PLANT RESEARCH INTERNATIONAL
WAGENINGEN UR

# Mapping yield variability of sorghum and millet in Mali

J.G. Conijn, H. Hengsdijk & B. Rutgers


Report 440

PLANT RESEARCH INTERNATIONAL
WAGENINGEN UR

# Mapping yield variability of sorghum and millet in Mali

J.G. Conijn, H. Hengsdijk & B. Rutgers

Plant Research International, part of Wageningen UR
Business Unit Agrosystems
March 2012

Report 440

Copies of this report can be ordered from the (first) author. The costs are € 50 per copy (including handling and administration costs), for which an invoice will be included.

**Plant Research International, part of Wageningen UR**
**Business Unit Agrosystems**

| | | |
|---|---|---|
| Address | : | P.O. Box 616, 6700 AP Wageningen, The Netherlands |
| | : | Wageningen Campus, Droevendaalsesteeg 1, Wageningen, The Netherlands |
| Tel. | : | +31 317 48 05 59 |
| Fax | : | +31 317 41 80 94 |
| E-mail | : | info.pri@wur.nl |
| Internet | : | www.pri.wur.nl |

# Table of contents

# Preface

This report is the result of the project 'Assess the demand for weather index-based insurance as a means of adaptation to climate change' (BO-10-009-112). The study has been carried out within the Policy Support Cluster International Cooperation, which is one of the major programmes for international research and capacity building at Wageningen UR. The Cluster is financed by the Netherlands Ministry of Economic affairs, Agriculture and Innovation. This report is a continuation of the study of Conijn *et al.* (2011a), which focused on mapping yield variability of maize in Mali. This report maps the yield variability of sorghum and millet in Mali.

Activities have been implemented in close coordination with the IFAD WFP Weather Risk Management Facility (WRMF) team. Launched in 2008 with the support of the Bill and Melinda Gates Foundation, the WRMF is a joint initiative of the International Fund for Agricultural Development (IFAD) and the World Food Programme (WFP). It draws on IFAD's experience in rural finance and on WFP's expertise in disaster-risk reduction and management.

The WRMF focuses on four areas:

- Building the capacity of local stakeholders for weather risk management by strengthening partnerships, offering technical assistance, and promoting knowledge exchange in the development and use of risk mitigation mechanisms, including weather index-based insurance (WIBI).
- Improving weather services, infrastructure and data management for weather risk management, including the development of WIBI, national weather risk management, early warning systems and vulnerability analysis.
- Supporting the development of an enabling environment by engaging with government partners and advocating national risk management frameworks and appropriate financial and weather risk-management strategies and policies.
- Promoting inclusive financial systems for poor people in rural areas, including innovative delivery channels and client education, which lead to better planning for and coping with weather shocks.

The WRMF strongly appreciated Wageningen UR support and the result of this work, as it will be instrumental to shape the ongoing and future activities in Mali and in other countries.

Francesco Rispoli
Technical Adviser, Policy and Technical Advisory Division
International Fund for Agricultural Development

# 1. Introduction

Weather is a significant factor for economic well-being in many countries of sub-Saharan Africa depending on agriculture as major livelihood. Especially, in areas with predominantly rain fed agriculture, weather variability is a major determinant of economic growth (e.g. IBRD/WB, 2006). Under the threat of possible adverse weather conditions, poor farm households will often choose low-risk, low return activities, and avoid costly innovations that could increase productivity (e.g. Ruben *et al.*, 2006). At the same time financial institutions tend to restrict lending to farm households if adverse weather conditions might result in widespread defaults (Skees *et al.*, 2006). The lack of access to credit restricts access to agricultural inputs required for increasing productivity and overall rural development. Hence, different risk coping strategies at different scales exist that may be effective in reducing risk exposure in the short run, but hinder growth and rural development in the long-run.

As anticipated climate change is expected to increase yield variability, especially in Africa, the development of new formal risk management tools has been called for (Skees *et al.*, 2006). One of the tools that received attention is the so-called 'weather index-based insurance' that distinguishes from traditional forms of insurance because compensation payments are based on an index that serves as proxy for losses rather than upon the individual losses of each policyholder. An index can be based on an objective measure such as rainfall in a certain period of the year that exhibits a strong correlation with the variable of interest, for example, crop yields (Hellmuth *et al.*, 2009).

The International Fund for Agricultural Development (IFAD) and the World Food Program (WFP) are working together through the Weather Risk Management Facility to further develop weather index-based insurance and other risk management tools. Although the potential benefits of weather index-based insurance in a number of case studies are promising, there remains a need for technical research assistance for the development and implementation of the tool in new areas (Hellmuth *et al.*, 2009).

One of the new focal areas of IFAD and WFP for implementing weather index-based insurance is Mali. To support this initiative Wageningen UR was requested to provide insight in the spatial and temporal variability of cereal yields across Mali. This resulted in the study of Conijn *et al.* (2011a) mapping the yield variability of maize across Mali. Such information can be used as a first step to identify areas where weather index-based insurance may be feasible and other areas where production risks are too high or too low reducing the chances for a successful implementation of weather index-based insurance. In 2011 the work on mapping yield variability continued with sorghum and millet, of which the results are described in this report. Since the report on the yield variability of maize (Conijn *et al.*, 2011a) the applied modelling and data framework (Conijn *et al.*, 2011b) has been further developed. In Chapter 2 the methodology and input data are described, including the differences compared to Conijn *et al.* (2011a). In Chapter 3 results for sorghum and millet are presented in maps. In the Discussion and conclusions (Chapter 4) we address the dynamics in area development of sorghum and millet and analyse the impact of the new framework configuration for the maize simulations (Conijn *et al.*, 2011b) to enable the assessment of the millet and sorghum simulation results in this report with the new framework configuration.

# 2. Material and methods

The core of the applied method consists of a dynamic crop growth simulation model linked to spatial databases with detailed information on soil properties, climate conditions and land use (Conijn *et al.*, 2011b). The crop growth simulation model is supplied with generic crop characteristics for tropical sorghum and millet. In the following the different components of the applied methodology are briefly described including differences with the method and data used in Conijn *et al.* (2011a) for assessing yield variability of maize.

## 2.1 Crop growth simulation model

The LINPAC crop growth model used in the yield calculations originates from Spitters (1987) and Spitters and Schapendonk (1990) and is one of the so-called LINTUL (Linear INTerpolation of Utilization of Light) models (Bouman *et al.*, 1996). LINPAC stands for the LINtul model for Perennial and Annual crops since it has been extended with a module allowing to simulate also perennial crops (Jing *et al.*, 2011). Crop dry matter production in such models is calculated as the product of light interception and a light use efficiency (LUE, g dry matter per MJ intercepted radiation). Light interception depends on leaf area index (LAI, $m^2$ leaf per $m^2$ ground) and the accumulated dry matter production is distributed among above- and belowground and (non-)harvestable parts. Dry matter distribution is governed by the developmental stage of the crop (DVS, dimensionless) which is driven by temperature and can also be influenced by day length.

The number of cropping cycles per year and the start(s) and end(s) of these cycles are calculated as function of soil moisture thresholds, i.e. adequate moisture conditions to start a cycle and prolonged drought conditions indicating the end, and the temperature sum required to complete the crop development. If the length of the determined cropping cycle is too short relative to what the crop needs, a 'no–cropping' situation is simulated which results in the simulation of only the soil water balance without crop vegetation.

Soil water availability for the crop is determined by calculating infiltration, evapotranspiration and percolation. The soil profile is divided in two horizontal layers, i.e. from soil surface to the actual rooting depth and from actual rooting depth to a crop- or soil-specific maximum rooting depth. Water infiltrates in the soil as a result of precipitation plus (possible) irrigation minus runoff which is a function of soil texture, slope and precipitation/irrigation rate. Percolation equals the amount of water in excess of the maximum storage capacity of each soil layer and infiltrates into the next layer. Percolated water at the bottom layer is assumed to be lost for the crop. EvapoTranspiration (ET, mm) is calculated in two steps: (1) potential ET is calculated with the Penman-Monteith equation and divided over potential soil evaporation (E, mm) and crop transpiration (T, mm) and (2) actual ET is a function of this potential E and T and the soil water availability in the rooted soil layer. If the actual T falls below the potential T, water stress occurs resulting in a proportional reduction of the LUE and LAI growth and an acceleration of leaf senescence. The crop model operates with a daily time step to simulate the effects of day-to-day variability in weather conditions.

Additional water stress is modeled for maize around the period of flowering (Conijn *et al.*, 2011a). For sorghum and millet such a period is absent as both crop types are more drought tolerant. Another change compared to the simulation of maize (Conijn *et al.*, 2011a) is the setting of the start and end of the growing season, which is now more dependent on a prolonged period of suitable growing conditions after the sowing date to calculate this date per grid cell and per year for sorghum and millet. The need for an improvement of this algorithm became apparent when simulating for other parts of the world because in some situations crop sowing started too early.

## 2.2 Soil data

In this study the 1:5 million scale FAO-UNESCO Digital Soil Map of the World (DSMW; FAO, 1995) is used for information on the spatial distribution of soil types in Mali, as in Conijn *et al.* (2011a) for maize. The legend of this global map contains 4,931 unique Soil Mapping Units (SMUs) and each grid cell is characterized by one SMU which can comprise a number of soil units (up to 8 different soil units per SMU). Mali comprises 89 different SMUs distributed over 15,269 grid cells that cover the whole country (1.25 million $km^2$ based on the sum of all grid cell areas). Most grid cells contain more than one soil unit and the areas of soil units are expressed as percentages of the grid cell. Each soil unit has unique soil properties, which may affect crop production. Selected soil properties for the crop model comprise (1) texture class, (2) slope class, (3) soil depth and (4) available water content. Available water content is defined here as the maximum amount of crop-available water that can be stored in the soil, i.e. the difference between field capacity (-33 kPa) and permanent wilting point (-1500 kPa). These properties were derived from the World Inventory of Soil Emission Potentials (WISE) database developed by the International Soil Reference and Information Center (ISRIC; Batjes, 2006). The soil parameter values and derived maps are considered as best estimates based on the current selection of soil profiles in WISE, the procedure for clustering the measured data, taxo-transfer scheme used for filling gaps in the measured data, and the spatial data of the DSMW. This information is considered appropriate for exploratory assessments at scale < 1:5 million. The gridded map used in the study for sorghum and millet has the same resolution of 5x5 arc minutes in latitude/longitude coordinates (ca. 9x9 $km^2$) as used for maize (Conijn *et al.*, 2011a). Two important differences exists in comparison with the simulation of maize yields: (a) the soil properties are now derived from WISE-ISRIC instead of derived from algorithms provided by the FAO and (b) both slope class and soil induced reduction factor are assigned a value of one, because WISE-ISRIC does not contain information for direct estimation of these parameters. These adjustments lead in general to a lower runoff (a) and a higher LUE (b), but for Mali the differences are relatively small because soil types with adverse chemical soil conditions (resulting in factor values below 1) and higher slope classes are not widespread.

## 2.3 Weather data

Weather data are obtained from the University of East Anglia Climate Research Unit (CRU, 2008). Here we use the dataset version CRU TS3.1 instead of CRU TS3.0 as used for the maize modeling (Conijn *et al.*, 2011a). The spatial resolution (30x30 arc minutes, i.e. 54x54 km; circa 290,000 ha) is the same for both datasets but the temporal resolution of monthly values for each year covers the period 1901 – 2009 in CRU TS3.1 and 1901-2006 in version CRU TS3.0. In addition, the historical data in CRU TS3.1 have been updated and improved compared to those available in CRU TS3.0. In the analysis for maize the historical data from 1976 – 2005 (30 years) was used (from CRU TS3.0), while in the analysis for sorghum and millet more recent data have been used from CRU TS3.1, i.e. data from 1981 – 2009 (29 years) comprising for each year in this period the monthly values of cloud cover, temperature, vapor pressure, rainfall and the number of rainy days. Data on wind speed were not available per year and, therefore, we used average values obtained from the climatology of 1961 – 1990, also provided by CRU (CRU CL1.0). Hence, compared to the maize analysis we have not only used a different time period of weather data but also the weather data for similar years may be different as the Climate Research Unit has updated weather data in CRU TS3.1.

As the crop model runs with a daily time step, the monthly values of the weather database were linearly interpolated to obtain daily values for cloud cover, temperature, vapor pressure and wind speed. This procedure is not adequate for precipitation because it commonly consists of a series of discrete and random events. Using average daily precipitation values in the crop model may underestimate the effect of water stress on crop production. A random generator is therefore used to distribute the monthly total precipitation over the number of rainy days in a month, which results in a pattern of days without rain and days with a variable amount of rain in each month.

## 2.4 Land use data

We have used the land use data from Monfreda *et al.* (2008) to derive spatially explicit information on the total harvested crop area and sorghum and millet area in Mali at a resolution of 5x5 arc minutes. Their global land use data are based on agricultural statistics from the period 1997 – 2003 in combination with remote sensing data. This data source is the same as used for maize (Conijn *et al.*, 2011a).

# 3. Results

## 3.1 Rainfall

In Figure 1 we show the average annual rainfall across Mali during the period 1976 – 2005 as used in Conijn *et al.* (2011a) and in the period 1981-2009 used in estimating yield variability of sorghum and millet in this study. In both cases average rainfall shows a clear strong North-South gradient with less than 100 mm per year in the North and more than 1200 mm in the extreme South of Mali. Although the differences in rainfall classes is small, rainfall from the period 1981-2009 appears to be a bit lower as the lower rainfall classes tend to advance towards the South of Mali.

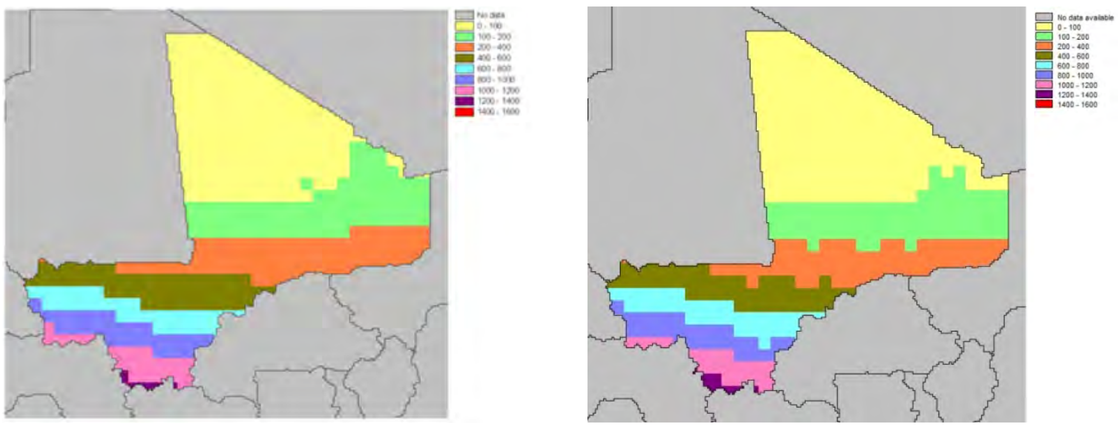


*Figure 1. Total average rainfall in mm per year across Mali in the period 1976 – 2005 (left side; CRU TS3.0) and in the period 1981-2009 (right side; CRU TS3.1).*

## 3.2 Sorghum and millet yield variability

For each 5x5 arcminutes grid cell in Mali and for each year in the period 1981 – 2009, the crop growth model is used to calculate daily soil water availability and crop growth as function of soil, weather and crop characteristics. These daily rates are integrated over time by the crop growth model resulting in crop dry matter yields per growth cycle and per year (= the sum of yields of all cycles in a year). To illustrate the risks of (extreme) low yields due to weather variability across Mali in the period 1981 - 2009, we have mapped the percentage of years with yields lower than an (arbitrary set) yield threshold expressed as a percentage of the average yield. Using a threshold of 25%, Figure 2a presents results of sorghum and millet for entire Mali, Figure 2b for the total harvested crop area in Mali and Figure 2c for the harvested sorghum and millet area in Mali.

Figure 2a, b and c hardly differ partly because almost all the cropped area is also used for growing sorghum and millet (Figure 2b *vs* 2c). Also the sorghum and millet maps hardly differ as they are largely cultivated in the same areas (Figure 2c) and their crop characteristics with respect to yield variability hardly differ. The risky areas for growing sorghum and millet are towards the North of Mali, i.e. the zone with 200-400 mm rainfall per year (Figure 1). In the South of Mali years with low yields are rare. Also the differences between sorghum and millet are small and if there are differences they are inconsistent, some sites show a somewhat lower risk for low sorghum yields, while other sites show lower risks for low millet yields. However, the general view is very similar for both crops, which confirms a similar tolerance to drought conditions.

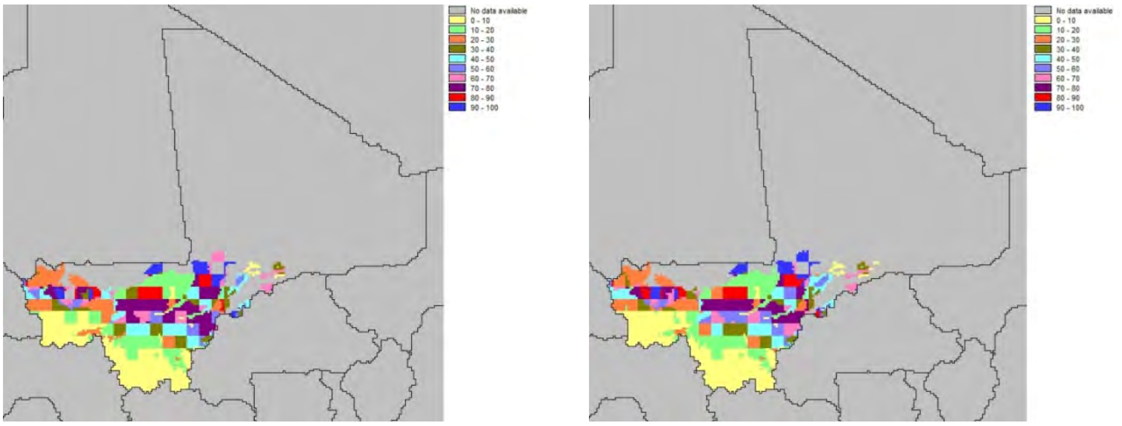


*Figure 2a.* *Percentage of years with low sorghum yields (left) and millet yields (right); Low yields are < 25% of the average simulated rain fed yield per grid cell in Mali. Grey areas in Mail refer to areas that are unsuitable for growing sorghum or millet, according to the model simulation.*

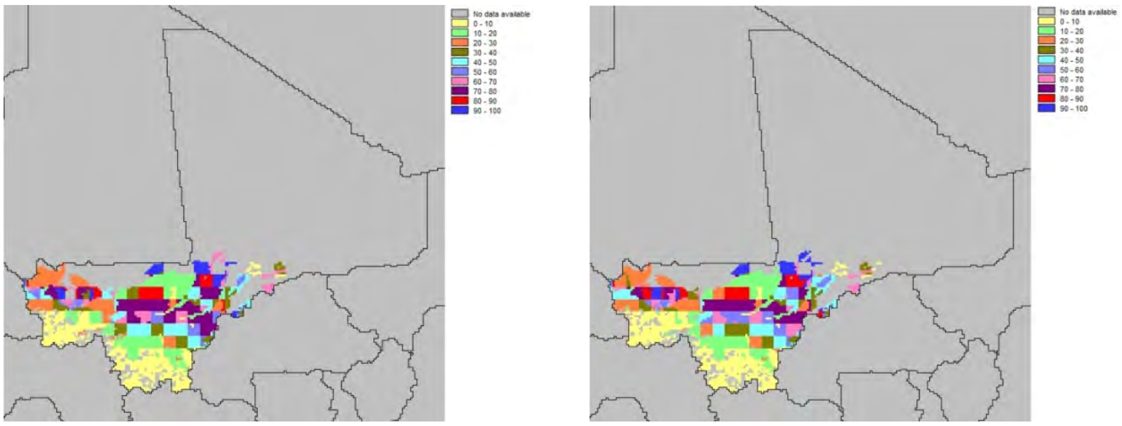


*Figure 2b.* *Percentage of years with low sorghum yields (left) and millet yields (right); Low yields are < 25% of the average simulated rain fed yield per grid cell used for growing arable crops in Mali around the year 2000. Grey areas in Mali refer to areas without arable crops and/or a zero simulated crop yield.*

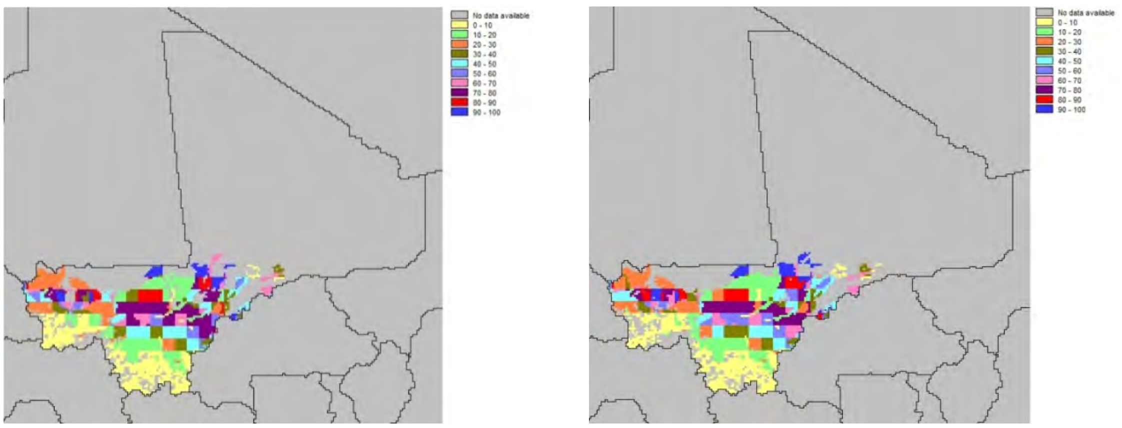


*Figure 2c.* *Percentage of years with low sorghum yields (left) and millet yields (right); Low yields are < 25% of the average simulated rain fed yield per grid cell used for growing sorghum and millet in Mali around the year 2000. Grey areas in Mali refer to areas without sorghum and millet cultivation and/or a zero simulated crop yield.*

The spatial risk maps shown in Figures 2a, -b, -c are based on a yield threshold of 25%, i.e. the percentage of years in which the simulated yield is less than 25% of the average yield simulated for the period 1981-2009. In Figure 3 results are shown with a threshold of 40% using the same simulated yields for each gridcell and for the millet and sorghum area. The shown risks in Figure 3 are somewhat higher because of tighter threshold, which causes more years to comply with the condition of a low yields (< 40% of the average). In general, the differences with Figure 2c are very small and hardly visible indicating that shifts among the different (legenda) classes are minor.

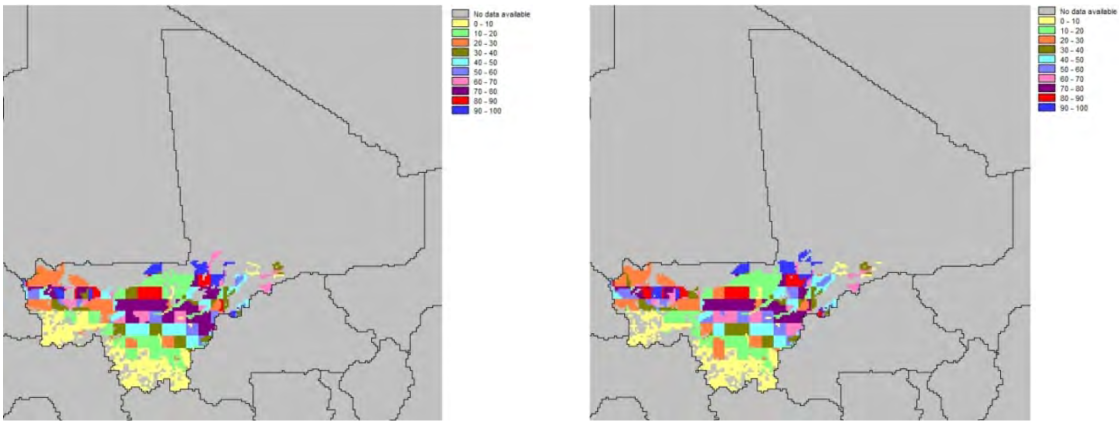


*Figure 3.* *Percentage of years with low sorghum yields (left) and millet yields (right); Low yields are < 40% of the average simulated rain fed yield per grid cell used for growing sorghum and millet in Mali around the year 2000. Grey areas in Mali refer to areas without sorghum and millet cultivation. Compare to Figure 2c.*

Consequences of further tightening of the threshold to a yield reduction of 50% or more compared to the long-term average simulated yields are shown in Figure 4 for sorghum and millet. Obviously, there is a gradual shift towards more yield risk but no major changes compared to Figure 3 and also differences between sorghum and millet remain similar.

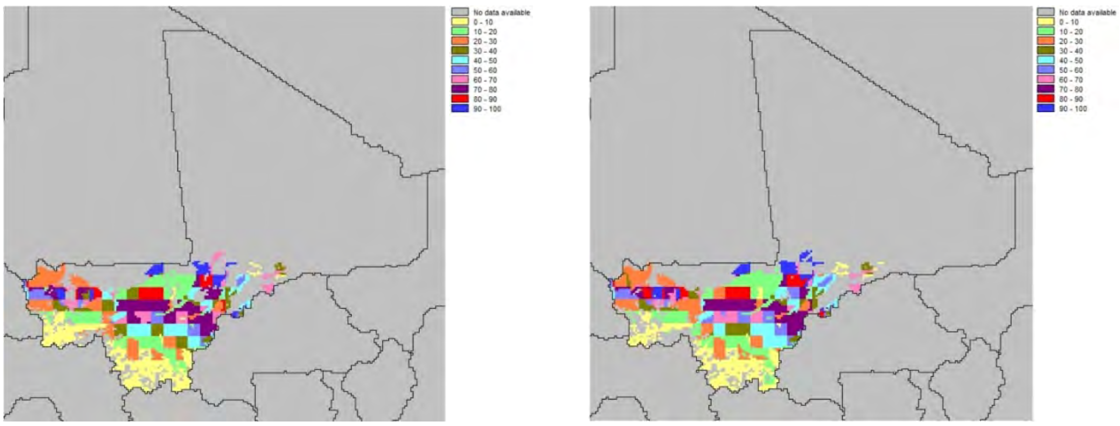


*Figure 4.* *Percentage of years with low sorghum yields (left) and millet yields (right); Low yields are < 50% of the average simulated rain fed yield per grid cell used for growing sorghum and millet in Mali around the year 2000. Grey areas in Mali refer to areas without sorghum and millet cultivation. Compare to Figure 2c and 3.*

# 4. Discussion and conclusions

Our crop area for sorghum and millet is based on Monfreda *et al.* (2008) who combined remote sensing information and sub-national census data from the period 1997-2003. Their estimate for the sorghum area is 515,637 ha, and 862,019 ha for the millet area in Mali. As a comparison, we show the FAOSTAT data for Mali covering the period 1997-2003 in Table 1. The Monfreda data only correspond well for the year 1997, but since that year the harvested areas of sorghum and particularly of millet have increased considerably according to FAOSTAT: the sorghum area increased to 822.331 ha in 2003 and the millet area more than doubled to 1.8 million ha. In 2009, the harvested millet area was decreased again to 1.5 million ha and the sorghum area increased to 1.1 million ha (FAOSTAT, not shown). Differences between the Monfreda database and FAOSTAT data have also been identified in Conijn *et al.* (2011b) without being able to indicate which data are more accurate. The advantage of Monfreda data is that they are spatially explicit, but Table 1 suggests that frequent updating of the data is required to maintain accuracy in the actual harvested crop areas.

*Table 1. Sorghum and millet harvested areas in Mali between 1997 and 2003 (FAOSTAT).*

| Harvested area | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 |
|---|---|---|---|---|---|---|---|
| Sorghum | 573,034 | 616,630 | 733,037 | 674,768 | 702,478 | 923,272 | 822,331 |
| Millet | 878,941 | 910,816 | 923,307 | 1,078,620 | 1,142,390 | 1,5557,590 | 1,888,890 |

As indicated in the Introduction comparison with the maize simulations (Conijn *et al.*, 2011a) is only possible to a limited extent since other climate and soil databases have been used in this study, while the procedure to set the start and end of the growing season has been changed in the crop growth simulation model (section 2.1). To show the impact of these changes on the results we compare in Figure 5 two maize simulations with both framework configurations, i.e. as used in Conijn *et al.* (2011a) and as used for the millet and sorghum simulations in this report.

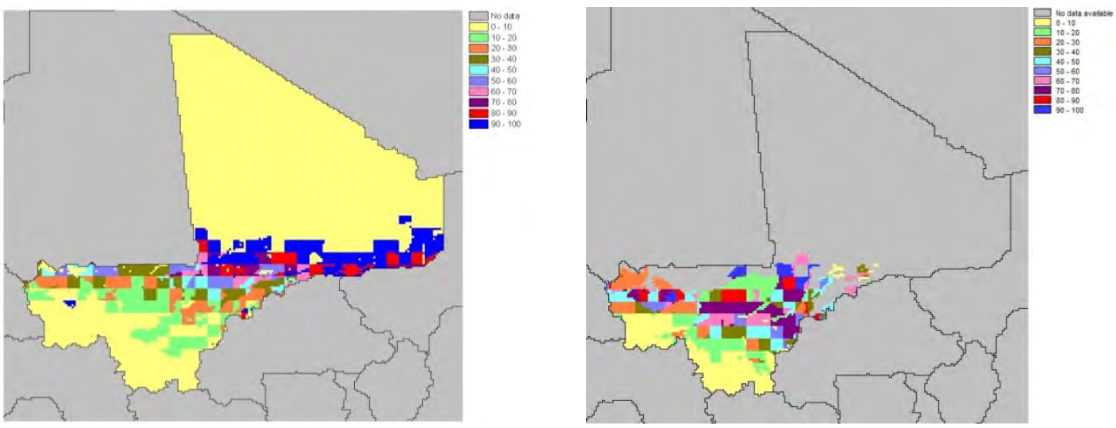


*Figure 5. Percentage of years with low yields (<25% of the long-term average rainfed maize yields) per grid cell. Left map is based on the model and data configuration as used in Conijn et al. (2011a; Figure 3a), and the map on the right is based on the configuration used in this report. Note that yellow colour (0-10 % of the years) in Northern Mali in the left map has been classified as 'no data available' in the right map as no maize can be grown in this area and consequently the percentage of years with low yields is zero.*

The differences are considerable: using the new framework configuration as used in this report for millet and sorghum the area where maize is grown is much smaller and corresponds much better with the actual harvested maize area (Figure 3c in Conijn *et al.*, 2011a). At the same time, the maize area that faces frequent years with low yields has shifted to the South. Since different data and procedures have been changed simultaneously in the new framework configuration it is difficult to indicate which change contributed most to the differences in simulation results as shown in Figure 5. Similarly, it is difficult to assess which framework configuration is more accurate. The new configuration is better able to simulate the actually harvested maize area, but marked differences remain as the actual harvested maize area is still overestimated in a number of regions (compare right-hand map in Figure 5 with Figure 3c in Conijn *et al.* 2011a). In general it stresses the importance of using accurate data on cropping seasons and sowing and harvesting dates of the various crops in the simulation. A likely improvement can be achieved by using statistical data on sowing crops as a forcing function in the simulation rather than determining this information depending on climate, soil and physiological crop characteristics (as is the case in the present calculations).

Yield variability of sorghum and millet hardly differs indicating a similar response to water limited conditions. This is further confirmed by the current cultivated areas of both crops, which is very similar (compare both maps in Figure 2c): Both crops are cultivated in the same locations. However, further empirical testing is needed to verify whether used millet and sorghum varieties in Mali show the same yield response to drought conditions, and thus similar yield variability.

# References


Batjes, N.H., 2006.
ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid (ver. 1.1). Report 2006/02, ISRIC - World Soil Information, Wageningen.

Bouman, B.A.M., H. van Keulen, H.H. van Laar & R. Rabbinge, 1996.
The 'school of de Wit' crop growth models: A pedigree and historical overview. Agricultural Systems 52: 171-198.

Conijn, J.G., H. Hengsdijk, B. Rutgers & R.E.E. Jongschaap, 2011a.
Mapping maize yield variability in Mali. Wageningen: Plant Research International, Report / Plant Research International 375.

Conijn, J.G., E.P. Querner, M.L. Rau, H. Hengsdijk, J.W. Kuhlman, G.W. Meijerink, B. Rutgers & P.S. Bindraban, 2011b.
Agricultural resource scarcity and distribution : a case study of crop production in Africa. Wageningen: Plant Research International, Report / Plant Research International 380.

CRU [University of East Anglia Climatic Research Unit], 2008.
CRU Time Series (TS) high resolution gridded datasets, [Internet]. NCAS British Atmospheric Data Centre. Available from http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_1256223773328276 Accessed November 15, 2011.

FAO, 1995.
The digital soil map of the world. Version 3.5. Food and Agriculture Organization of the United Nations, Roma.

Hellmuth, M.E., D.E. Osgood, U. Hess, A. Moorhead & H. Bhojwani (eds.), 2009.
Index insurance and climate risk: Prospects for development and disaster management. Climate and society no. 2. International Research Institute for Climate and Society (IR), Colombia University, New York, USA.

IBRD/WB [International Bank for Reconstruction and Development/ World Bank], 2006.
Ethiopia: Managing water resources to maximize sustainable growth. Country water resources assistance strategy. Report no. 36000-ET.

Jing, Q., S. Conijn, R. Jongschaap & P. Bindraban, 2011.
Modeling energy crops for biomass production on large spatial scales. (submitted to Biomass and Bioenergy).

Monfreda, C., N. Ramankutty & J.A. Foley, 2008.
Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochemical cycles 22: GB1022, doi:10.1029/2007GB002947.

Ruben, R., G. Kruseman & A. Kuyvenhoven, 2006.
Strategies for sustainable intensification in East African highlands: labor use and input use. Agricultural economics 34: 167-181.

Skees, J., A. Goes, C. Sullivan, R. Carpenter, M. Miranda & B. Barnett, 2006.
Index insurance for weather risk in lower income countries. GlobalAgRisk, Inc.

Spitters, C.J.T., 1987.
An analysis of variation in yield among potato cultivars in terms of light absorption, light by utilization and dry matter partitioning. Acta Horticulturae 214: 71-84.

Spitters, C.J.T. & A.H.C.M. Schapendonk, 1990.
Evaluation of breeding strategies for drought tolerance in potato by means of crop growth simulation. Plant and Soil 123: 193-203.