparison

Location	Rotation	Crop variety ¹	Fixed optimal (Fix) sowing date IDSOW for model calibration and application (Julian day) ²	Growth duration ³ (days)	TSUM1 (°C.d) ⁴	TSUM2 (°C.d) ⁴	Optimized (Opt) sowing date as based on modelling (Julian day) ⁵	FAO begin of sowing period (Julian day) ⁶	FAO end of sowing period (Julian day) ⁶
Dori	Single	Sorghum short	182	80	720	680	182	166-182	181-196
Dori	Single	Sorghum long	182	100	880	920	172	166-182	181-196
Ouagadougou	Single	Maize short	174	90	810	660	194	152-166	181-196
Ouagadougou	Single	Maize long	174	110	920	930	184	152-166	181-196
Ouagadougou	Single	Sorghum short	174	90	750	710	174	166-196	181-212
Ouagadougou	Single	Sorghum long	174	110	890	950	174	166-196	181-212
Bobo-Dioulasso	Single	Maize short	166	90	730	590	186	121-135	135-166
Bobo-Dioulasso	Single	Maize long	166	110	820	820	166	121-135	135-166
Bobo-Dioulasso	Single	Sorghum short	166	90	680	640	156	182-196	196-212
Bobo-Dioulasso	Single	Sorghum long	166	110	790	850	156	182-196	196-212

¹ short= short duration crop variety, long= long duration crop variety

² For the model calibration and application the *fixed optimal* sowing date (as based on local expert knowledge and indicated as variant *Fix*) per location is used; for Ouagadougou no optimal sowing date was available and hence, an intermediate date between those for Dori and Bobo-Dioulasso was used

³ Growth duration is assumed to be the period from sowing to maturity, of which the period from sowing to crop emergence is estimated at about 5 days; durations were based on local expert knowledge

⁴ Photo-period sensitivity is assumed to be negligible for the short-duration and high productive crop varieties

⁵ These sowing dates are derived with a modelling optimization approach and used eight different sowing dates (i.e. fixed optimal sowing date -30 to +40 days), of which the 'optimized' sowing date that gave the highest grain yields on average over the 15 year period, is presented here.

⁶ Sowing dates from FAO for sorghum were not given and hence, the sowing dates for millet are shown here; FAO does not give separate values for short and long varieties; FAO data are derived from <http://www.fao.org/agriculture/seed/cropcalendar/welcome.do>

Table 3. Differences between the sowing date and rule *variants* performed to analyse the effects of sowing date on the yields and their variability and the effects of different sowing rules for establishing the sowing date; each variant was applied to thirty simulation runs in total, consisting of ten crop variety-locations combinations (see Table 2) times three loss fractions of rainfall by surface runoff (i.e. 0.00, 0.10 and 0.20); each simulation run was done for 15 years (1990-2004)

Variant ¹	Sowing date fixed or sowing rule	Criterion for sowing rule ²	Earliest sowing date (Julian day)	Latest sowing date (Julian day)	Other characteristics and remarks
Fix	Fixed	-	-	-	Fixed optimal sowing dates IDSOW as given in Table 2 for all crop-location combinations ³
Opt	Fixed	-	-	-	Optimized date as based on runs for eight sowing dates ⁴
Fix+30	Fixed	-	-	-	Fixed optimal sowing date + 30 ⁵
LpAv1	Rule	WAVMN>1.0	136	212	Sowing period set around optimal sowing dates ⁶
LpAv2	Rule	WAVMN>2.0	136	212	Idem ⁶
LpAv3	Rule	WAVMN>3.0	136	212	Idem ⁶
LpRa1	Rule	MCRAIN≥2.0	136	212	Idem ⁶
LpRa2	Rule	MCRAIN≥3.0	136	212	Idem ⁶
LpRa3	Rule	MCRAIN≥4.0	136	212	Idem ⁶
MpAv1	Rule	WAVMN>1.0	160	200	Sowing period set shortly around optimal sowing dates ⁷
MpAv2	Rule	WAVMN>2.0	160	200	Idem ⁷
MpAv3	Rule	WAVMN>3.0	160	200	Idem ⁷
MpRa1	Rule	MCRAIN≥2.0	160	200	Idem ⁷
MpRa2	Rule	MCRAIN≥3.0	160	200	Idem ⁷
MpRa3	Rule	MCRAIN≥4.0	160	200	Idem ⁷
SpAv1	Rule	WAVMN>1.0	IDSOW – 10 ⁸	IDSOW + 10 ⁸	Sowing period set differently per location ⁸
SpAv2	Rule	WAVMN>2.0	IDSOW – 10 ⁸	IDSOW + 10 ⁸	Idem ⁸
SpAv3	Rule	WAVMN>3.0	IDSOW – 10 ⁸	IDSOW + 10 ⁸	Idem ⁸
SpRa1	Rule	MCRAIN≥2.0	IDSOW – 10 ⁸	IDSOW + 10 ⁸	Idem ⁸

SpRa2	Rule	MCRAIN $\geq$ 3.0	IDSOW – 10 ⁸	IDSOW + 10 ⁸	Idem ⁸
SpRa3	Rule	MCRAIN $\geq$ 4.0	IDSOW – 10 ⁸	IDSOW + 10 ⁸	Idem ⁸
MpIIRa2	Rule	IAVMN>0.8 & MCRAIN $\geq$ 3.0	160	200	Sowing period set shortly around optimal sowing dates ⁷ , initial rooting depth= 10 cm ⁹

¹ Acronym combinations as used for the different sowing date and rule variants, are explained in the text at the beginning of

Section 3, with e.g. short, medium and long sowing periods indicated by respectively, *Sp*, *Mp* and *Lp*.

² Criteria for sowing are: a) **WAVMN** --> available soil water (cm) in maximally rooted depth that is minimally required for sowing ; b) **MCRAIN** --> cumulative amount of rainfall (cm, as counted between earliest and latest possible sowing date) that is minimally required for sowing; c) **IAVMN** --> initial available soil water (cm) in initial rooting depth that is minimally required for sowing

³ Fixed optimal sowing dates (i.e. IDSOW) as based on local expert knowledge (see Table 2)

⁴ Sowing dates are equal to fixed optimal sowing date (Table 2) -30, -20, -10, 0, +10, +20, +30 and +40 days, respectively; the simulation runs were only performed for a runoff loss fraction of the rainfall of 0.10

⁵ Sowing date is assumed to be delayed by on average 30 days, which represents a sowing period of 60 days after the optimal sowing date, as related to labour shortage for tillage, sowing, weeding and mulching of all the fields and the need for re-sowing some of the fields

⁶ Sowing period starts 30 days before the first fixed optimal sowing date and ends 30 days after the last optimal sowing date as given in Table 2

⁷ Sowing period starts 6 days before the first fixed optimal sowing date and ends 18 days after the last optimal sowing date given in Table 2

⁸ Sowing period starts 10 days before the fixed optimal sowing dates (IDSOW) from Table 2 and ends 10 days after IDSOW

⁹ Initial rooting depth (RDI) at crop emergence is set to 10 cm in all variants.

765

766 **Captions**

767 Figure 1 Mean and SD of simulated grain yields of sorghum (left: short duration variety;
768 right: long duration variety) for the period 1990-2004 at Dori, Burkina Faso (surface runoff
769 set to 10% of the rainfall) for different sowing date and rule variants (see Table 3 for
770 information about all variants)

771 Figure 2 Mean and SD of simulated grain yields of maize (left: long duration variety) and
772 sorghum (right: long duration variety) for the period 1990-2004 at Ouagadougou, Burkina
773 Faso (surface runoff set to 10% of the rainfall) for different sowing date and rule variants (see
774 Table 3 for information about all variants)

775 Figure 3 Mean and SD of simulated grain yields of maize (left: long duration variety) and
776 sorghum (right: long duration variety) for the period 1990-2004 at Bobo Dioulasso, Burkina
777 Faso (surface runoff set to 10% of the rainfall) for different sowing date and rule variants (see
778 Table 3 for information about all variants)

779 Figure 4 Mean and SD of simulated grain yields of sorghum (short duration variety) for the
780 period 1990-2004 at Dori, Burkina Faso with the mean loss fraction of rainfall by surface
781 runoff set to 0% (left) and 20% (right) for different sowing date and rule variants (see Table 3
782 for information about all variants)

783 Figure 5 Simulated grain yields of maize (left: long duration variety) and sorghum (right:
784 long duration variety) over a period of 15 years at respectively, Dori, Ouagadougou and Bobo
785 Dioulasso, Burkina Faso (surface runoff set to 10% of the rainfall) for the fixed optimal
786 sowing date (variant Fix) and for the fixed optimal sowing date plus 30 days of delay (variant
787 Fix+30)

788 Figure 6 Simulated grain yields of sorghum (long duration variety) at Dori (top) and
789 Ouagadougou (middle) and of maize (long duration variety) at Bobo Dioulasso (bottom),
790 Burkina Faso over a period of 15 years (surface runoff set to 10% of the rainfall) for different
791 sowing dates (in Julian day)

792

793 Appendix A. Mean results of the water-limited simulation runs for sorghum (short variety) in Dori for the different sowing date and rule variants with runoff
 794 loss fraction of precipitation equal to 0.10 (exception is variant Opt (see Table 3) for which only the results for the sowing date with the highest water-limited
 795 grain yield are given); the differences between the variants are given in Table 3; each simulation run was performed for 15 years (1990-2004)

796	Variant ¹	Sowing	Emergence	Growth	Leaf	Stem	Grain	CV of	Total	CV of	Maximal leaf	Harvest	Relative
797		date	date	duration	weight	weight	weight	grain	above-ground	total above-	area index	index ³	water-limited
798								yield ²	biomass	ground biomass ²			yield fraction ⁴
799		(Julian	(Julian	(days)	(kg DM	(kg DM)	(kg DM	(%)	(kg DM	(%)	(m ² m ⁻²)	(-)	(-)
800		day)	day)		ha ⁻¹)	ha ⁻¹)	ha ⁻¹)		ha ⁻¹)				
801	Fix	182.	186.	75.	1318.	2339.	2725.	66.10	6382.	65.26	2.56	0.46	55.51
802	Opt	182.	186.	75.	1318.	2339.	2725.	66.10	6382.	65.26	2.56	0.46	55.51
803	Fix+30	212.	216.	74.	2777.	3015.	771.	104.69	6563.	27.02	5.24	0.10	20.31
804	LpAv1	136.	140.	51.	32.	59.	91.	230.55	182.	227.97	0.06	0.17	1.84
805	LpAv2	153.	156.	65.	274.	617.	899.	170.23	1789.	176.95	0.53	0.42	17.62
806	LpAv3	162.	166.	70.	601.	1167.	1517.	112.16	3285.	109.80	1.15	0.45	30.54
807	LpRa1	156.	160.	65.	299.	685.	1033.	146.78	2017.	155.06	0.58	0.43	20.20
808	LpRa2	159.	163.	71.	376.	873.	1352.	122.98	2601.	128.67	0.73	0.49	26.58
809	LpRa3	164.	167.	71.	513.	1130.	1609.	117.04	3252.	121.51	1.00	0.50	32.18

810	MpAv1	160.	164.	74.	287.	576.	923.	161.22	1786.	168.43	0.54	0.56	17.66
811	MpAv2	167.	170.	74.	585.	1260.	1763.	107.88	3608.	111.29	1.14	0.53	34.91
812	MpAv3	176.	179.	74.	1056.	1764.	2270.	85.65	5090.	78.95	2.01	0.47	45.50
813	MpRa1	176.	179.	74.	1098.	1908.	2344.	78.48	5350.	75.18	2.10	0.49	46.64
814	MpRa2	178.	182.	74.	1311.	2230.	2609.	74.40	6150.	66.48	2.51	0.46	52.61
815	MpRa3	182.	186.	75.	1596.	2466.	2654.	66.78	6716.	55.29	3.02	0.41	54.03
816	SpAv1	172.	176.	74.	720.	1490.	2247.	83.99	4456.	87.77	1.38	0.54	44.40
817	SpAv2	176.	180.	74.	1044.	1958.	2476.	77.87	5478.	70.67	1.99	0.47	49.62
818	SpAv3	179.	182.	74.	1344.	2262.	2595.	74.32	6200.	68.30	2.57	0.45	52.38
819	SpRa1	182.	185.	74.	1421.	2395.	2597.	69.70	6413.	61.34	2.71	0.43	52.86
820	SpRa2	183.	186.	74.	1514.	2600.	2804.	60.39	6919.	51.62	2.90	0.42	57.53
821	SpRa3	185.	189.	74.	1671.	2771.	2715.	61.12	7157.	48.34	3.23	0.39	55.80
822	MpI1Ra2	182.	185.	74.	1572.	2454.	2642.	67.82	6668.	57.71	2.98	0.42	53.92

823 ¹ Variant description, see Table 3

824 ² Coefficient of variation for grain yields and total above-ground biomass over 15 years

825 ³ Harvest index is equal to the grain yield divided by the total above-ground biomass

826 ⁴ Relative water-limited yield fraction is equal to the water limited grain yield divided by the potential (= irrigated) grain yield

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6