PLANT RESEARCH INTERNATIONAL
WAGENINGEN UR

Mapping maize yield variability in Mali

J.G. Conijn, H. Hengsdijk, B. Rutgers & R.E.E. Jongschaap

Report 375

Mapping maize yield variability in Mali

J.G. Conijn, H. Hengsdijk, B. Rutgers & R.E.E. Jongschaap

Plant Research International, part of Wageningen UR
Business Unit Agrosystems Research
February 2011

Report 375

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 Research

Address	:	P.O. Box 616, 6700 AP Wageningen, The Netherlands
	:	Wageningen Campus, Droevendaalsesteeg 1, Wageningen, The Netherlands
Tel.	:	+31 317 48 05 44
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 work 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.

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). 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 maize yields across Mali. This 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.

This report describes the first results of the mapping of yield variability of maize in Mali. In Chapter 2 the methodology and input data are described. In Chapter 3 the results are presented in maps and Chapter 4 discusses some issues to improve the applied methodology.

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. In addition, the model is supplied with generic crop characteristics of tropical grain maize. In the following the different components of the applied methodology are described.

2.1 Crop growth simulation model

The 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). 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 a 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 an acceleration of leaf senescence.

Additional water stress is modeled for maize around the period of flowering. The ratio of cumulative actual T over potential T shortly before and after flowering is computed and used to determine the sink strength of the grains to accumulate dry matter during grain filling. This ratio affects the dry matter production after flowering and is therefore positively correlated with ultimate grain yield.

The crop model operates with a daily time step to simulate the effects of day-to-day variability in weather conditions.

2.2 Soil data

In this study the Digital Soil Map of the World (DSMW; FAO, 1995) is used for information on the spatial distribution of soil types in Mali. This gridded map has a resolution of 5x5 arc minutes in latitude/longitude coordinates and grid cells in Mali have an area of approximately 9x9 km (8100 ha). 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 comprise (1) texture class, (2) slope class, (3) soil depth, (4) available water content and (5) a soil induced reduction factor (the first four are derived from algorithms provided by the FAO). 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 (pF = 2.0) and permanent wilting point (pF = 4.2). The reduction factor limits crop growth and has been estimated as function of soil type in case of Acrisols (factor = 0.75), Solonetz (factor = 0.5) and if the phase description in the FAO soil database refers to saline/sodic conditions (factor = 0.25) to account for adverse soil chemical conditions.

2.3 Weather data

Weather data are obtained from the Climate Research Unit (CRU; http://www.cru.uea.ac.uk/cru/data/) and have a spatial resolution of 30x30 arc minutes (i.e. 54x54 km; circa 290,000 ha) and a temporal resolution of monthly values for each year in the period 1901 - 2100. The period 1901 - 2006 represents historical data and data from the period 2007 - 2100 are predicted values using a number of global circulation models and four emission scenarios (source: Tyndall Centre). In our analysis we have used historical data from 1976 - 2005 (30 years) comprising for each year in this period the monthly values of cloud cover, temperature, vapor pressure, rainfall and the number of rainy days (the so-called 'CRU TS 3.0' database). 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 CL 1.0').

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 data from Monfreda et al. (2008) to derive spatially explicit information on the total harvested crop area and maize 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.

3. Results

3.1 Rainfall

Figure 1 shows the total average rainfall per year across Mali during the period 1976 - 2005. 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.

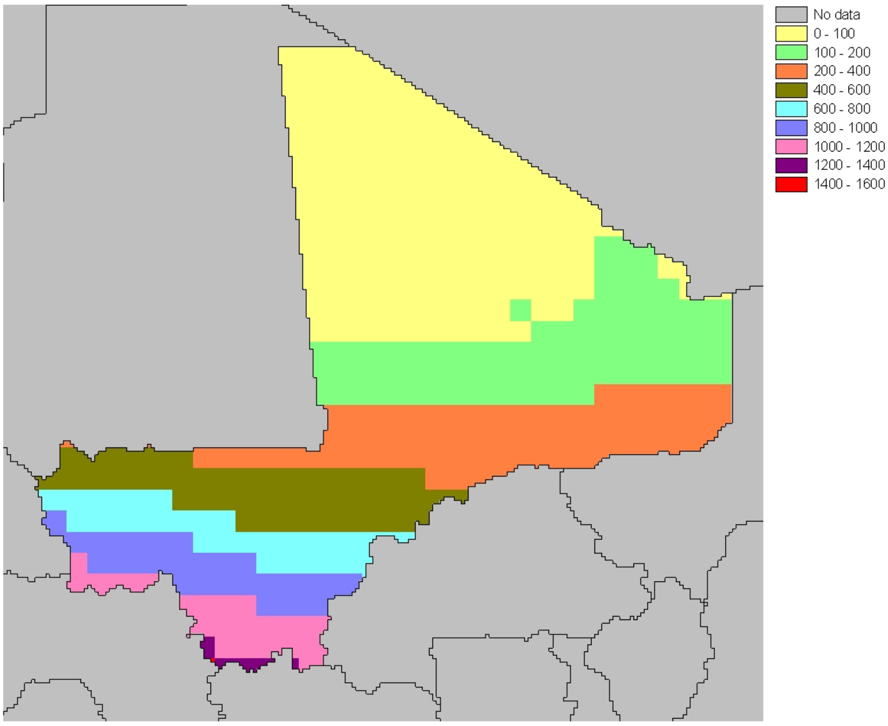

Figure 1. Total average rainfall in mm per year across Mali (period: 1976 - 2005).

The standard deviation runs from almost zero in the North to more than 150 mm in South and West Mali (Figure 2a). Very high values (between 250 - 300 mm) are only found in one grid cell in the extreme South of Mali which also had the highest rainfall (>1400 mm). The coefficient of variation of rainfall (standard deviation / average) ranges from almost 0% to over 100% during the period 1976 - 2005 (Figure 2b). However, the coefficient of variation of rainfall in the majority of the crop land area in Mali is between the 10 and 30%.

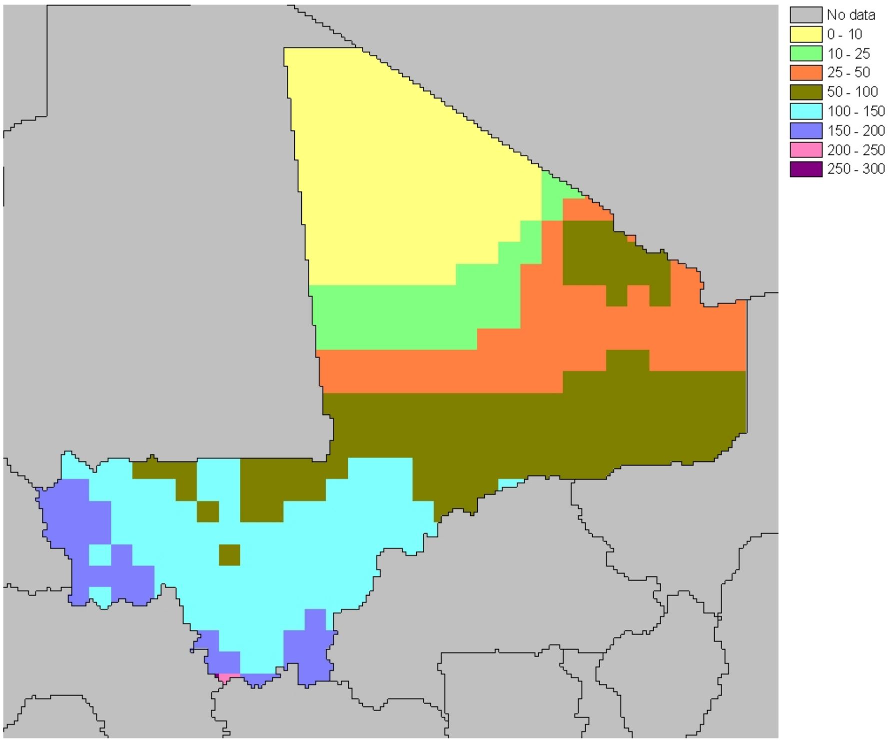

Figure 2a. Standard deviation of total rainfall in mm per year in Mali (period: 1976 - 2005).

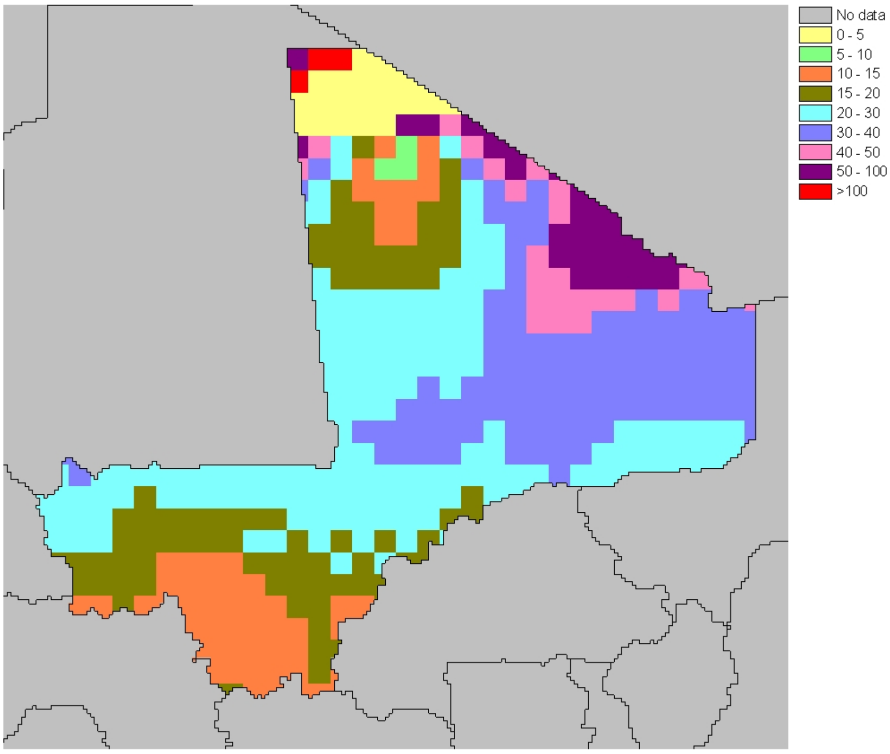

Figure 2b. Coefficient of variation of total rainfall in % in Mali (period: 1976 - 2005).

3.2 Maize yield variability

For each 5x5 arc minutes grid cell in Mali and for each year in the period 1976 - 2006, 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 1976 - 2005, 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 3a presents results for entire Mali, Figure 3b for the total harvested crop area in Mali and Figure 3c for the harvested maize area in Mali. For example, the red coloured areas in these figures indicate that in 80 to 90% of the years the yield is less than 25% of the average maize yield in these areas. Hence, this analysis provides insight in the spatial distribution of risk of (extreme) low yields (including crop failure) due to the (historical) weather conditions in combination with soil properties and crop (i.e. maize) characteristics.

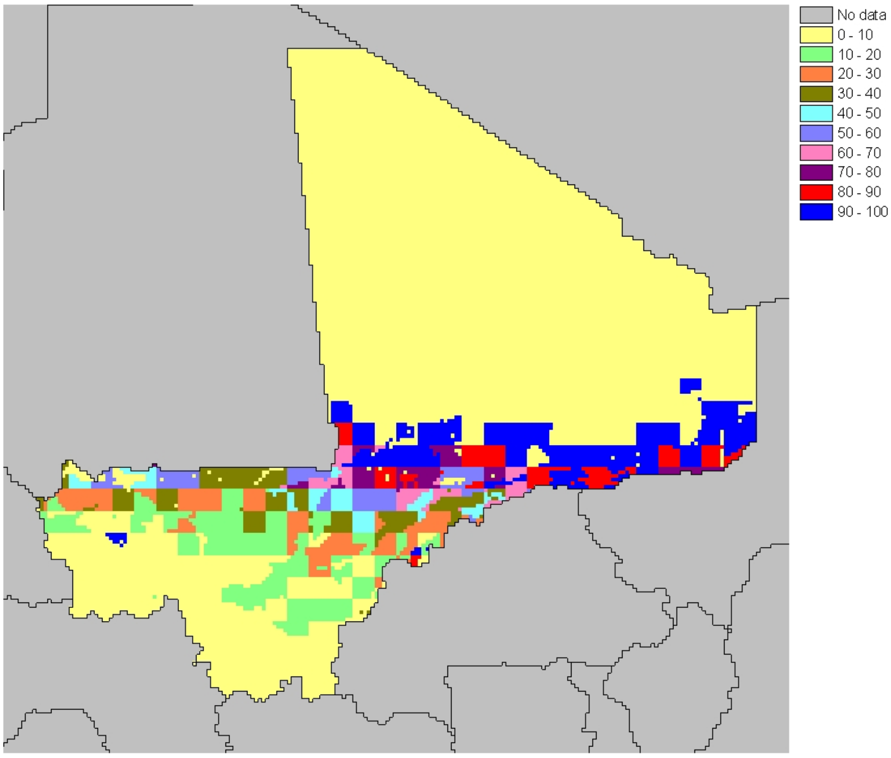

Figure 3a. Percentage of years with low yield, here defined as < 25 % of the 30-years average rain fed yield per grid cell in entire Mali.

Large areas of low risks are in the North and South of Mali. In the North the risk is low because growing maize is not possible (not enough rainfall). In the South there are also areas with zero yields (due to soil conditions hampering crop growth), but most of the low risk in the South can be explained by the absence of high variability in weather conditions. Rains are more evenly distributed over the growing season and (extreme) low rain fed yields do not occur frequently (< 10%). Moving from the South-West towards the North-East the risk on low yields increases distinctively, illustrating the increase in variability of weather conditions combined with the soil characteristics that determine the soil water balance and the sensitivity of maize to drought. The risks of the area that lies just below the zero yield region in the North of Mali are very high (> 90%: dark blue colour). These high risks are associated with a low frequency of years with sufficient rainfall to allow a maize cropping season, because in only a few years (< 3) rainfall is adequate to grow maize. It is expected that these areas are not used for cropping or maize growing unless irrigation is possible.

Figures 3b and 3c are subsets of Figure 3a and they show the same risks for only the total harvested crop area (Figure 3b) and the harvested maize area (Figure 3c) in Mali. By focusing on grid cells with harvested maize areas (Figure 3c), the results of the crop growth model (supplied with maize growth parameters) are linked to those areas where maize is actually cultivated in Mali and risks of maize cultivation can be analysed more precisely.

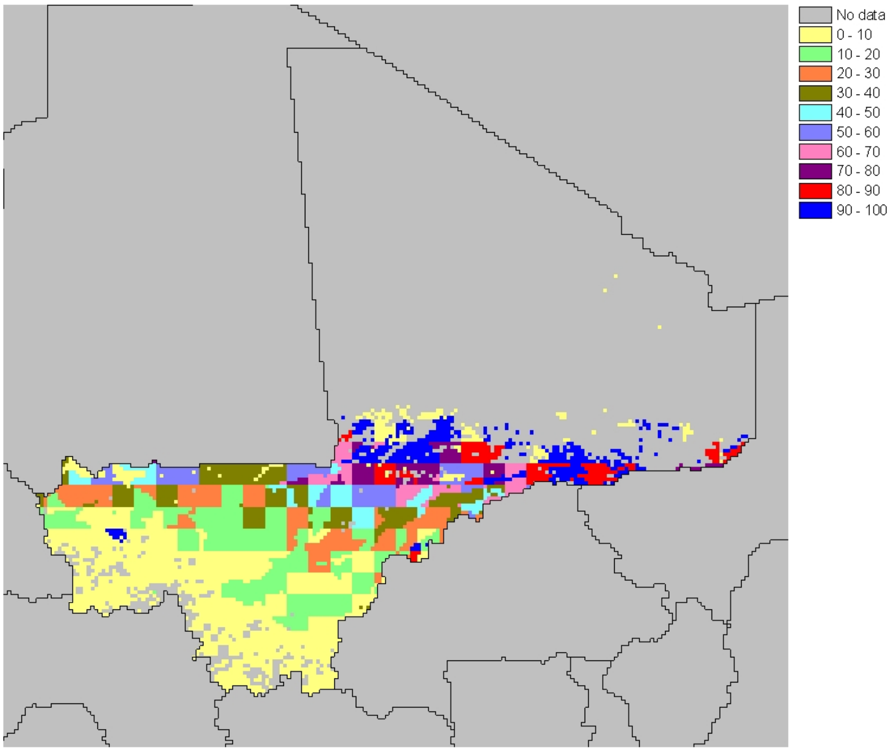

Figure 3b. *Percentage of years with low yield, here defined as < 25% of the 30-years average rain fed yield per grid cell used for growing arable crops in Mali around the year 2000 (= subset of 3a). Grey areas in Mali refer to areas without arable crops (Monfreda et al., 2008).*

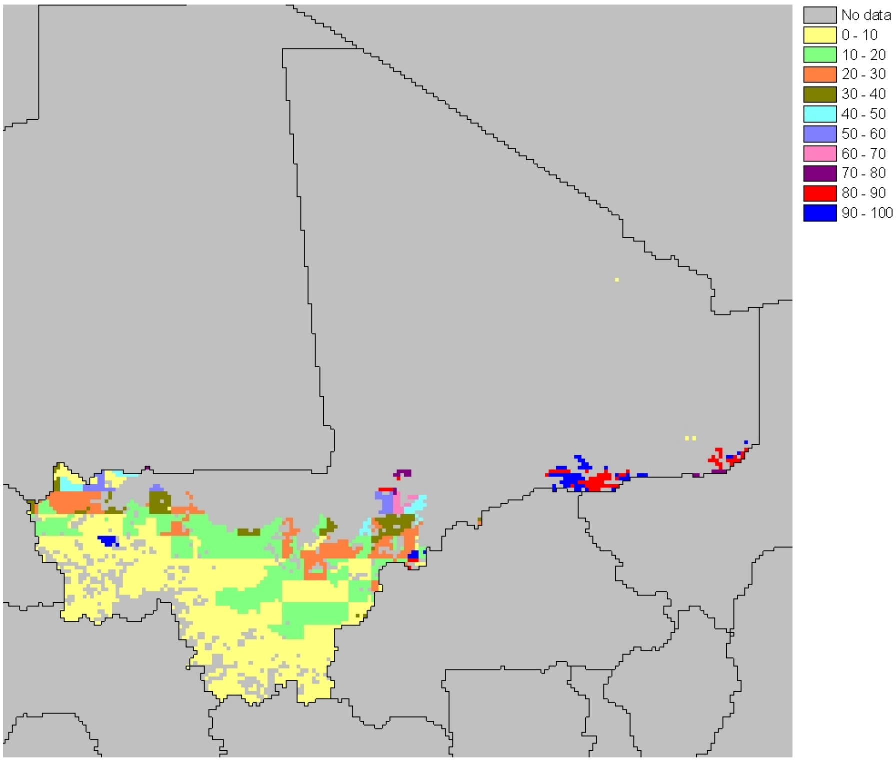

Figure 3c. *Percentage of years with low yield, here defined as < 25% of the 30-years average rain fed yield per grid cell used for growing maize in Mali around the year 2000 (= subset of 3b). Grey areas in Mali refer to areas without maize cultivation (Monfreda et al., 2008).*

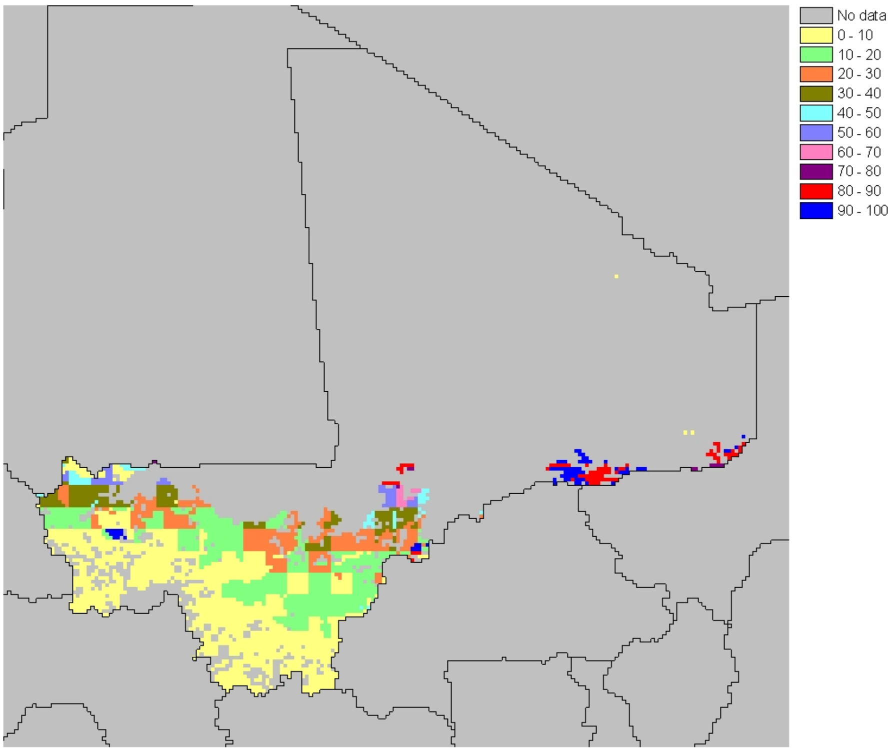

Figure 4. *Percentage of years with low yield, here defined as < 40% of the 30-years average rain fed yield per grid cell used for growing maize in Mali around the year 2000 (compare with Figure 3c).*

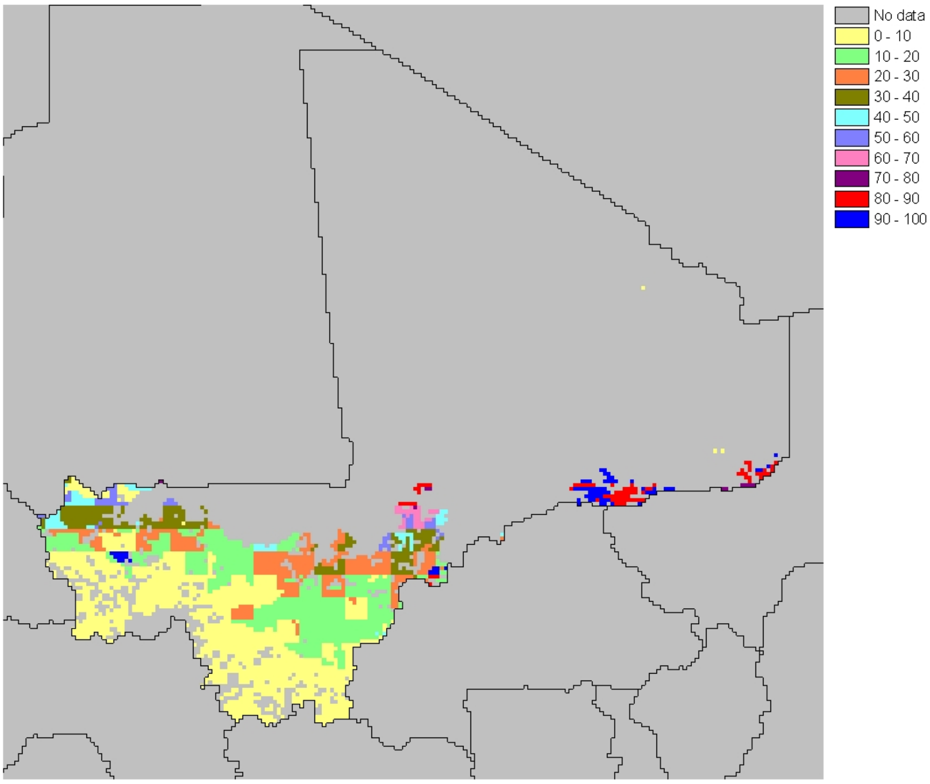

Figure 5. *Percentage of years with low yield, here defined as < 50% of the 30-years average rain fed yield per grid cell used for growing maize in Mali around the year 2000 (compare with Figure 3c).*

Spatial risk distribution as illustrated in Figures 3a, b and c depends on the selected yield threshold (i.e. < 25% of average grid cell yield). In Figure 4 results are shown with a threshold of 40% using the same calculated yields (1976 - 2005; n = 30) for each grid cell and only for the maize area (hence, it compares with Figure 3c). Logically, risks in Figure 4 are higher because the threshold is set at a higher value, which causes more years to comply with the condition of low yield (< 40% of the average). Figure 5 gives a similar map using a threshold of < 50% of the average yield per grid cell.

Based on the 40% threshold (Figure 4), we analysed the maize area that might be suitable for weather index-based insurance within the period 1975-2005. The total harvested maize area in Mali is estimated at 160,000 ha around the year 2000 (Monfreda et al., 2008).[1] We assume that only those maize areas are of interest for a weather index-based insurance that face a probability of 10 to 30% that yields are 40% below the average yield in a grid cell, i.e. the combination of the probability classes 10-20 and 20-30 in Figure 4. This total suitable area is about 45,000 ha, but in most years the area with yields below 40% of the average is much less than 20,000 ha, and in some years the risk is even zero (Figure 6). This shows that unfavourable weather conditions causing low yields are spatially scattered in the selected maize region.

1 National statistics from FAOSTAT report for the same period a harvested area of maize of circa 275,000 ha, increasing towards circa 400,000 ha in recent years. The difference between FAOSTAT and Monfreda et al. (2008) is due to the use of different statistical databases.

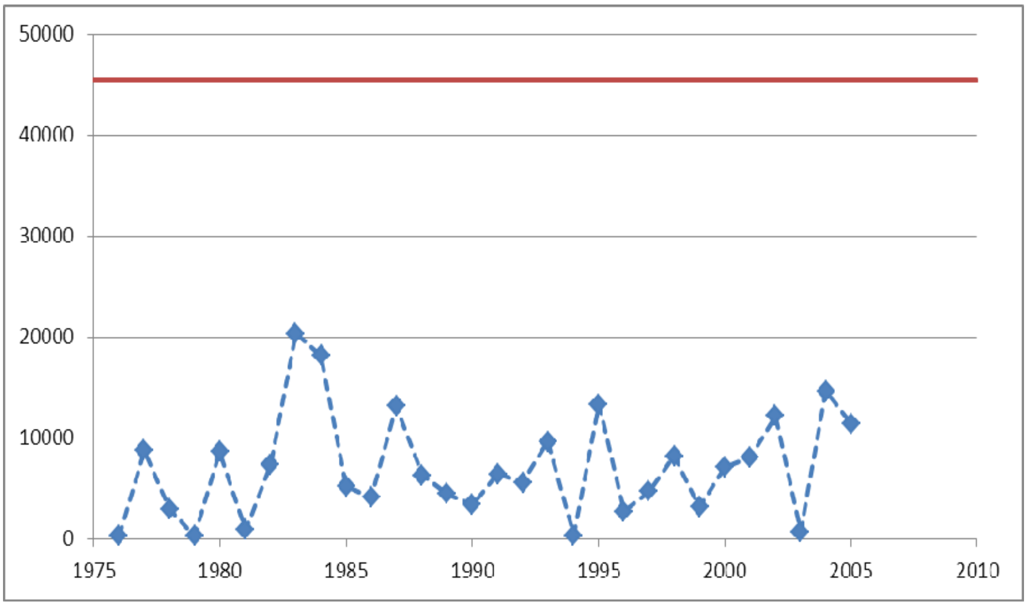

Figure 6. *Maize area (ha) per year with a yield of 40% below the average grid cell yield. The red line indicates the total maximum maize area, here selected by combining probability classes10-20 and 20-30 from Figure 4.*

4. Discussion and conclusions

This study shows that there are substantial areas with maize in Mali that face moderate risks of low rain fed maize yields, here defined as the probability to have a yield of less than a percentage of the long-term location-specific average yield once every ten years to once every four or five years (probability classes 10-20 and 20-30 in Figures 3c, 4 and 5). These areas with moderate risks could be selected for further (on-the-ground) research on the suitability of weather index-based insurance products for maize production. Areas with lower risks are probably less interesting because farmers may not experience a risk due to weather variability that is severe enough to pay for the insurance premium and those areas with higher risks may not be suitable for insurance products because the premium for the farmers would be too high due to frequent occurrence of (extreme) low yields.

Future development and application of the methodology described in this report should aim at four aspects. First, the methodology can be improved by using crop calendar data (start and end of growing season) if accurate data are available for Mali. In the present approach crop cycles have been estimated as function of the weather and soil data in each year and these could be compared and possibly improved with empirical data on crop cycles. Most available crop calendar data give a (broad) range of possible sowing dates because of the inter-annual variation in the start of the rainy season (e.g. http://www.fao.org/agriculture/en/). Variability in the start of the crop cycle must be maintained in the methodology by using the weather information per year from the weather database combined with either a calculated, an empirical or expert-based window of appropriate sowing dates (Therond et al., 2011). For example, in (parts of) Mali crop cycles start in June or July depending on location-specific moisture conditions (pers. comm. Andrea Stoppa).

Second, besides maize also yield variability maps of other important (food) crops are needed (such as sorghum and millet). The crop growth model used in the methodology is generic but should be supplied with crop-specific characteristics to quantify yield variation of other crops. It is expected that these crop specific characteristics of sorghum and millet are available from the literature (e.g. Verberne et al., 1995).

Third, calibration of the crop growth model can be performed by comparing the calculated yields with the spatial distribution of actual crop yields provided by Monfreda et al. (2008). If accurate data are available on the crop characteristics of local varieties, these data can also be used directly to supply crop parameters or indirectly for calibration of the crop growth model. Furthermore, the methodology should be validated with on-the-ground data of weather and crop yields. For this long time series of data from weather stations and experimental stations are needed to assess the actual variability and compare this with the calculated variability of the methodology, for example in rainfall and crop yields.

Finally, the present methodology can be linked to other (local) databases (e.g. with weather and soil data) and other methodologies, such as the approach to calculate actual evapotranspiration based on remote sensing data (Rosema et al., 2010). The actual ET as calculated by the crop growth model in our approach can be compared with the actual ET based on remote sensing. Further, improvements of calculating yield variability can be investigated by using the remote sensing ET in the crop growth model and by establishing the relation between yield and actual ET under different conditions. New combinations of data and methodologies could improve the calculation of the yield variability and may be helpful in the development and implementation of weather index based insurance.

References

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.

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.

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.

Rosema, A., M. de Weirdt, S. Foppes & C. Wilczok, 2010.
FESA Micro-Insurance. Methodology, validation, contract design. EARS Earth Environment Monitoring BV, Delft, Netherlands.

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.

Therond, O., H. Hengsdijk, E. Casellas, D. Wallach, M. Adam, H. Belhouchette, R. Oomen, G. Russell, F. Ewert, J.E. Bergez, S. Janssen, J. Wery & M.K. van Ittersum, 2011.
Using a cropping system model at regional scale: Low-data approaches for crop management information and model calibration. Agriculture, Ecosystems and Environment (in press).

Verberne, E., G. Dijksterhuis, R. Jongschaap, H. Bazi, A. Sanou & M. Bonzi, 1995.
Simulation des cultures pluviales au Burkina Faso (CP-BKF3): sorgho, mil et mais. Research Institute for Agrobiological and Soil Fertility, Wageningen, Netherlands, Bureau National des Sols INERA and Intstitut d'Etudes et de Recherches Agricoles, Burkina Faso, No. 18. 53 pp.