PROMISE

Predictability and variability of monsoons, and the agricultural and hydrological impacts of climate change

Final Scientific Report for Work Package 3100

Project reporting period: April 2000 to March 2003 (months 01-36)

Other partners having contributed to this work:

CERAAS, Thiès (Senegal)
Agrhymet, Niamey (Rep Niger) [Sub-contractor]
IRD, Grenoble (France)
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1. Objectives

Workpackage 3100 is entitled "Seasonal prediction of crop yields and assessment of climate change impacts on crop productivity", with deliverables 3101 (Identification of parameters for crop models and evaluation of seasonal prediction and crop models), 3102 (Integrated system for interpretation of seasonal forecasts in terms of crop development and yield) and 3103 (Assessment of impacts on crop productivity). The objective of WP 3100 is therefore to develop tools to derive agronomic scenarios (crop performance) from seasonal and longterm climate simulations, and to evaluate these scenarios. Target areas for these activities are the Sahel (main annual crops) and India (groundnut).

The University of Reading investigated the case of groundnut in India, and developed a general large-area crop modelling approach based on data analysis. Partner 2 (Cirad) applied these objectives by developing an existing crop model (which operates on smaller spatial scales) for grain crops in the semi-arid and arid zones of West Africa, where a simple yield forecasting system is already in place, run by the Agrhymet centre for the 9 CILSS countries. The specific objectives for this region were as follows:

1. Develop or adapt a crop model, based on an analysis of the environmental variables and system properties the model needs to be sensitive to.

2. Validate the crop model for on-farm and on-station situations.

3. Evaluate the crop model's accuracy at different geographical scales (levels of aggregation = sizes of pixels), and explore possible solutions to reduce scale sensitivity.

4. Develop or adapt a GIS environment for crop model implementation and data analysis.

5. Conduct first model applications.

The results are to contribute to the development of improved, technical and scientific strategies for GCM based, seasonal and inter-annual yield forecasting, thereby targeting semi-arid areas is West Africa and India.

2 – Large-area modelling

In order to combine weather and crop forecasting techniques, a common spatial scale must be identified. There must be a proven correlation between weather variables and yield on this common scale in order for modelling work to have any chance of success. Rainfall is the dominant climatic determinant of groundnut yield in India. Correlations between rainfall and yield vary from region to region. In order to identify any existing coherent pattern in this relationship, a mathematical technique which takes account of both spatial and temporal variability is needed. This variability has been explored using empirical orthogonal function (EOF) analysis. A coherent, large scale pattern emerges for both rainfall and yield. On the subdivisional scale, the first Principal Component of rainfall is well correlated with the first PC of yield (r^2=0.53, $p<10^{-4}$), demonstrating that the large-scale patterns picked out by the EOFs are correlated. Further, district-level EOFs of the yield data demonstrate the validity of upscaling these data to the subdivisional scale. Similar patterns are produced using data on both these scales, and the first PCs are very highly correlated (r^2=0.96). Hence a common spatial scale (the subdivisional scale, ~ 300 km) has been identified (Figure I), typical of that used in seasonal weather forecasting, which can form the basis of crop modelling work for the case of groundnut production in India. Details of this work can be found in Challinor et al (2003a).

It is large area models, then, as opposed to point models, that are the appropriate choice for GCM-driven groundnut modelling in India (Figure I). Such large area models would incorporate a point-wise phenology model, with inputs and outputs designed to be representative of an intermediate spatial scale (between the single point or plot and the common spatial scale identified above). Further upscaling of crop model output could be achieved by running the model using a distribution of inputs which is representative of the spatial variability within the subdivision. In the case of India, districts or agro-meteorological zones are ideal for this purpose.

Another distribution can be developed from the GCM ensembles to represent uncertainty in the weather forecasts. The output of the system will then be a distribution of district-level potential yields (since pests and diseases are not modelled). By comparing model output with measured distributions of district yield, a distribution function representative of the yield gap can be obtained. By assuming that this function is constant in time, or by identifying different functions for different pest/disease scenarios, the system can then be used to predict yield on the subdivisional scale.

The overall structure of the model system is shown in Figure II. This includes spatial representation of soils, mathematical distributions that capture the uncertainties in the crop model, and a novel method of deriving the patterns of actual crop yields from those of potential (model output) yields. The format and parameters for the central crop model (GLAM, General Large Area Model for annual crops) have been finalised and coded.

Figure I: *Schematic representation of the scaling issues relevant to combined crop and weather forecasting systems: a) scales of current GCM and crop simulation models; b) common scale for response of groundnut yield to rainfall identified by Challinor et al (2001), c) proposed scale of large area crop model*

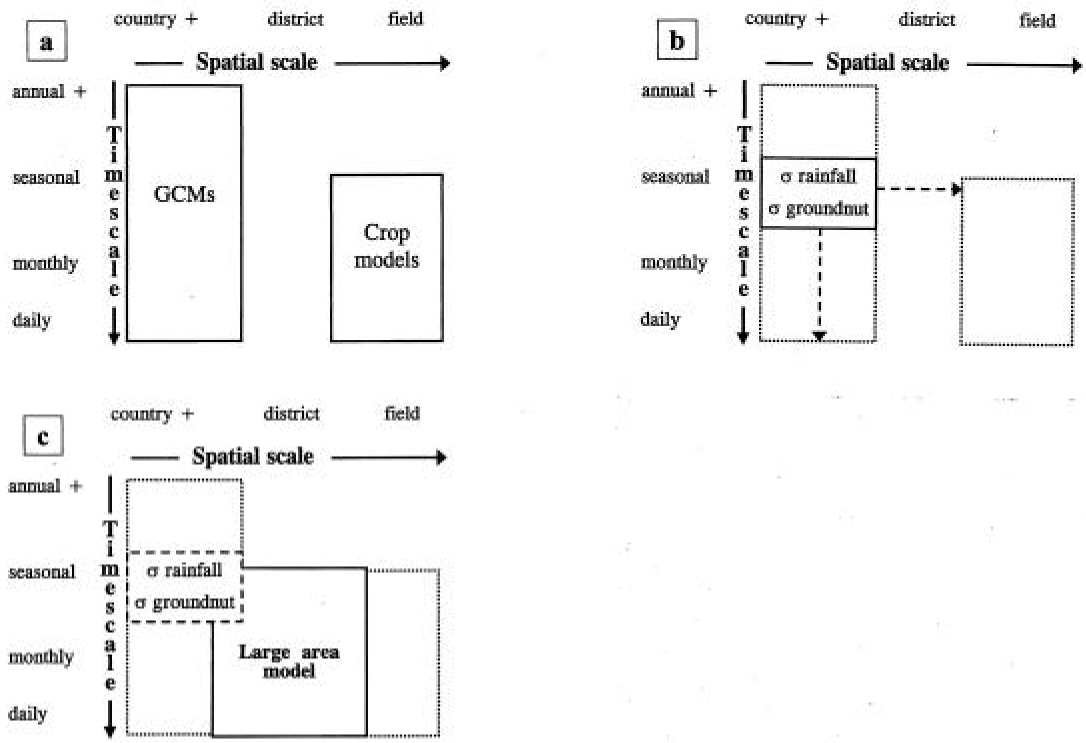
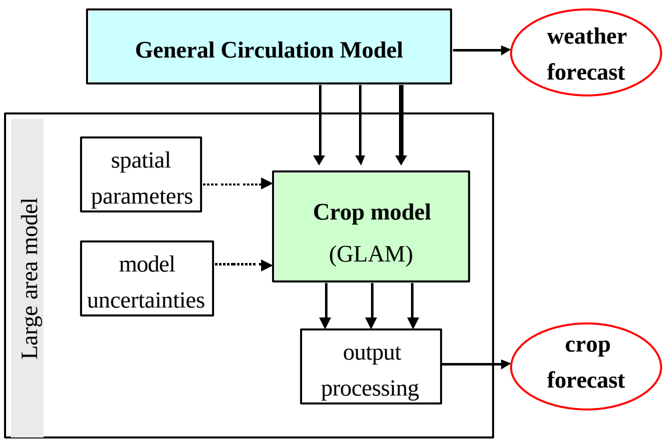
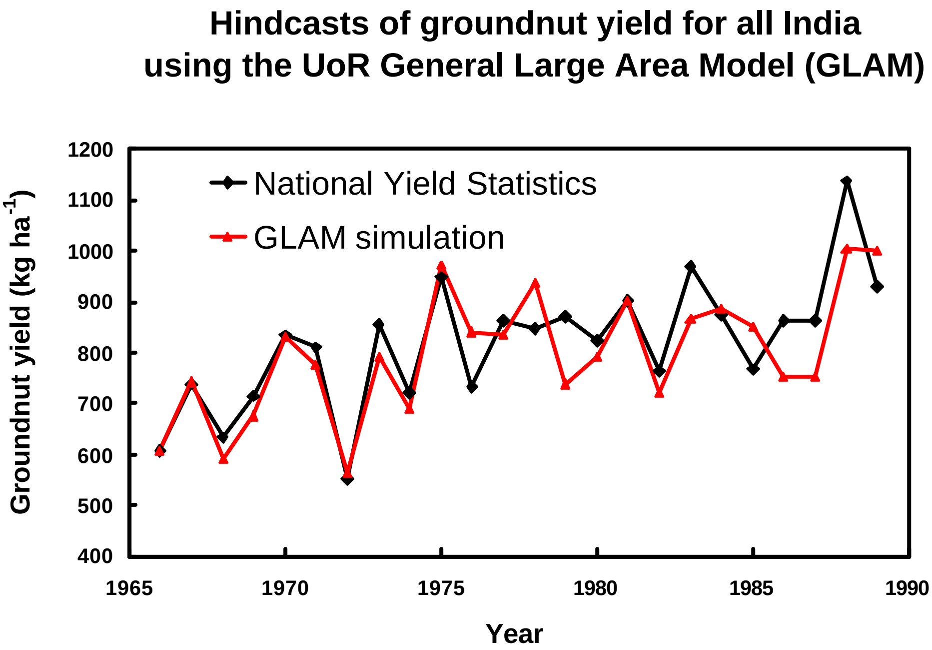


Figure II. Diagram of the combined seasonal weather/ crop forecasting system.



The large area model (GLAM) was tested for groundnut yield across India in deterministic mode. Optimal model parameters and diagnostic outputs such as the Specific Leaf Area were consistent with field experiments. Optimal parameters were stable over space and time. All parameters except the yield gap parameter were stable across two input weather datasets. The optimal yield gap parameter varied only across space and input data set; hence it can account for some of the bias in input weather data in addition to some of the yield gap . Temporal stability in optimal parameters was disrupted if a two- rather than one- piece linear yield technology trend is assumed for the full twenty-five year period. Hence for any future operational system, care will be needed when accounting for the technology trend.

Three sites have been examined in detail - grid cells from Gujarat in the west, Andhra Pradesh towards the south, and Uttah Pradesh in the north. Agreement between observed and modelled yield was variable, with correlation coefficients of 0.74, 0.42 and 0, respectively. Skill was highest where the climate signal was greatest, and correlations were comparable to or greater than correlations with seasonal mean rainfall. Yield from all 35 cells were aggregated to simulate all-India yield (see below). The correlation coefficient between observed and simulated yields was 0.76, and the root mean square error was 8.4% of the mean yield. The results outlined briefly above have been presented in detail in Challinor et. al. (2003b).



References cited in section 1

Challinor, A.J., J. M. Slingo, T. R. Wheeler, P. Q. Craufurd and D. I. F. Grimes, 2003a: Towards a combined seasonal weather and crop productivity forecasting system: Determination of the spatial correlation scale. *Journal of Applied Meteorology*, in press.

Challinor, A.J., T. R. Wheeler, J. M. Slingo, T. R. Wheeler, P. Q. Craufurd and D. I. F. Grimes, 2003b: Design and optimisation of a large-area process-based model for annual crops. Submitted to *Agricultural and Forest Meteorology.*

3. Local-scale modelling

3.1. Development of a crop model suited to Promise objectives for West Africa

Features of existing and future yield forecasting systems for West Africa

The DHC drought alert and yield forecasting system of Agrhymet (Niamey) for the 9 CILSS countries in West Africa uses a simple crop water balance model called SARRA (Samba et al. 2001), originally developed at CIRAD. About 2 months into a cropping season, it uses near-real time weather data, completed with historical climate records, to estimate millet yields for the current season. In accordance with the model's purpose to predict drought effects, it uses only potential evapotranspiration (PET) and daily rainfall as input parameters. The foremost shortcoming of this system is its inability to simulate the onset of the seasonal rains (monsoon), which is an important determinant of yield.

Future agricultural forecasting systems for the Sahel that would both be able to use seasonal weather forecasts and climate change scenarios such as those simulated with global circulation models (GCM) also need to provide more detail of crop response, for a number of reasons:

- Climate change affects not only rainfall and PET, but also solar radiation and thus, biomass production in a direct way. A crop model simulating carbon assimilation is therefore required.
- Changes in climatic conditions cause adaptive responses in the agricultural system. Immediate, *tactical* adjustments such as sowing date are already included in DHC, but other short-term adjustments (choice of crop variety, plant population) and long-term, *strategic* adjustments (zoning of crop "belts" and choice of crop, in / extensification of system) are presently not considered. At least for the climate change scenarios, tactical adjustments need to be considered, because the static hypothesis (non-adaptation) is generally wrong. It is therefore necessary to assume that the farmer optimises, for example, sowing date and choice of variety. However, feedbacks from markets and demography, to name the most important externalities, cannot be predicted and will be explicitly ignored.
- The need to drive biomass and yield with biophysical resources (energy and water) requires the concept of an "attainable" yield ceiling (limited only by water, radiation, population and genotype) and farmer's yield (usually, significantly below the attainable maximum, resulting from many unknown, yield-reducing factors). This leads to the concept <u>of radiation-driven and water-limited yield</u>, as opposed <u>to water-driven yield</u>.
- Future forecasting will face critical issues of scale, because GCM outputs will come at different resolution (or levels of aggregation), and may be quite different from the weather experienced by the crop at the plot level. Integrated climate-crop modelling systems therefore need to handle appropriately the loss of variability caused by aggregation.

Development of SARRA-H, a crop model for PROMISE

Based on the above, the crop water balance model SARRA was developed into a full crop model called SARRA-H (for <u>H</u>abillé, dressed) that continues to operate at the plot level with daily time steps, but is distinguished by the following, additional features:

- Radiation driven <u>carbon assimilation</u>, limited by a <u>physiological drought function</u> ("P-factor", FAO system based on fraction of transpirable soil water (FTSW) in the root zone)
- Calculation of <u>ground cover</u> from biomass allocated to form leaf area, and of <u>available soil water</u> using a dynamic root front
- Separation <u>of evapotranspiration</u> (ET) into E and T components using fraction ground cover as weighting criterion, and PET as driving force
- Introduction of <u>photoperiod</u> and <u>thermal time</u> to set the pace of phenological development

- Stress dependent conversion of biomass into grain yield
- Model sensitivity to crop population density

Versions of this model were developed for dryland cereals and groundnut. Written in Delphi language, the model is object based and features an extensive graphic interface. The model was developed in close collaboration with regional partners in West Africa (CERAAS in Senegal and Agrhymet in Rep. Niger), and in consultation with crop physiologists of Reading University.

A GIS environment for crop model implementation and data analysis.

A GIS tool developed at Cirad called Almanach, developed in the same programming environment as SARRA-H (Delphi), was adapted to suit the objectives of PROMISE (Lo Seen et al., 2001; Baleux et al., 2001). Almanach is a single executable program that uses a standard Microsoft Windows user interface. This permits inexperienced computer users to access the data, run the model and view the results. The tool allows the user to display on a map the input and output variables of the crop model. Some GIS specific functions are included in this tool like pan, zoom, layout to create printed maps as well as a query tool that allows the user to extract data from the data set to use in another software.

The link between the GIS tool and the crop model is not yet fully implemented. At this point, the GIS tool can display maps of the input and output data from the crop model, but the two softwares are independent.

3.2. On-farm and on-station validation of the crop model

For the on-station calibration and validation of SARRA-H, detailed datasets on millet were provided by CERAAS, permitting growth analyses for 3 years and several water regimes at the Bambey site in Senegal.

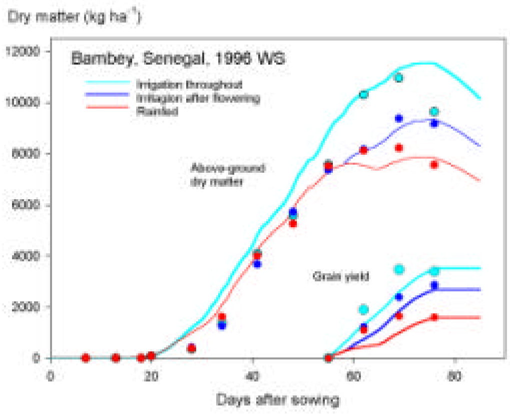


Fig. 1. Simulated (lines) and observed (points) biomass and yield of a millet crop in summer 1996 in Bambey, Senegal.

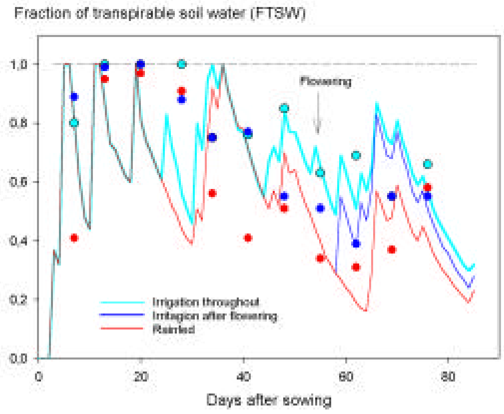
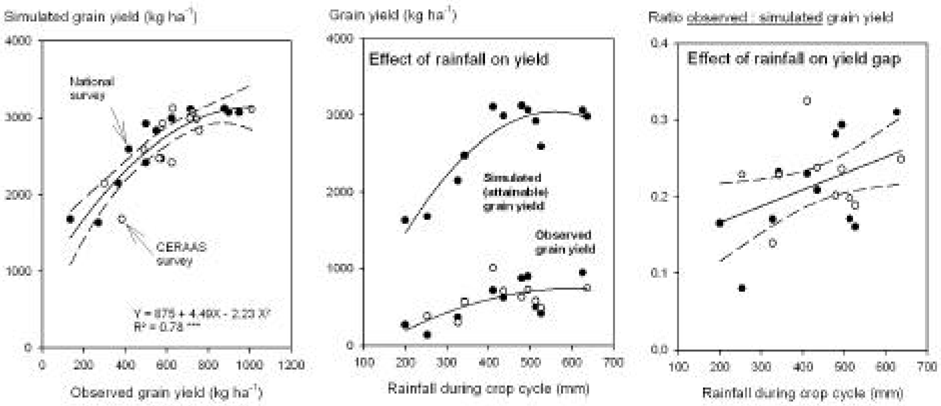


Fig. 2. Simulated (lines) and observed (points) fraction of transpirable soil water (FTSW) in the field for the same crops as in Fig. 1. Simulations take into account drought dependent progress of the root front.

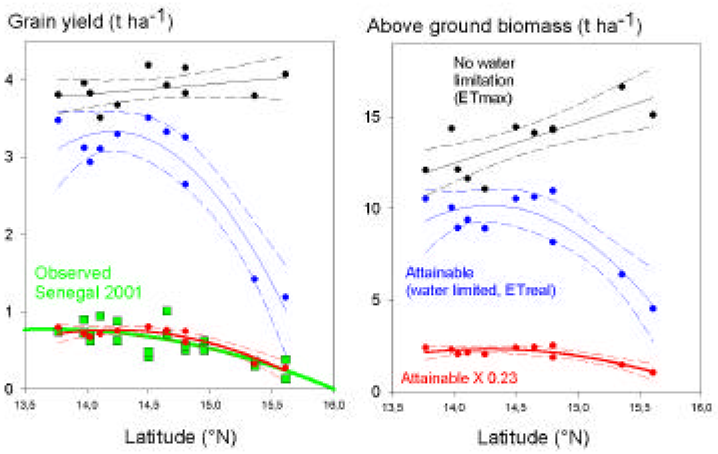
The model represented realistically the dynamics of dry matter, yield (Fig. 1) and water use (Fig. 2) of the crop in various stress situations, with attainable yields of up to 11 t/ha (above-ground biomass) and 4 t/ha (grain). By contrast, the model over-estimated 3-4 fold farmer's millet yields surveyed for 2001 in various regions of Senegal (data aggregated for groups of villages), covering 200-650 mm rainfall (cumulative during crop growth), and 13.8° to 15.7° N latitude (Fig. 3). Indeed, according to practitioners' experience, farmers' yields are usually between 0.2 and 1.0 t/ha depending on rainfall, but may reach 4 t/ha occasionally. Importantly, the crop model explained 78% of yield variation among sites, indicating that climate explains most of the variation of yield, whereas the low absolute level of yields compared to the attainable level must be due to other factors.

Fig. 3. On-farm validation of the SARRA-H crop model in Senegal, 2001. Left: relationship between simulated (attainable) and observed grain yield for millet. Centre: Simulated and observed grain yield as a function of rainfall received during the season. Right: Relationship between the fraction observed : simulated grain yield and seasonal rainfall, indicating that the yield gap increases as rains decrease.



A comparison between potential (water unlimited), attainable (water limited) and actual farmers' yields (Fig. 4) indicated that with increasing latitude, potential yield increases due to increased radiation, and attainable and farmers' yields decrease due to water limitation. Above-ground biomass production was thereby more sensitive to solar radiation, and grain yield was more sensitive to water limitation.

Fig. 4. Simulated potential, attainable and farmers' yield levels as a function of latitude in Senegal. Broken lines indicate 5%-confidence interval.



3.3 Evaluate and minimise model sensitivity to geographical scale

Pilot study on crop performance using simulated climate scenarios

A pilot study was conducted on the impact of simulated climate change scenarios on peanut yields in Senegal, using a preliminary version of SARRA-H and preliminary climate simulations for 1950-79 *and 2010-39 time sclices. Climate simulations were provided by Meteo-France and CNRM (Toulouse) using the ARPEGE model (Syahbuddin 2001). Although the predictions have little validity due to flaws in the preliminary version of the crop model used (e.g., poor fit of leaf area kinetics) and in the climate simulations (significant latitudinal shift of iso-lines for weather variables), this study raised important methodological issues related to scale.*

The main problem was related to differences in intensity distribution of daily rain totals between plot level (synoptic stations) and simulations (200 x 200 km pixels) for the same period and geographical area (Fig. 5: case of Koudougou). ARPEGE under-estimated the number of dry days (<1 mm) and the number of days with heavy rains (> 25 mm), while over-estimating the frequency of small rains (1 < X < 25 mm). This phenomenon was interpreted to be a result of pixel size, with large pixels ignoring local variability (local storms).

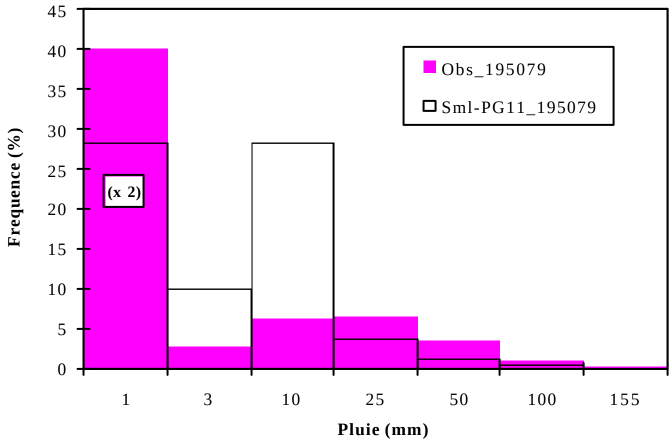


Fig. 5. Frequency distribution of daily rainfall for 1950-79 observed at Koudougou in Senegal and simulated with ARPEGE for a pixel that includes the same site.

Crop yields respond to local weather, and regional yield means are therefore not a linear function of regional weather means. Yields are very sensitive to intensity distribution and frequency of rainfall events because event size determines the fraction of water running off, evaporating, infiltrating and percolating. This is critical in arid environments where the season begins with a dried-out soil and a superficial wetting front that gradually descends as a function of percolation (which can be a large or small fraction of rainfall). SARRA-H is sensitive to these processes. Furthermore, the crop model simulates farmers' decision when to sow, which depends on rain event size. In fact, rainfall distribution is as important as quantity for achieving favourable seedbed conditions.

In this pilot study using ARPEGE climate (1950-79), yields were under-estimated because simulated sowing was generally late and the root system shallow, owing to inaccurate simulation of rainfall distribution. The 2010-39 time slice gave a further yield decrease due partly to lower solar radiation, and partly to higher temperatures resulting in shorter crop duration.

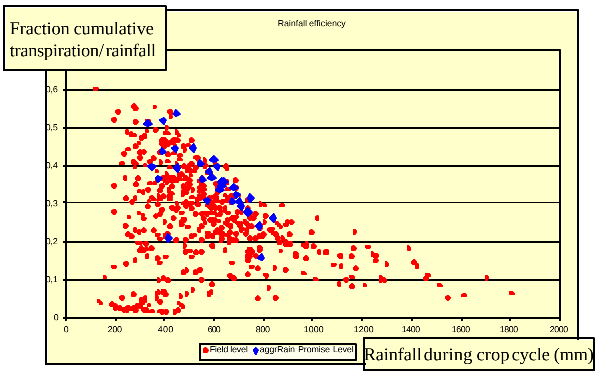
Model sensitivity to spatial aggregation and disaggregation of rainfall

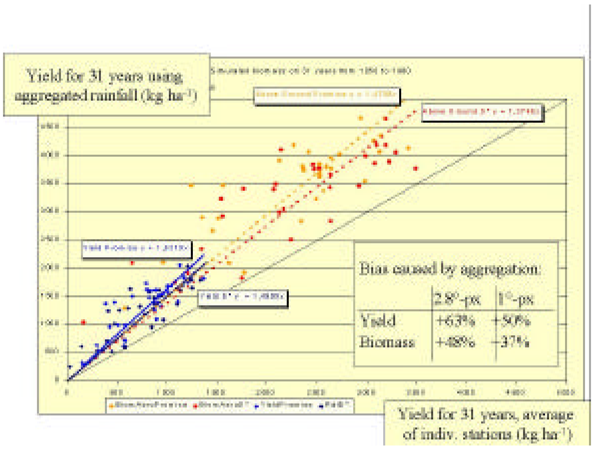
The sensitivity of plot-scale crop simulation to spatial aggregation of climate was tested by experimentally aggregating and disaggregating available rainfall data for an area in Senegal centered on 14.5°N 15°E. The study area covered 7 weather stations (1° pixel square) or 17 stations (2.8° pixel). Aggregation (up-scaling) of yield and rainfall data for the pixels using simple or weighted averages by kriging gave the same results. Analyses were done for 31 years (1950-1980).

Running the crop model for points (plot scale) and large aggregated pixels gave very different partitioning of water (Fig. 6) and yield levels for millet (Fig. 7). On average, the "useful" fraction of rains (transpiration) was much greater when aggregated data was used, reflecting an under-estimation of runoff and deep drainage due to "smoothened" rainfall distribution. This led to an over-estimation of yield by 63% for the 2.8° pixel (50% for 1°).

Fig. 6. Simulated fraction of useful rainfall (seasonal transpiration over rainfall during crop cycle) for 31 years on individual locations (red) and an aggregated, 2.8° pixel (blue). Simulations with SARRA-H.

Fig. 7. Relationship between yield (blue) and biomass (red) simulated with aggregated rains (2.8° and 1° pixels) and plot level rain distribution using SARRA-H.





Disaggregation of large pixels to permit plot-scale crop simulation

The results of scaling studies showed clearly that plot level water balances cannot be predicted with spatially aggregated rainfall data. On the other hand, it was shown that plot level intensity distribution of rains is a major determinant of crop water use and thus, yield. A disggregation (down-scaling) tool developed at IRD in Grenoble, France (T Lebel, unpublished) was therefore used to reconstitute point (plot) data from large pixels using a probabilistic method calibrated for Sahel environments (Niamey, Rep. Niger). The method essentially creates a user-defines number of virtual locations within the pixel at which rainfall is distributed according the passage of virtual rain fields.

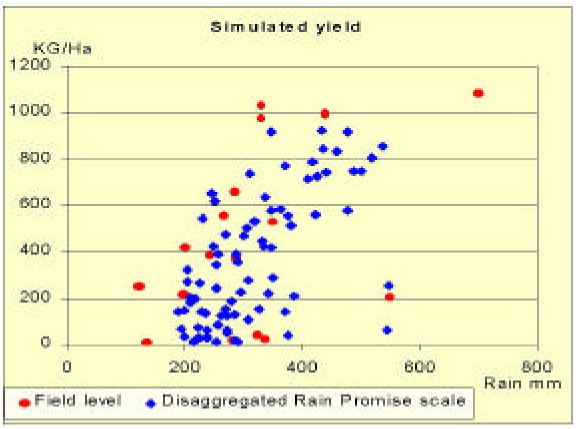


Fig. 8. Millet yields simulated with SARRA-H on a 2.8°-pixel in Senegal for 1972, using observed climate for 17 locations, and 82 hypothetical locations reconstituted from the aggregated pixel with a down-scaling model (T Lebel, IRD, unpublished).

Figure 8 shows the disaggregation results for the extreme example of 1972, a disastrous drought year in the Sahel. The combination of SARRA-H and the down-scaling model gives a reasonable accuracy of case distributions on the yield-rainfall scatter, and can therefore be used for agronomic impact simulations on large pixels. Further research is needed, however, to calibrate and validate this method for different types of climate and different seasons, and to improve handling of the combined tool, which at this stage is still quite cumbersome. Lastly, it must be noted that climate change may affect the values of down-scaling parameters in an unknown fashion.

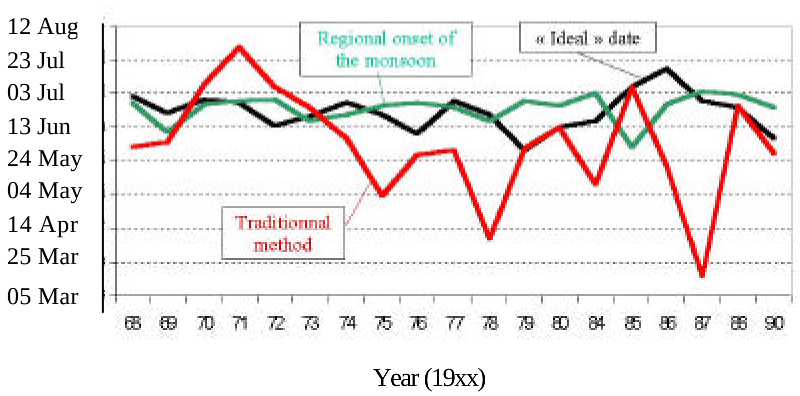
This work was conducted in collaboration with other PROMISE partners, notably IRD in Grenoble, France (T Lebel and team).

3.4 First crop model applications

In collaboration with partner 7 (CNRS and LMD,Paris), SARRA-H was used to evaluate different criteria for sowing dates of millet) in the Niamey area (Rep Niger), namely a regional criterion (onset of monsoon) and a local criterion (1st rain event >20mm, followed by re-sowing after 20d if the crop fails). One of the important future applications of GCM based forecasting might be advice on when and what to plant, depending on the onset date of the rainy season. Agrhymet's current DHC yield forecasting system is not able to predict the onsets of rains, and simulates the crop at mid-season using observed rainfall and the local (farmers') criterion for sowing dates.

Sowing dates derived from regional and local criteria were evaluated by comparing grain yield with that achieved with the "ideal" sowing date, determined by simulating all possible dates (Fig. 9). The exclusively climate and hydrology driven analysis suggests that over a 32-year period, the farmer's local criterion gives earlier and much more variable sowing dates than the regional criterion, and that the regional criterion gives sowing dates that are very close to the simulated, local optimum. This translates into 75% ± 26%SD of maximal yield (optimal date) when the regional criterion is used, as opposed to 56% ± 36%SD for the farmers' rule. However, this result must be interpreted with caution because it does not consider the higher soil N availability and lower weed pressure associated with earlier (farmers') sowing dates.

Fig. 9. Simulated sowing dates for millet at Niamey from 1968 to 1990 using 3 criteria. Red: farmers' rule based on local rain events. Green : Regional meteorological rule based on onset of monsoon. Black : Retrospectively « ideal » date giving the highest simulated yields. Simulations with SARRA-H by B Sultan, 2002.



3.5 Socio-economic and policy implication

The work presented is mainly methodological in nature and thus provides limited new knowledge that can be used "on the ground". However, the crop model SARRA-H has been made available to Agrhymet for use in its existing yield forecasting system, where it can provide information on the productivity of different crops and crop varieties, or levels of crop intensification. In conjunction with the downscaling software, SARRA-H can be directly used to translate GCM outputs into potential impact on crops. The socio-economic impact is potentially very high, provided that yield predictions are made available to decision makers in politics and production in a timely fashion, but this depends in the first place on how good and how cheap GCM weather and climate forecasts are going to be.

3.6 Discussion and conclusion

Significant progress has been made towards establishing a toolbox for evaluating the impact of GCM output scenarios on crops in semiarid environments. This toolbox comprises a generic, plot-level crop model suited for West African grain crops (e.g., millet, sorghum, maize, peanut) and a down-scaling tool translating aggregated "pixel" weather into local "point" weather. This is of great methodological significance because as it turned out, the limited spatial resolution of GCM outputs (for both technical and cost reasons) leads to systematic errors in the plot-level water balance, particularly with respect to the fraction of water effectively used for transpiration and growth. These errors are particularly large in semi-arid environments, where rainfall distribution is comparatively erratic and where, because of high evapotranspiration, only relatively large rains are able to replenish the soil water reserve.

The crop models used in this study are sensitive to effects of temperature (including effects on phenology and respiration), solar radiation, the evaporative demand of the atmosphere, and rainfall. We did not look into the impact of carbon dioxide concentration because most West African grain crops are C4-type cereals that are inherently largely insensitive to it. By contrast, it was deemed necessary to simulate not just the impact of climate on crops as they behave now, but to be also able to simulate short-term, tactical adjustments, such as sowing dates, choice of varietal type and crop population density, all of which the farmer would try to optimise when faced with changing conditions. Strategic adjustments, however, such as change of cropping system or land use or the introduction of irrigation, were not considered.

Unfortunately, it was not possible to use the new tools to measure the impact of concrete GCM scenarios, because climate simulations of satisfactory quality could not yet be provided. We suggest that given the great importance of rainfall size distribution for the crop and field-level water balance, further work on GCM applications for agriculture should put more emphasis on the intra-seasonal variability of weather, particularly rainfall, both in terms of short-term predictions and climate change . Lastly, we restate the importance, at least for semi-arid environments, of reliable and timely predictions of the onset of the rainy season. This information is crucial for sowing dates and the choice of crop and crop variety -- unless a modified cropping system is developed that uses less variable sowing dates associated with the regional onset of monsoons as described earlier. In this hypothetical case, nitrogen catch crops and/or weed suppressive crops may be necessary to occupy the land between the first major rains and the "true" onset of the monsoon, from when on the crop can be safely sown. This vision, as it were, is one of the many add-on results generated by PROMISE, and deserves to be further explored.

<u>Further documentation of the results for section 3:</u>

Lo Seen D, Areola M, Clopes A, Scopel E, Begue A. 2001. Coupler modèle agronomique et système d'information géographique. <u>In</u> : Modélisation des agrosystèmes et aide à la décision. Collection Repères. CIRAD INRA, France.

Baleux F, Begue A, Corbet JD, Rollin D, Grellet G, White JW. 2001. L'almanach numérique de planification à Madagascar. In : Modélisation des agrosystèmes et aide à la décision. Collection Repères. CIRAD INRA, France.

Haris Syahbuddin. 2001. Effet du changement climatique sur le rendement de l'arachide (Arachis hypogaea L.) dans de cas du Sénégal, réalisé avec le modèle ARPEGE Climat V. 3.0 et SARRA-H. Masters thesis, Météorologie Tropicale, Ecole Nationale de la Météorologie, Toulouse, France, 129 pages.

Samba A, Sarr B, Baron C, Gozé E, Maraux F, Clerget B, Dingkuhn M. 2001. La prévision agricole à l'échelle du Sahel. In: Malézieux E, Trébuil G, Jaeger M (Eds.). Modélisation des agro-écosystèmes et aide à la décision. Cirad and INRA, Montpellier, France, p. 243-262.

(Further publications are soon to appear, including refereed articles on SARRA-H applications and a chapter on SARRA-H as part of a book on agricultural decision aids for Africa, published by IFDC (International Fertiliser Development Center).)