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Open Source geoprocessing tools and meteorological satellite data for crop risk zones monitoring in sub-Saharan Africa

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ABSTRACT
In Sub-Saharan Africa analysis tools and models based on meteorological satellites data have been developed within different national and international cooperation initiatives, with the aim of allowing a better monitoring of the cropping season. In most cases, the software was a stand-alone application and the upgrading, in terms of analysis functions, database and hardware maintenance, was difficult for the National Meteorological Services (NMSs) in charge of agro-hydro-meteorological monitoring. The web-based solution proposed in this work intends to improve and ensure the sustainability of applications to support national Early Warning Systems (EWSs) for food security. The Crop Risk Zones (CRZ) model for Niger and Mali, integrated in a web-based open source framework, has been implemented using PL/pgSQL & PostGIS functions to process different meteorological data sets: a) the rainfall precipitation forecast images from Global Forecast System (GFS) b) the Climate Prediction Center (CPC) Rainfall Estimation (RFE) for Africa c) Multi-Sensor Precipitation Estimate (MPE) images from EUMETSAT Earth Observation Portal d) the MOD16 Global Terrestrial Evapotranspiration Data Set.
Restful Web Services upload raster images into the PostgreSQL/PostGIS database. PL/pgSQL functions are used to run the CRZ model to identify installation and phenological phases of the main crops in the Region and to create crop risk zones images. This model is focused on the early identification of risks and the production of information for food security within the time prescribed for decision-making. The challenge and the objective of this work is to set up an open access monitoring system, based on meteorological open data providers, targeting NMSs and any other local decision makers for drought risk reduction and resilience improvement.

Keywords: Food security; crop model; open data, web services; Sub-Saharan Africa

INTRODUCTION
Agriculture in Sub-Saharan Africa is characterized by traditional techniques and is strongly dependent on climatic conditions and rainfall, whose variability has a strong impact on people's livelihood and community socio-economic development.
In general, low rainfall during the growing season can lead to lower crop yields and, sometimes, to food crises (Sultan et al., 2005). Crop yields may suffer significantly with either a late onset or early cessation of the rainy season, as well as with a high frequency of damaging dry spells (Mugalavai et al., 2008).

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For the most important Sahelian rainfed crops, the early identification of crop risk zones is essential to intercept agricultural drought phenomena, detecting seeding delay and failure, and monitoring crops water conditions in each growth stage (Bacci et al., 2009a).
Since the early 1990s, crop monitoring analysis tools and simulation models based on meteorological satellite data (Samba, 1998; CNR-IBIMET, 2006; Traore et al., 2010) have been developed within different international cooperation programs to allow monitoring of the cropping season in CILSS (Permanent Interstates Committee for Drought Control in the Sahel) countries. Software was usually a stand-alone application transferred to the National Meteorological Services (NMSs), but without continuous user support and updates. Furthermore, the scarcity of funds for hardware and software maintenance, besides the unavailability of timely meteorological data, led to the failure of regular drought monitoring activities carried out by National Early Warning Systems (EWSs) for food security.
This paper presents the "4Crop" web application, an open source solution to meet the needs of a long-term sustainability of operational tools for drought risk identification and forecasting that balances the lack of sufficient and timely acquisition of ground data using meteorological satellite open data sets. This web application is based on the Crop Risk Zone (CRZ) model, the updated version of the Zone à Risque (ZAR) model (CNR-IBIMET, 2006) distributed as stand-alone software to the NMSs of CILSS countries within the framework of SVS (Vulnerability Monitoring in the Sahel, 2002-2008) Project, funded by Italian Cooperation and implemented with the World Meteorological Organization and the AGRHYMET Regional Center in Niger.
The ZAR model was utilized as a valid tool to support the analysis of the Multidisciplinary Working Groups (MWGs) of CILSS countries which usually produce a 10-day agro-hydrometeorological bulletin from June to September that provides summaries on the agrometeorological, hydrological, and agricultural situations. In the past the seeding failures zones map produced by the ZAR model contributed to assessing the last severe food security crisis that occurred in Niger in 2005-2006 (http://www.wamis.org/countries/niger.php).
The ZAR model was validated with field data collected in 2006 and 2007 in Mali, Niger and Senegal within the framework of the AMMA project (Bacci et al., 2009b). An operational test was also performed on the 2009 campaign in Burkina Faso, Chad, Mauritania, Mali, Niger and Senegal in collaboration with the NMSs (Bacci et al., 2010).
In this context the challenge of the 4Crop web application is to give open access to CRZ model outputs and results. The goal is to support Sub-Saharan EWSs and any other local users in decision making and foster drought risk reduction and resilience for food security; moreover, the approach proposed here is meant to encourage the integration and sharing of interoperable and open source solutions and thus contribute to the setting-up of distributed climate services (Hewitt et al. 2012) in developing countries.

METHODOLOGY

The CRZ model for crop risk zones monitoring in Sub-Saharan Africa (Vignaroli et al., 2016) runs 2 different modes:

- diagnostic mode: drought monitoring during the agropastoral season, allowing NMSs to identify agricultural drought risk areas and to support decision making in agricultural drought management at local and national level. This type of early warning information empowers National EWSs decision making, as it is an input to estimate food insecurity, to better identify potentially vulnerable populations and assess food crises risks within the 'Harmonized Framework" put in place by CILSS with EU, FAO and WFP (CILSS, 2014).

- predictive mode for "advisory-support" activities to farmers carried out by the Agricultural Extension Services, who are in charge of implementing the most appropriate strategies to minimize drought risk for crops (i.e. identification of the optimal sowing period, choice of varieties based on the expected growing season length, adoption of suitable cropping practices for soil water management) and to build farmers resilience.

The model is composed of different modules (Figure 1): crop installation monitoring (at 5- or 10-day periods), crop growth following the installation phase (at 5- or 10-days periods), sowing conditions forecast (at 5 days) and forecast of crop conditions in the risk areas (at 5 days).
The most important model data input are:

- Cumulated Rainfall Estimate Images (5 – 10 dd), with a 0.1° and 0.03° resolution for RFE and MPE data respectively.
- Cumulated Precipitation Forecast (240 h) at 0.25° resolution
- 10-days PET (Potential Evapo-Transpiration) at 0.01° resolution
- Average start of growing season (last 10 years or more) at 0.03° resolution
- Average end of growing season (last 10 years or more) at 0.03° resolution
- Soil Water Capacity at 0.1° resolution.
- Phenological phases' length and crop coefficient - Kc for each simulated crop (Allen et al., 1998).

The model allows users to customize some parameters: crops and varieties, sowing conditions (rain threshold and period) and geographical extent of analysis area. At present the model has been tested on the following four crops with different growing cycle length (days): pearl millet (85 days and 130 days), cowpea (75 days), groundnut (100 days and 140 days), sorghum (110 days).

Meteorological satellite data set and download chains

Due to the lack of a dense weather station network in Africa and of the availability and consistency of long-term rainfall data for the Sahel Region, satellite-derived open data sets have been used as input data for the model. NCEP/NOAA Global Forecast System (GFS) is the reference data source for forecast images, the Climate Prediction Center (CPC) Rainfall Estimator for daily Rainfall Estimates (RFE) over the African continent and/or the historical series of satellite rainfall estimates data, derived from MSG images provided by EUMETSAT Earth Observation Portal. In addition, monthly average Potential Evapotranspiration gridded data required by the CRZ model have been downloaded from MOD16 Global Terrestrial Evapotranspiration Data Set.
Data download chains from different providers have been implemented for each data set to store row data in GeoTiff and NetCDF-CF Open Geospatial Consortium (OGC) standard, to establish automatic procedures that provide the input data for the monitoring of the cropping season for the CRZ model. At the end of the download procedures, the JAX-WS Restful Service is called to upload the raster images in PostgreSQL & Post GIS database to feed the CRZ model.

Although at present the low resolution of Precipitation Forecasts images available for the Sahel region can represent a limit to the accuracy of results at local scale, the national experts of Meteorological Services can evaluate the reliability of results on site. Waiting to be able to access images with a higher level of resolution, a statistical downscaling of GFS images from 0.25 ° to 0.1 ° spatial resolution could be performed in order to improve the rainfall forecast skill through a better representation of the deep convection phenomena (Guarnieri et al., 2006).

Open Source geoprocessing tools for CRZ model implementation

The CRZ model was developed using PL/pgSQL - SQL Procedural Language for PostgreSQL database system and PostGIS library built-in PostgreSQL. Each CRZ module is composed of a main PL/pgSQL function, performing initialization processes, and an iteration of functions for crop simulation processes. The CRZ modules work on input vector and raster data stored previously in the GeoDataBase.

For example in the “Installation module” (Figure 2) the initialization processes set the parameters defined by the user (e.g. crop type, season length, country name) and extract the input data from GeoDB (e.g. daily RFE, daily PET images, season end and average sowing date images). All raster input images are clipped with the country’s boundaries so time and resource consuming are optimized for the following processing phases. Within the installation module the iteration of functions generates module outputs (e.g. crop installation, sowing failures, etc.). The ST_MapAlgebra, as callback function, performs pixel-by-pixel operations over raster images defined by the CRZ model algorithm.

At the end of the iteration cycles of each module, the main PL/PgSQL function stores the results in the GeoDB with all metadata information related to the model run.

Finally a JAX-WS, using the PostGIS predefined functions, publishes classified output images on 4Crop web Interface (Figure 3).

User Centered Approach for 4Crop web application

For implementation of the 4Crop web application, user requirements were defined through a User Consultation Process (UCP) involving the technical staff of Niger and Mali National Meteorological Services. In the first phase of 4Crop web development, the operators/users were interviewed in order to understand their specific needs in terms of usage, information products (maps and reports), and also to assess the usability needs in view of their previous experience with the ZAR model stand-alone software. The interviews allowed to better focus on user requirements, particularly for User Interface (UI) development. In the second phase the UI was shared with the users, through a design project management and collaboration platform (InVision), to obtain their feedback and further suggestions.

RESULTS AND DISCUSSION

4Crop web application (Figure 4), targeting Niger and Mali National Meteorological Services, is implemented on a coherent Open Source web-based Spatial Data Infrastructure to treat all input and output data in an interoperable, platform-independent and uniform way. It utilizes the CRZ model to evaluate impacts due to drought stress during the whole crop growing cycle over large areas, providing MWGs, Agricultural Extension Services and farmers with information to implement appropriate and timely response strategies to minimize risk exposure.

During the cropping season, from the first 10 days in May to the last 10 days in September, the

CRZ model produces the following outputs:
1. Installation module (Figure 5):
   - crop installation (areas where sowing and crop installation conditions occurred)
   - sowing failures (areas where sowing conditions occurred but not installation conditions)
   - re-sowing (zones where, after a sowing failure, sowing conditions again occurred)
   - comparison between the actual and average crop installation
   - comparison between the actual and last year's crop installation
2. Monitoring module:
   - phenological phases (for areas where crop installation occurred: the actual crop phase)
   - crop water needs satisfaction (for areas where crop installation occurred: the water stress level)
   - soil available water (for areas where crop installation occurred: the water actually available in the soil)
3. Forecast module:
   - sowing condition forecast (for areas where forecasted rainfall will satisfy sowing conditions)
   - installation forecast (for areas where last dekadal rainfall estimation satisfies the sowing conditions and the forecast rainfall will satisfy installation conditions)
   - crop water needs satisfaction forecast (for areas where crop installation occurred, the forecast water stress level).

In order to avoid any language barrier, which could prevent a wider use of the web application, 4Crop is available in French, the official language of the target countries.
The choice of adopting a web-based approach was thoroughly discussed with end users: the cost-benefit balance finally indicated that overcoming the problems due to software updating and input satellite data download through a web-based approach would be of greater benefit than the limited advantages ensured by a stand alone software. NMSs are nowadays reaching good quality internet connections in the capital cities of most Sahelian countries.
Moreover the great advantage in using PostGIS and PL/pgSQL is having a unique environment for managing raster data instead of the use of external GIS raster software for preprocessing satellite images for the model runs.

CONCLUSIONS

The 4Crop overall approach, including the UCP, could represent an enabling factor to allow a switch from generic advice to precise information, to improve planning, the decision-making process and response measures of various stakeholders. Indeed, the web application increases the accessibility of accurate drought risk information for different stakeholders; it provides specific advice for end users at different decision-making levels, bridging the gap between available technology and local users' needs. Lastly, especially in developing countries, open source solutions can play an important contribution to capacity building in local Institutions, which are the main actors in planning and implementation of prevention and response policies to potential food crises.
Moreover 4Crop can contribute to the setting-up of distributed climate services, allowing stakeholders at different levels to access and share information products through web services and standard protocols.

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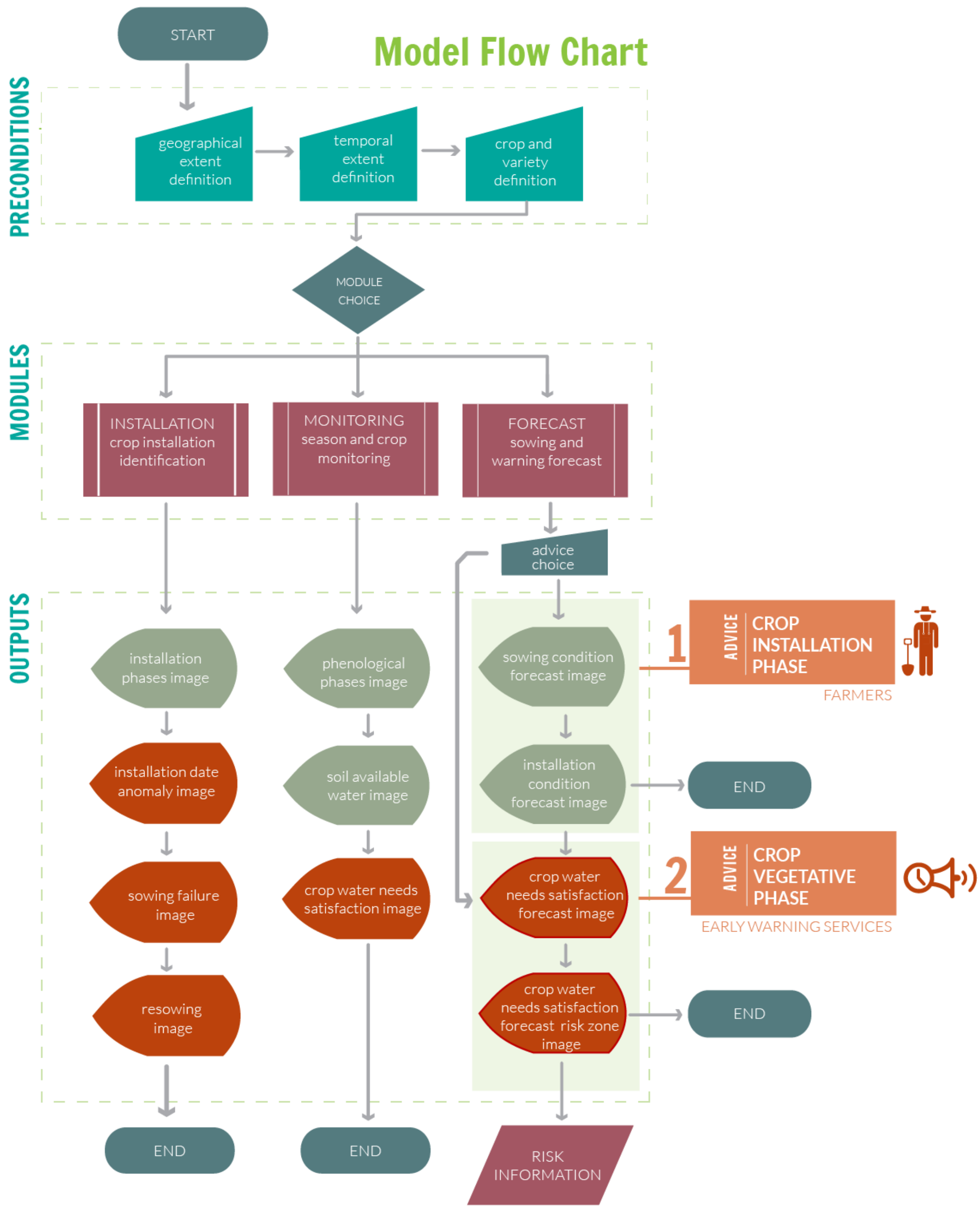

Figure 1 - Crop Risk Zone Model Flow Chart

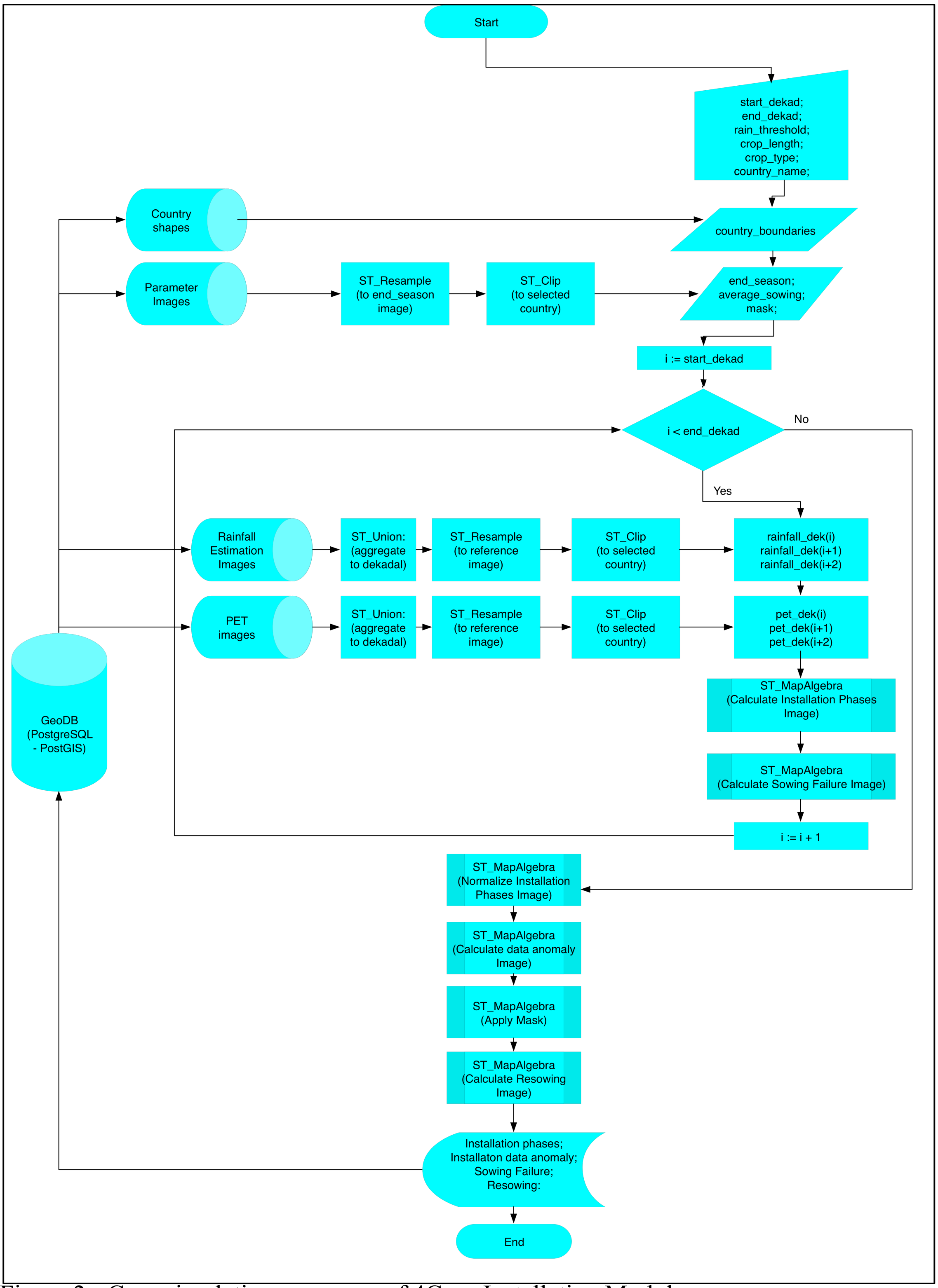

Figure 2 - Crop simulation processes of 4Crop Installation Module

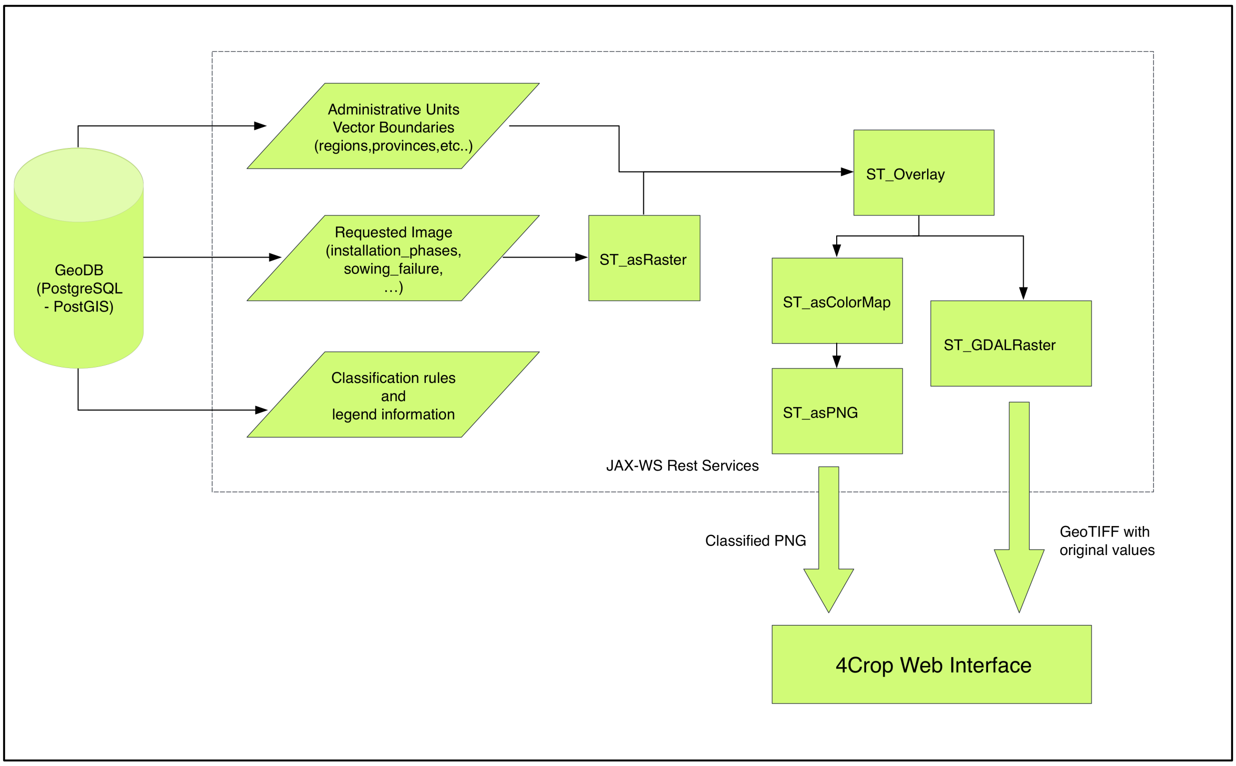

Figure 3 - JAX-WS Rest Services

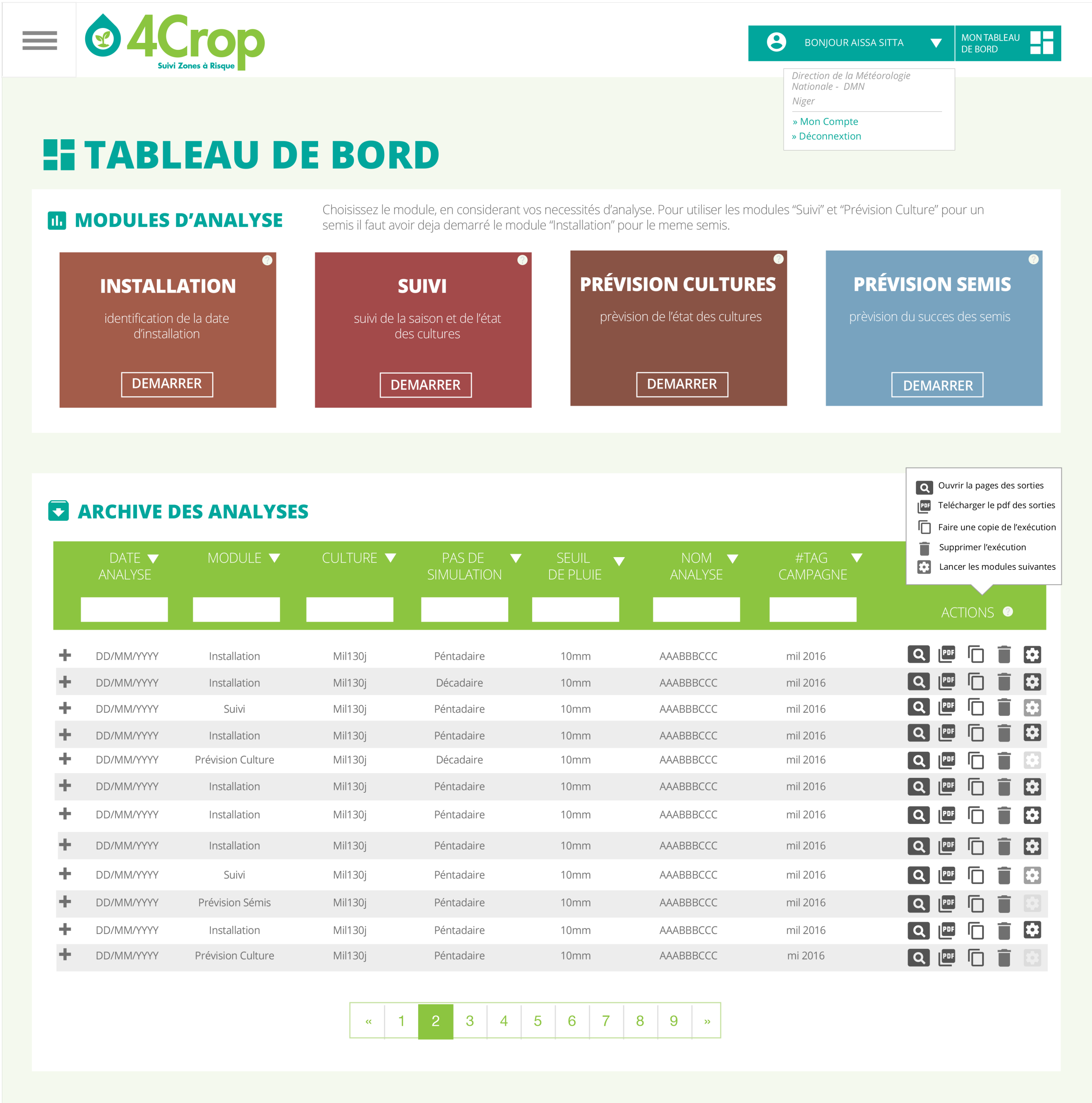

Figure 4 - 4Crop Web Application Interface

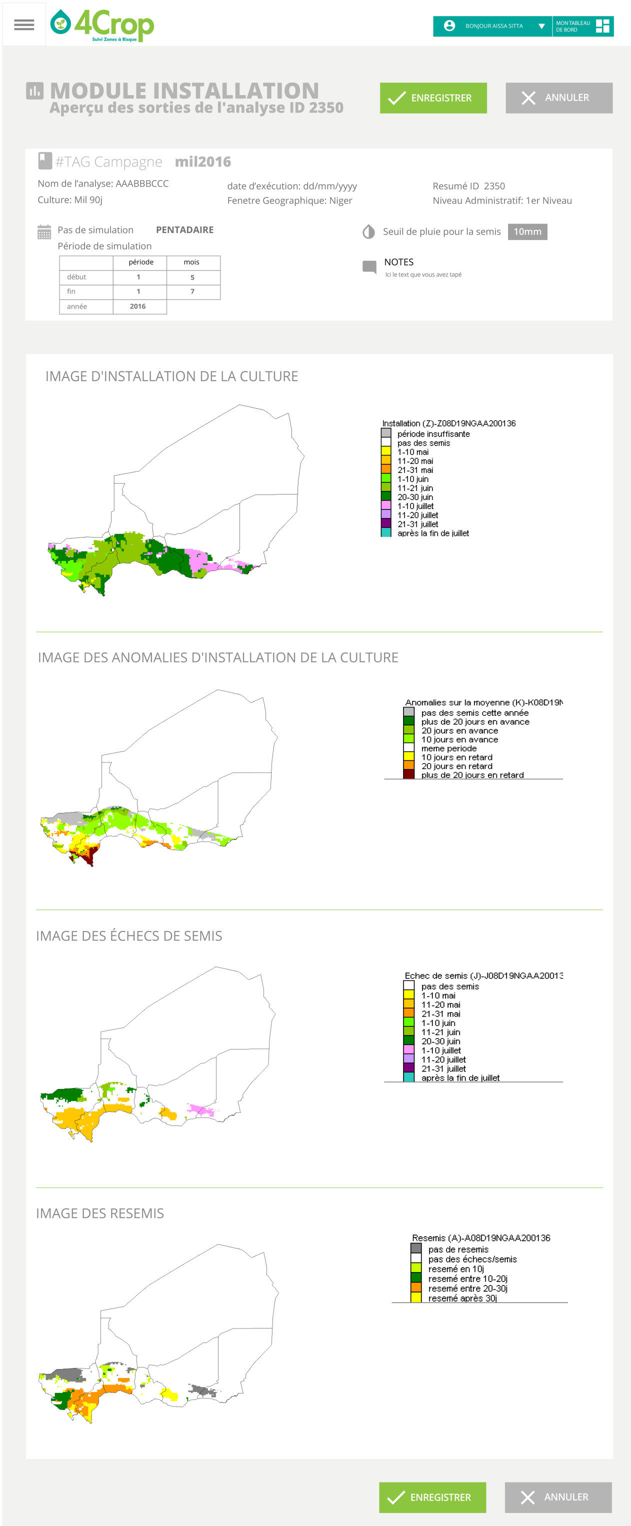

Figure 5 – CRZ Installation Module: output for Niger