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Designing AfriCultuReS services to support food security in Africa

Alexandridis, T.K.[1*], Ovakoglou, G.[1], Cherif, I.[1], Gómez Giménez, M.[2], Laneve, G.[3], Kasampalis, D.[1], Moshou, D.[1], Kartsios, S.[4], Karypidou, M.C.[4], Katragkou, E. [4], Herrera García, S.[5], Kganyago, M. [6], Mashiyi, N.[6], Pattnayak, K.[7], Challinor, A.[7], Pritchard, R.[8], Brockington, D. [8], Kagoyire, C.[9], and Suarez Beltran, J.[2]

[1] Department of Hydraulics, Soil Science and Agricultural Engineering, School of Agriculture, Aristotle University of Thessaloniki, Thessaloniki, 54124, Greece

[2] GMV Aerospace and Defence S.A.U., Remote Sensing Services and Exploitation Platforms Division. Isaac Newton 11 (PTM), E-28760 Tres Cantos, Spain

[3] Scuola di ingegneria Aerospaziale – Sapienza Università di Roma, Italy

[4] Department of Meteorology and Climatology, School of Geology, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

[5] Meteorology Group, Dpto. de Matemática Aplicada y Ciencias de la Computación, Universidad de Cantabria, Santander, Avda. de los Castros, s/n, 39005, Spain

[6] Earth Observation directorate, South African National Space Agency, The Enterprise Building, Mark Shuttleworth Street, Pretoria, 0001, South Africa

[7] Institute for Climate and Atmospheric Science, School of Earth and Environment, The University of Leeds, LS2 9JT Leeds, UK

[8] Sheffield Institute for International Development, The University of Sheffield, Western Bank, Sheffield S10 2TN, UK

[9] Center for Geographic Information Systems and Remote Sensing, University of Rwanda, Rwanda

*Contact author: thalex@agro.auth.gr

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Abstract

Earth Observation (EO) data are increasingly being used to monitor vegetation and detect plant growth anomalies due to water stress, drought, or pests, as well as to monitor water availability, weather conditions, disaster risks, land-use/land-cover changes and to evaluate soil degradation. Satellite data are provided regularly by worldwide organizations, covering a wide variety of spatial, temporal and spectral characteristics. In addition, climate and crop growth models provide early estimates of the expected weather patterns and yield, which can be improved by fusion with EO data. The project "AfriCultuReS" is capitalizing on the above to contribute towards an integrated agricultural monitoring and early warning system for Africa, supporting decision making in the field of food security. The aim of this paper is to present the design of EO services within the project, and how they will support food security in Africa. The designed services cover the users' requirements related to climate, drought, land, livestock, crops, water, and weather. For each category of services, results from one case study are presented. The services will be distributed to the stakeholders and are expected to provide a continuous monitoring framework for early and accurate assessment of factors affecting food security in Africa.

Keywords: earth observation, agricultural monitoring system, early warning system.

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1. Introduction

The World Food Summit determines that a population is food secure "when all people, at all times, have physical, social, and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for active and healthy life" (FAO, 2009). This concept includes different dimensions related to food availability (sufficient quantities of food with appropriate quality), food access (to a nutritious diet), utilization (to reach a state of nutritional well-being where all physiological needs are met via diet, clean water, sanitation, and health care), and stability (access to adequate food at all times) (FAO, 2006).

In 2017, 31 percent of the total number of food insecure people in the world (821 million people) were in Africa (CDKN, 2019). In various parts of Africa, climate change has produced lower animal growth rate and productivity in pastoral systems; impacted on agricultural pests patterns; increased desertification, which affects 46 out of 57 African nations; and increased the frequency and intensity of droughts (CDKN, 2019; IPCC, 2019). Droughts and desertification processes impact adversely on water resources, which play a key role in agricultural management practices (Falkenmark & Galaz, 2007) via a) withdrawal of water for irrigation; b) land cover change (e.g. when forests are converted to agricultural land); and c) alterations in water division due to changes in land use management (Deutsch et al., 2010). In addition, land degradation has decreased agricultural incomes in different countries, with significant consequences for livelihoods; for example, in Ghana, loss of agricultural income due to land degradation was anticipated to cause a 5.4 percent increase in national poverty rates between 2006 and 2015 (Diao & Sarpong, 2011). It has been argued, though, that many statistics for African economy lack reliable data, which is an important constrain to decision making (Jerven, 2013). Thus, there is an urgent need for accurate and widely available multi-source information such as land use, farm statistics, crop models, and climate projections to contribute to well-informed agricultural risk assessments, decision making, and governance at multiple levels.

Earth Observation (EO) technology has become a common tool to monitor agricultural production systems and food insecurity in industrialized and emerging countries (Rembold et al., 2019; Whitcraft et al., 2019); however, its single use in the context of food security poses challenges related to estimate crop areas and production forecast (Fritz et al., 2019) . EO data has to be combined or fused with multiple data sources to accurately predict crop production in complex food and farming systems. Consequently, agricultural monitoring systems are often based on rainfall data, sample field measurements, agricultural statistics, agro-meteorological modelling, and EO-based methods. An example of agricultural monitoring systems that covers Africa is the CropWatch Cloud (http://cloud.cropwatch.com.cn/) that is deployed via Alibaba Cloud and provides users access to Earth observation information layers for crop monitoring. Another example is the Agricultural Market Information System (http://www.amis-outlook.org/), an inter-agency platform to enhance food market transparency and encourage international policy coordination in times of crisis.

The EC funded H2020 project "AfriCultuReS: Enhancing Food Security in African Agricultural Systems with the Support of Remote Sensing" (Grant Nº 774652) uses EO-based products, meteorological and climate data to develop an integrated agricultural monitoring and early warning system for Africa to support decision making in the field of food security. The target sectors of the AfriCultuReS project are: the public sector, the agribusiness sector, the financial sector and the academic sector. We have engaged with potential users from eight African countries through several workshops and surveys to collect specific requirements and feedback about data and products useful for monitoring and assessing agricultural production, and to understand capacity building needs. According to user's feedback, we developed a service portfolio with seven services (i.e. climate, drought, livestock, land, crop, weather, and water). In this paper, we

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present how these services have been designed and implemented with several case studies.

2. Material and methods

2.1. Study areas

The focus of the AfriCultuReS activities is on the following regions in Africa: Equatorial and Central Africa, East African Highlands, Gulf of Guinea, Great Horn of Africa, North Africa Mediterranean, Sahel and Southern Africa. More specifically, eight pilot countries were selected in the aforementioned regions (Figure 1): Tunisia, Niger, Ghana, Ethiopia, Kenya, Rwanda, Mozambique, and South Africa. The AfriCultuReS services were developed in these eight African pilot countries considered to reflect the diversity of climate, eco-systems, and farming conditions in Africa. Test sites within the pilot countries were selected for testing products at finer spatial scales. Work in each of the eight countries is carried out in close collaboration with a local African partner organization, a full list of which can be found on the AfriCultuReS website (www.africultures.eu).

[Figure 1 somewhere here]

According to the Koeppen climate classification, which uses the transition zones between two biomes and climate variables to define boundaries between regions, there are four first-order climate classifications divisions in Africa: tropical, dry, mesothermal and the East African highlands. From north to south, the typical climate changes from warm Mediterranean over the coasts of North Africa to semi-arid and warm desert over the Sahara, switching to tropical savanna and monsoon climate over the equatorial regions, and then changing again to humid subtropical and warm/temperate oceanic at the south.

The delineation of the major farming systems provides a useful framework within which appropriate agricultural development strategies and interventions can be determined. The decision to adopt very broad farming systems inevitably results in a considerable degree of heterogeneity

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within any single system. However, the alternative of identifying numerous, discrete, micro-level farming systems in each country - which could result in hundreds or even thousands of systems worldwide - would complicate the interpretation of appropriate regional and global strategic responses and detract from the overall impact of the analysis. Only the major farming systems have, therefore, been identified and then mapped in order to estimate the magnitudes of their populations and resource bases. Each of these broad systems is characterised by a typical farm type or household livelihood pattern, although significant sub-types are described where appropriate.

The classification of the farming systems in the Global South has been based on the following criteria (Dixon, Gibbon, & Gulliver, 2001):

- Availability of natural resources (water, land, grazing areas and forest), climatic conditions, landscape, farm size, tenure and organization.
- Dominant pattern of farm activities and household livelihoods (such as type of crops, livestock, trees, aquaculture, hunting and gathering, processing and off-farm activities), main technologies used, which determine the level of intensity of production and integration of farming activities.

Based on these criteria, the following eight broad categories of farming system have been distinguished:

- Irrigated farming systems, embracing a broad range of food and cash crop production;
- Wetland rice-based farming systems, dependent upon monsoon rains supplemented by irrigation;
- Rainfed farming systems in humid areas of high resource potential, characterised by a crop activity (notably root crops, cereals, industrial tree crops - both small scale and plantation - and commercial horticulture) or mixed crop-livestock systems;

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- Rainfed farming systems in steep and highland areas, which are often mixed crop-livestock systems;
- Rainfed farming systems in dry or cold low potential areas, with mixed crop-livestock and pastoral systems merging into sparse and often dispersed systems with very low current productivity or potential because of extreme aridity or cold;
- Dualistic (mixed large commercial and small holder) farming systems, across a variety of ecologies and with diverse production patterns;
- Coastal artisanal fishing, often mixed farming systems; and
- Urban-based farming systems, typically focused on horticultural and livestock production.

2.2. User Requirements and EO data identification

Gaining understanding of user needs necessitated addressing three main issues: the crops most important to food security in the eight focus countries, the most important agricultural risks in each country, and the kinds of EO-based products which could best contribute to ameliorating these risks. Secondary data sources used to understand these issues included the EarthStat (Monfreda, Ramankutty, & Foley, 2008) and FAOSTAT databases in the case of key crops, and an in-depth review of academic literature in the case of agricultural risks.

Secondary data were complemented by engagements with potential users through surveys, as well as through rounds of in-country stakeholder workshops organised in collaboration with local African partner organisations in 2018 and 2019. Representatives were invited to workshops from the four identified user sectors (public sector, academia, finance and agribusiness), although representation of different sectors varied between countries. Further rounds of workshops are planned for 2020 and 2021, during which potential users will be able to interact with the AfriCultuReS platform and provide further input into design and functionality.

These various data sources were combined, analysed and translated into users' requirements following the Group on Earth Observation (GEO) User Requirements Registry (URR) approach (http://www.geo-tasks.org/urr-tutorials) and linking this information to the GEO Societal Benefit Areas (SBAS) (https://www.earthobservations.org/sbas.php). Requirements mainly cover the SBAS of Food Security and Sustainable Agriculture and Water Resources Management. Finally, users' requirements have been stored in a database. Similar review processes will follow in order to adjust and consolidate the database.

Questionnaires and surveys were also sent to local partners to identify EO, meteorological, and in-situ data available for the regions of interest. In order to satisfy the users' needs and to produce food security related estimates and warnings, a broad range of EO raw and processed data were investigated. The EO products that were considered are either already available from third parties or being produced by the project. For the selection of the relevant EO-based geo-data the following key characteristics were taken into account: the spatial, temporal, and spectral resolutions; the radiometric resolution; the timeliness of data; the accuracy of data; the swath width; the launch date, availability of archive data and continuity of data provision; the simplicity and easiness of access; the interoperability; and the automation.

2.3. Development of AfriCultuReS' services

In order to provide the information identified through the analysis of the users' requirements, several services have been proposed at various temporal and spatial scales. For instance, the early warning system based on the climate seasonal forecast provides one month in advance information for the next season in order to identify the intensity and occurrence of drought events and plan accordingly the planting dates and growing season of crops. In addition, climate change services provide the needed information for the authorities to define and establish mitigation and adaptation measures (e.g. identifying new optimal crops) for climate change.

As a general rule, after extensively analysing the project's needs in particular in terms of EO products to be developed, several guidelines were followed for the implementation of AfriCultuRes' services. The same guidelines have been taken into consideration for the selection, processing, and management of the EO data. These guidelines are:

- to deliver space-based agricultural production services that will be aligned with the African Space Policy and Strategy and AfriGEOSS, the African segment of the Group on Earth Observation (GEO) in the domain of food security and
- to rely upon the data and services provided by Copernicus and the GEO initiatives, as well as other third party EO data and value-added services, such as the ESA Food Security Thematic Exploitation Platform, or the Landsat archive on Amazon Web Services.

The AfriCultuReS services rely on the users' exploitation of information products that alone, or in combination with other information products, satisfy the users' requirements. Figure 2 depicts the whole value-added cycle from data, through information and knowledge layers up to decision making or wisdom which will be followed for the design of the AfriCRS' services.

[Figure 2 somewhere here]

In addition, in order to address the diversity of users (i.e. decision and policy makers to farmers and land managers) and needs, the products within AfriCultuReS project were developed following a multi-scale approach. As a result, three spatial scales were considered as indicated in Table 1.

[Table 1 somewhere here]

The definition of the project's service portfolio in support of enhanced food security decision making was mostly based on the exploitation of EO data. The analysis of users' needs and the technological capacity of project partners have gone a step further into the detailed definition of the services' components, leading to the seven general categories of services described hereafter.

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2.3.1 Climate services

The Climate services provide information about mid-term climate variability and long-term climate change scenarios. To this aim, the current state-of-the-art climatic information was considered. In particular, at seasonal scale, the multi-model seasonal forecast system provided by the Copernicus Programme (https://www.copernicus.eu/) through the Copernicus Climate Data Store (https://climate.copernicus.eu/climate-data-store) was used, while at decadal scale and climate change projections, the Phase 6 of the Coupled Model Intercomparison Project (CMIP6) and CORDEX-Africa (Hewitson, Lennard, Nikulin, & Jones, 2012) were considered, respectively; both of them distributed through the Earth System Grid Federation (Carenton-Madiec, Denvil, & Greenslade, 2015). All this climatic information was downloaded and post-processed to make it remotely available through the Santander User Data Gateway (UDG, http://www.meteo.unican.es/udg-wiki, (Cofiño et al., 2018) in order to obtain the final products defined/requested by the users by applying the tools included in the framework climate4R (Iturbide et al., 2019).

2.3.2 Crop services

Crop services provide manifold information for decision making on crop production. The AfriCultuReS Crop services include crop and calendar yearly mapping, frequent crop phenology and condition monitoring, as well as forecasts on expected yield for main crops, based on crop growth models. These multi-scale crop services, including the crop early warning service, provide the basis for evidence-based decision making on food security. Current and seasonal maps on crop land use and main crops grown, allow the precise identification, location and acreage of production areas. These inputs are a cornerstone of planning and prioritization of zonal interventions to improve crop cultivation conditions or to cope with food production shortages.

In the case of crop condition assessment, this is done directly through the use of vegetation indices such as NDVI and LAI or using the same period comparing indicator Vegetation Condition Index (VCI) which compares the current NDVI to the range of values observed in the same period in previous years. VCI is widely used to monitor vegetation and drought conditions (Quiring and Ganesh, 2010). VCI was designed to evaluate vegetation health, while separating the weather-related component of the NDVI from the ecological element. Next, the VCI data is characterized using the vegetation condition classes previously proposed (0.7-1: normal vegetation condition, 0.5-0.7: moderate vegetation condition, 0.3-0.5: poor vegetation growth, <0.3 extremely poor growth condition) (Qian et al., 2016). The service at high resolution is based on NDVI and LAI historical values retrieved from Sentinel-2 images (Figure 3).

[Figure 3 somewhere here]

2.3.3 Drought services

Drought is the major disaster affecting food production, alone drought accounted for the 19% of the crop and livestock losses by disasters in Africa during the period 2005 to 2014 (FAO, 2017) .The Drought services provide mid-term drought monitoring, forecasts and warnings. The Drought service addresses two main types of drought: meteorological and agricultural drought. Meteorological drought is defined by a precipitation deficiency threshold over a predetermined period of time. In turn, agricultural drought is defined by the availability of soil water to support crop and forage growth rather than by the departure of normal precipitation over some specified period of time. The impact of drought on food production depends on the intensity, duration and spatial coverage of drought.

In case of the Seasonal Drought Forecast service, it is based upon the calculation of the standardised precipitation evapotranspiration index (SPEI), which is able to provide an estimation of the onset, duration and intensity of a drought event (Vicente-Serrano, Beguería, & López-Moreno, 2010). In addition, SPEI allows for a multi-scalar analysis, by calculating its values on different temporal windows. The multi-scalar nature of SPEI enables the identification of the return time of different drought types (Schwalm et al., 2017).

2.3.4 Land services

The Land services provide facts on land cover current situation and land cover changes as well as abiotic factors that affect, or can affect, food production. Land use competition between agricultural and/or pastoral land with other uses, mainly urban areas expansion, constitute a key factor when tackling sustainable land use planning. The increasing demand of space for urban and other non-food production activities development is increasingly relegating food production to land areas lesser suitable for human and economic activities. These changes lead to lower productivity of agricultural land. In addition, other factors, like land degradation, soil erosion or the occurrence of recurrent natural disasters, while not always coincident with land use-cover transformations, exacerbate the decrease of land productivity. With three proposed Land services, AfriCRS will contribute to an improved and informed decision making aiming at mitigating the adverse effects of the above factors on Land and Food security.

In particular, the high resolution burnt areas mapping service uses multi-temporal Sentinel-2 datasets to compute the Normalized Burn Ratio (NBR), which is a spectral index that combines the near infrared (NIR) and shortwave-infrared (SWIR) bands to distinguish between burned and unburned areas (Key and Benson, 2006):

$$NBR = \frac{R_{NIR} - R_{SWIR}}{R_{NIR} + R_{SWIR}}$$

where R_{NIR} and R_{SWIR} are the reflectance of the NIR and SWIR spectral bands, corresponding to band 8 (0.842 μm) and 12 (2.190 μm) of the MSI sensor of Sentinel-2.

The Differenced Normalized Burn Ratio (dNBR) index was also calculated, defined as:

$$dNBR = NBR_{pre} - NBR_{post}$$

that is, the difference between the NBR values computed by using a pre-fire and a post-fire image allows the detection of the burned areas as well as to quantify the severity of the damage by introducing appropriate thresholds on the possible values of dNBR. The dNBR index provides a continuous scale of differences that can be related to a magnitude of ecological change, which in turn offers a conceptual model for the severity of damage caused to vegetation in the burned area: the greater the change detected due to fire, the greater the severity. A relativized form (RdNBR) of the dNBR has been introduced (Miller & Thode, 2007) to remove the biasing effect of the pre-fire condition. The RdNBR is defined as:

$$RdRBR = \frac{dNBR}{\sqrt{abs\left(NBR_{pre}/1000\right)}}$$

Employing RdNBR allows, in principle, creating categorical classifications using the same thresholds for fires occurring in similar vegetation types without acquiring additional calibration field data on each fire. However, an alternative relativized burn severity index, the Relativized Burn Ratio (RBR) was recently introduced (Parks, Dillon, & Miller, 2014). This index is defined as:

$$RBR = \frac{NBR\ pre - NBR\ post}{NBR\ pre + 1.001}$$

The dNBR maximizes reflectance changes in plants and soil due to drastic changes like forest fires. Like RdNBR, RBR is a relativized version of dNBR, designed to detect changes even where pre-fire vegetation cover is low. It was demonstrated that both RBR and RdNBR are less correlated to pre-fire NBR than dNBR, indicating that the relativized metrics are better at detecting high severity effects across the full range of pre-fire vegetation cover. The RBR is an improvement upon dNBR in terms of correspondence to field measures of burn severity and overall classification accuracy. Furthermore, the reduced variability in RBR thresholds values among fires indicates that RBR thresholds are more stable compared to RdNBR thresholds and are thus more transferable among fires and eco-regions. By using suitable thresholds, the range of values of RBR can be exploited to provide the burn severity in the form of discrete thematic categories, distinguishing, generally, between "no burned", "low severity", "moderate severity" and "high severity".

The burnt areas maps give an effective support to estimate damages and plan management. This service provides key information to many diverse applications such as forestry, agriculture, risk management and give the possibility to assess the amount of crop, forested and pastoral areas affected to fire. The high spatial resolution service consists of an automated satellite-based dataset of RBR maps computed continuously for the area of interest. The data are computed using Sentinel-2 L2A images downloaded automatically from the Copernicus Hub. The AfriCultuReS burned area service at medium spatial resolution is taken from the Copernicus Global Land Services that is based on PROBA V images.

2.3.5 Livestock services

The Livestock service provide satellite-based products to support livestock agricultural management decisions. To this end, the service entails multi-scale historical assessment, seasonal and on-the-go pasture and rangeland mapping and condition monitoring. This includes the assessment of the capacity of these environments to ensure sustainable livestock production and the sustainability of the rangelands. Pastoralism is a vital part of the economies of many African countries, practiced in about 43% of Africa's land mass (FAO, 2018). Livestock is generally the rural households' most valuable assert, providing nutritional requirements, transport, and profits for their livelihoods. However, rangelands and grasslands, as the major source of feed for grazing and browsing livestock, are faced with several challenges, including; bush encroachment, the proliferation of invasive alien plants, wildfires, droughts and as well as displacement due to competing land-uses (Sullivan & Rohde, 2002). In order to tackle these phenomena and ensure their sustainability, farmers, land managers and decision-makers have to be more effective in their implementation of land use management approaches and plan ahead of time to avoid the pitfall of a forage shortage and reduce degradation of grasslands (Müller, Quaas, Frank, & Baumgärtner, 2011). Livestock service provides spatially explicit, objective and actionable information such as recommendations on carrying capacity and stocking rates, status and conditions of rangelands and grasslands, as well as risks facing productivity, to inform better range management decisions that will maintain agro-ecological integrity for current and future use.

In case of the grazing and rangeland mapping service at high-resolution, it is generated based on Sentinel-2, and the training data generated from European Space Agency (ESA) Climate Change Initiative (CCI) prototype high-resolution land cover map of Africa as well as machine learning approaches such as Random Forest. On the other hand, the coarse resolution product, i.e. Global Rangeland Mask from the Joint Research Centre (JRC) as well as South African National Land Cover are used as reference for compassion purposes. The ESA CCI-LC for Africa (released in September 2017) is a prototype land cover map covering the entire African continent at high spatial resolution of 20m based onSentinel-2 images acquired in 2016 (Lesiv et al., 2017). On the other hand, the South African National Land Cover (2017/18) is provided by the Department of Rural Development and Land Reform (DRDLR) based on Landsat 8 images with 30m spatial resolution acquired in 2017 and 2018. JRC-Global Rangeland Mask over Africa is generated from land cover/land use dataset from Vancutsem, Marinho, Kayitakire, See, and Fritz (2013) at 1 km spatial resolution, available from https://mars.jrc.ec.europa.eu/asap/ (Rembold et al., 2019).

2.3.6 Water services

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The Water services provide geospatial products for water bodies extent mapping and lake water quality assessment and monitoring. Other products are designed to deliver information on soil water availability for crop growing, as well as crop water consumption. According to FAO (Turral, Burke, & Faurès, 2011), the impacts of climate change on the global hydrological cycle are expected to modify the patterns of water supply and demand for agriculture, the dominant user of freshwater. The extent and productivity of both irrigated and rainfed agriculture can be expected to change. As a result, the livelihoods of rural communities and the food security of a predominantly urban population are at risk from water-related impacts linked primarily to climate variability. The rural poor, who are the most vulnerable, are likely to be disproportionately affected. Adaptation measures that build upon improved land and water management practices are fundamental in boosting overall resilience to climate change.

2.3.7 Weather services

The Weather services provide seven-day to near real-time deterministic weather forecasts at continental scale (0.25° longitude x 0.25° latitude). In addition, probabilistic weather forecasts will serve to deliver early warnings on weather extremes at continental scale (0.5° longitude x 0.5° latitude). In the short term, weather factors may produce food production shortages and what is more, extreme weather events in a climate changing environment produce extreme shortages. Projected impacts vary across crops and regions and adaptation scenarios, reaching yield losses of more than 25%, compared to the late 20th century (Porter et al., 2017). Therefore, weather forecasts, both short-term and medium range, are required for making decisions., day-to-day farm management requires weather information for the schedule of farming practices, for example, the application of fertilizers requires some water in the upper to mid layers of the soil, the spaying must be done on non-windy days, etc. Weather conditions are also a key driver for the outbreak of pests and diseases, like fungal diseases, knowing in advance the likelihood of these events can support early decision making towards the mitigation of the adverse effects of weather on food production.

3. Results

3.1. Identified user requirements and list of EO-data

Gathering user needs has provided service providers with valuable information about data gaps and farming systems in the project's pilot countries, in order to refine the suite of AfriCultuReS services. In particular, the user requirements for which EO products are relevant are related to the provision of information for: the selection of the most appropriate crops for the given growing conditions; the optimization of fertilization in order to achieve an optimum crop production; sowing/planting advice for rain-fed agriculture; data and tools for effective irrigation planning based on crop water requirements (CWR) at irrigation systems; and the facilitation of timely agricultural management practices. One of the main concerns reflected during some of the national workshops was related to the water availability and droughts at different time scales, from climate seasonal forecast to decadal and long-term climate change projections, as it strongly affects the crop planning and growth, and the livestock management. Moreover, climate and weather information is also needed as input for the crop models.

The list of the users' requirements identified through review of secondary sources and engagements with potential users in the AfriCultuReS' pilot countries can be summarized by the following:

- EO monitoring of crop conditions, crop pests, crop diseases, and crop management.
- Provide ready to use information for irrigation management.
- Provide a smart system to predict crop yield for tackling hunger and disasters that affect crops.
- Integrate information on traditional cultivation techniques for the assessment of the most

appropriate land for agricultural production.

- Support the development of an index-based insurance.
- Enhance service provision to farmers by county governments (policy monitoring, seed and fertilizer subsidy, field extension services, crop insurance, precision farming, early warning for drought, pests, diseases, disaster management, agricultural downstream logistics, farm-level calendars).
- Produce information for main crops yield forecasting.
- Set-up index-based livestock insurance against extreme events for pastoralist to minimize their risk.
- Calibrate and evaluate climate services at local and regional scale, meteorological information based on the available national and/or international observational networks is needed.
- Provide information on the likelihood of extreme weather conditions (frost, high temperatures and heat waves, extreme precipitation events) related with agricultural activities.

The user requirements were then connected to actual services, intended to be designed and developed by the AfriCultuReS project. For the implementation of these services a set of EO products was identified as most appropriate. The EO products are presented in Table 2 along with the data source or provider for each considered scale.

[Table 2 somewhere here]

3.2. The AfriCultuReS' service portfolio

Following the guidelines described in section 2 and taking into consideration the identified users' requirements and the availability of relevant EO products, the AfriCultuReS' service portfolio was designed. It is presented in Table 3.

[Table 3 somewhere here]

Due to the large number of services developed, one representative service per service category identified in section 3.2 is provided below. A case study accompanies each service description.

3.2.1 Climate services: AFRICRS-S1-P02 – Seasonal Climate Forecast and Early Warnings

Climate services aim to provide seasonal forecast and decadal and long-term climate projections at continental and, when possible, local or regional scales. At seasonal scale, these services obtain one month in advance the expected climate evolution for the next months (typically 6-9 months) as given by the state-of-the-art seasonal forecast systems produced by the Copernicus initiative. As a result, this service will allow to plan proper adaptation measures according to the expected seasonal climate conditions.

Case study

As an example, the seasonal forecast of 2-meters mean daily air temperature for autumn 2019 is shown in Figure 4 at continental scale, including the tercile plot corresponding to Rwanda. In this figure, the most probable tercile (lower than normal, normal, and higher than normal) for each grid box is shown in colours (blue, yellow and red, respectively) whilst the transparency of the bubbles represents the uncertainty of the forecast as given by the hindcast (retrospective forecast). This is illustrated more in detail in the tercile plot in which the forecast for each year and the observed tercile are shown, reflecting the capability of the forecast system to predict each class in the past and, as a result, the uncertainty associated to the new forecast.

[Figure 4 somewhere here]

3.2.2 Crop services: AFRICRS-S2-P02 – Crop condition monitoring (high resolution)

The crop condition assessment service consists in providing information about the status of vegetation and crops through the VCI.

Case study

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As an example, one of the Tunisian test areas has been considered, that is, Jendouba. Figure 5 shows the historical max and min NDVI computed on the area by using S2 images acquired from January 2018 to 13 July 2019. In addition, Figure 5 shows the VCI map computed by using the S2 image acquired on the 23 of July 2019. VCI is presented with 4 classes according to Qian et al, (2016).: (4) normal vegetation condition, (3) moderate vegetation condition, (2) poor vegetation growth, (1) extremely poor growth condition.

From the map of VCI the statistics on the distribution of VCI values for the pixels classified as crop or grass or shrub were retrieved. They are 81.5% for (1), 4.37% for (2), 3.11% for (3), and 11% for (4).

[Figure 5 somewhere here]

3.2.3 Drought services: AfriCRS-S3-P01 - Seasonal Drought Forecast

The Seasonal Drought Forecast service aims to provide the probability of drought conditions for the next season one month in advance in order to plan proper adaptation measures according to the predicted drought conditions, using the time series of the SPEI index.

Case study

As an example, the one month in advance seasonal forecast of the SPEI for the drought affecting South Africa in 2016 is shown in Figure 6. On the one hand, panel (a) shows that drought conditions (blue colour) were predicted for all the continent. The dot-size and the transparency show, respectively, the percentage of members corresponding to the most probable tercile and the skill of the prediction as given by the evaluation of the hindcast against the observations, in this case the EWEMBI dataset. Based on this, only the south and mid-centre of the continent show reliable forecast of those drought conditions. Tercile plot (panel b) shows, for a location or a (climatologically homogeneous) region, the probability predicted for each tercile in the historical period and the target season, in this case the Spring 2016. The white dots show the observed tercile reflecting the capability (or not) of the seasonal forecast system to reproduce the observations. This skill is shown together the forecast in order to reflect its uncertainty according to historical predictions. As could be expected, for this particular season and region (green box in panel (a)), all the members predicted normal or dry conditions for the season and the uncertainty of the prediction is very low, leading to a high confidence in these results, Thus, a source of valuable information is established to farmers and authorities to plan adaptation measures based on the given forecast.

[Figure 6 somewhere here]

3.2.4 Land services: AFRICRS-S4-P03 – Disasters mapping and monitoring (Burnt areas mapping, high resolution)

This service provides key information to many diverse applications such as forestry, agriculture, risk management and give the possibility to assess the amount of crop, forested and pastoral areas affected to fire. The service consists of an automated satellite-based map dataset for burnt areas by continuously updating data available on the area of interest, using Sentinel-2 L2A images.

Case study

As an example, one of the Tunisian test areas has been considered. The burnt area map at high resolution has been computed using Sentinel-2 images. The image corresponds to the tile T32SMF (see [Figure **7 somewhere here]**
).

[Figure 7 somewhere here]

Figure 7 shows an example of a RBR map, based on Sentinel-2, computed for one of the test area Jendouba (Tunisia) of the AfriCultuReS project. The map has been computed by using two Sentinel-2 images acquired on 17th and 22nd August 2019. Four fire severity levels are distinguished: unburned, low, moderate and high. Monitoring burned areas could help in assessing the loss of agricultural areas as well, in case of wooded areas, the damage severity and the potential susceptibility to soil erosion.

3.2.5 Livestock services: AFRICRS-S5-P01 - Grazing and Rangeland Mapping (high resolution)

Pastoralism is often listed as one of the major livestock production systems in Africa (Dixon et al., 2001), thus making an obvious contribution to economic development through agriculture and a supply of affordable food products. Dixon et al. (2001) point out that for the about 55% of the Africa land surface described as arid and semi-arid lands (ASALs), 47% is arid and is largely suitable for pastoralism only, while Agyemang (2017) indicates that according to the Africa Union pastoral areas occupy about 40% of the entire Africa's land mass. Livestock production, both large and small-scale commercial, depends mainly on rangelands. Subsistence farmers in rural communities also depend directly on rangelands for their livelihoods.

Case study

As an example, South African rangelands were mapped using Sentinel-2 data at 20m resolution and Random Forest (RF) classifier. The training data were generated from ESA CCI-LC, i.e. Africa Prototype Land Cover Map (released 2017). A visual comparison of the preliminary rangeland map for South Africa (Figure 8d) with a reclassified National Land Cover map (NLC 2017/18) and the JRC-Global Rangeland Mask (Figure 8e) indicates huge differences between the maps. The observed differences may be due to a number of factors, related to dates of acquisitions of input data, differences in spatial resolutions and temporal compositing methods used. For example, the rangeland map in Figure 8a is based on Sentinel-2 data acquired in 2019 March/April at 20m spatial resolution, while the map in Figure 8b is based on Landsat 8 collected between 2017 and 18 and Figure 8c, i.e. JRC Rangeland mask is based on MODIS data. Another contributing factor of the difference is the accuracy of ESA CCI-LC, i.e. 65% (Lesiv et al., 2017), while NLC has about 96%. Therefore, future work will involve improvement of the rangeland map.

[Figure 8 somewhere here]

3.2.6 Water services: AFRICRS-S6-P03 – Soil Moisture Monitoring (coarse resolution)

Soil Moisture Monitoring service provides decadal information about moisture conditions in different soil depth for Africa's continental tile. This information is provided through the Copernicus Global Land Service 10-day Soil Water Index (SWI), with a mean value computed over a period of 10 days. SWI quantifies the moisture condition at various time intervals from which the depths in the soil can be retrieved, according to the equation: T = L/C, where T is a factor determining how fast the soil moisture content decays with the time, L is the depth of the reservoir layer referring to the soil profile extending downward from the bottom of the soil surface layer which is accessible to C-band scatterometers and C is a pseudo diffusivity constant. The soil moisture is defined as the amount of water (m^3/m^3) contained in soil layers identified according to their depth measured from top surface. Soil moisture is intimately involved in the feedback between climate and vegetation, since local climate and vegetation both influence soil moisture through evapotranspiration, while soil moisture and climate determine the type of vegetation in a region. Changes in soil moisture therefore have a serious impact on agricultural productivity, forestry and ecosystem health. Thus, SWI is used in soil-vegetation-atmosphere transfer schemes to improve the accuracy of general circulation models or to improve the understanding of the feedback between climate and vegetation. Soil moisture is directly derived from SWI (SWI10) by comparing actual observations with the long-term statistics, based on the 10-year period 2009-2018. This product is displayed in a regular latitude/longitude grid (plate carrée) with the ellipsoid

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WGS 1984 (Terrestrial radius=6378km). The resolution of the grid is 0.1° and is provided as multi-band GeoTIFF.

Case study

The SWI10 product for the country of Tunisia was considered as a case study (see Figure 9).

[Figure 9 somewhere here]

3.2.7 Weather services: AFRICRS-S7-P02 – Weather Extremes Early Warning (coarse resolution)

Early warning systems regarding weather extremes are widely used around the globe, providing valuable information about potential extreme weather conditions and risk information in order to protect lives, livelihoods and assets. The Weather Extremes Early Warning service (AFRICRS-S7-P02) aims at informing end users about temperature and precipitation extremes every day for the upcoming seven days by utilizing the NCEP Global Ensemble Forecasting System (GEFS: (Hou, Toth, & Zhu, 2004; Toth & Kalnay, 1993, 1997; Wei, Toth, Wobus, & Zhu, 2008; Wei et al., 2006).

The service addresses the probability of extreme temperature in 3hr time and daily intervals and precipitation extremes at daily basis. Extremes (0.01, 0.05, 0.1, 0.9, 0.95, 0.99 quantiles) are defined by the ERA5 reanalyses dataset (C3S, Climate Data Store) or any other additional dataset fit for purpose. The service products come at 0.5^{o} x 0.5^{o} horizontal resolution at continental (Africa, -20o – 55oE, -40o – 40oN) scale, in graphics (.png) and NetCDF format.

Case study

As a case study, the extreme precipitation products (0.9, 0.95, 0.99 quantiles) on 25th of September 2019 (forecast day 1) and on 29th of September 2019 (forecast day 5), of the 24th of September 2019 (12UTC) GEFS prognostic cycle are illustrated in **Error! Reference source not found.** and Figure 11. Shaded contours depict the probability of precipitation occurrence (%) above a specific

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threshold, which has been computed by the climatology (ECMWF/ERA5 dataset). According to **Error! Reference source not found.**, extreme precipitation was likely to occur in the central parts of Mozambique (over 90 % probability, in all quantile plots) on 25th of September 2019, while the southern parts of South Africa were prone to extreme precipitation events on 29th of September 2019 (see Figure 11).

[Figure 10 somewhere here]

[Figure 11 somewhere here]

4. Discussion

4.1. Issues of accuracy and operationality

For each AfriCultuReS' service the relevant scale(s) for implementation was defined. While climate, weather, and drought services run using coarse resolution global Numerical Weather Prediction (NWP) models, other services such as crop and land services are more meaningful at high resolution, where a higher level of detail about the crop types and farmlands are used. Other services such as vegetation condition are run at all scales from high to low resolution in order to feed other services and provide information for multi-level decision making.

Each scale has pros and cons. Low resolution products present little detail but cover a wide area. High resolution products on the other hand provide a high level of detail but for a limited area. Heavier processing burden and storage requirements when using high resolution data need to be taken into account.

Regarding the temporal scale the services will be provided, for each service and according to users' requirements the appropriate time scale is selected. Time scales for weather forecast and climate change monitoring vary from a few days to the end of the century. A crop growth monitoring service has dekadal (10-day composites) time steps, while a land cover product is considered stable throughout the year. Besides, each pilot country has its specificities e.g. different crop calendars and growth seasons which result in specific requirements in temporal analysis. Monitoring services require frequently available data; this condition was fulfilled by the use of Copernicus 10-day products and Sentinel-1 and 2 images with 5 to 6 days revisit time.

As a result, for the selection of the most useful products for each specific service a consensus was made between the thematic accuracy of the data and the temporal and spatial resolutions of the data so that to allow the operational implementation of the service.

A rather common constraint of satellite EO data is the cloud cover, where the surface reflectance of optical wavelengths or emissivity of thermal wavelengths is disrupted by the cloud, and there is large distortion at the cloud's shadow. Depending on the nature of the service, the workaround was to use lower resolution (but more frequent) satellite images, for which there is a higher chance to be acquired on a date without cloud cover, to use composite products (e.g. MODIS 8-day composite LAI product) which incorporate cloud filling techniques in order to overcome the issue of gaps from cloud cover and to use microwave images (e.g. SAR) that are not affected by cloud.

For all service products accuracy information is reported. For some service products that are federated and need few additional processing (e.g. Copernicus products), the accuracy given by the service provider is directly reported. For those requiring some pre-processing, which may not provide equally accurate results when applied in the various agro-ecological zones in Africa, or for newly implemented methodologies some extra validation work is being performed, as part of the project's validation phase. Therefore, the data are tested at different levels according to available reference data and the level of processing. The reference datasets include non-EO data collected for the purpose of AfriCultuReS through new campaigns at test sites, historical non-EO data available to project partners and identified through questionnaires for data availability, EO products of higher spatial resolution, as well as data coming from other reliable sources.

4.2. Case studies assessment and relation to food security

A case study was presented in this paper for each category of services thus providing seven specific examples of food security-related service outputs in specific areas of the African continent.

The climate services provided the seasonal forecast of precipitation and temperature at continental and national scale for autumn 2019 reflecting both the forecast and its uncertainty as defined by the corresponding hindcast. In general, warmer than normal conditions were predicted for this season. The climate services also provide information about mid-term climate variability and long-term climate change scenarios enhancing the user's knowledge and understanding about the impacts of climate on their field, allowing enhanced decision making. One of the most significant impacts of climate variability and climate change is the potential increase of food insecurity and malnutrition. All the components of food security are affected by climate related issues: crop quantity and quality as well as yield are affected by the change and variability of climate patterns such as rainfall or temperature, threatening food availability; the deterioration of the agro-climatic conditions could lead to the increase of the price of major crops, affecting the food access to low income population; climate risks are tightly woven with calorie intake, recurrent extreme events lead to the modification of the traditional diet affecting the health conditions in societies with low coping and adaptation capacity; food stability is also threatened by the occurrence of uneven phenomena affecting food production.

The crop condition service provided some statistics on crop condition over a specific area showing some deviation of the current vegetation condition from the historical minimum and maximum values thus highlighting the areas where vegetation growth status is poor.

In the case of the seasonal forecast and early warnings of drought conditions, the drought event occurred in spring of 2016 was considered as an example reflecting, one month in advance, the high probability and confidence for drought conditions during this season. This kind of forecast may let the farmers and authorities to establish adaptation measures according to the climate conditions predicted. Drought information may lead to adjustments in crop selection, cropping patterns and water use efficiency measures (de la Poterie et al., 2018).

A burnt area was successfully identified using a pre- and post-fire events S2 images and applying the RBR index in the Jendouba area in June 2019. This can lead to the estimation of the biomass loss and to support through monitoring recovery and rehabilitation operations.

An example of rangeland map of South Africa was presented for the livestock service. The monitoring of rangeland extent is important to ensure that there is enough forage for the livestock and to monitor the degree to which overgrazing has already taken place. The service will provide information not only on the extent of rangelands but also on its condition on which forage production is also dependent.

The SWI10 product is used to monitor soil moisture at coarse resolution over Africa. Through the Copernicus SWI10 product the resolution at which soil moisture can be determined directly with Earth observation is considerably improved providing critical information to farmers' organisations and agencies responsible for water management and irrigation.

The Weather Extremes Early Warning precipitation maps provide an insight on the probability of extreme precipitation occurrence over Africa (0.5° x 0.5° horizontal resolution), based on an ensemble of model runs and according to climatology thresholds. Deterministic precipitation forecasts (mm, at 3 hourly intervals), are also available at finer scale (0.25° x 0.25° longitude-latitude). The precipitation product is a critical input to various AfriCultuReS services including drought early warning and crop yield prediction.

As shown above, many products and services are interconnected. The early warning for drought uses input from the weather service and crop condition products. For the livestock service, information on land cover, pastures conditions, and water availability are required.

5. Conclusions

In the present paper the concept behind the description of services of the AfriCultuReS project was presented with results regarding the users' requirements collected through review of secondary sources and engagement with potential users. Based on these requirements a list of services related to the climate, drought, land, livestock, crops, water and weather was established and relevant EO products were selected for their implementation. Several case studies were presented from the application of the selected methodology in the project's pilot sites, pilot countries, or over the whole African continent according to the appropriate spatial scale. Future communication will be presented regarding the integration of these services into the project's platform, their validation by the users' and their demonstration over a different area in Africa.

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Tables:

Table 1: Spatial scales for the AfriCultuReS products.

Spatial scale	Description and relevance
Coarse: 1:1.000.000 - 1:4.000.000	Useful at a continental and regional level especially for applications such as drought monitoring or extreme weather risk assessment. The scale is relevant to address the needs of decision and policy makers from regional institutions in agribusiness, finance, security, etc.
Medium: 1:250.000 - 1:1.000.000	Useful for monitoring vegetation status, flood risk assessment, or water resources assessment at a national to provincial scale. The scale is appropriate to address information needs of national and provincial government ministries.
High: 1:10.000 - 1:250.000	Useful for crop yield prediction, crop health and anomalies detection at a landscape to field level. The scale can address information needs of farmers and land managers.

Table 2: List of selected EO data and provider per pilot country and scale level

EO products	Coarse	Medium	High
LULC	FAO GLC-SHARE	500m MCD12Q1 v6 Land Cover (LC) v2 (2015)	Tunisia: OSS 30m (2015-2016), Kenya: 15m 2015, Ethiopia: OSS 30m (2014-2015), Ghana: OSS 30m (2014-2015), Niger: OSS 30m (2014-2015)
Rangeland		250m JRC rangeland mask	
NDVI	1km 10day Copernicus v2.2	300m 10day Copernicus v1	Sentinel-2
NDVI anomaly		250m 8day NDVI Anomaly (GMOD09Q1)	
VCI (Vegetation Condition)	1km 10day Copernicus		Sentinel-2

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EO products	Coarse	Medium	High
LAI	1km 10day Copernicus v2	300m 10day Copernicus v1 NOAA Climate Data Record (CDR) of AVHRR	Sentinel-2
FAPAR		NOAA Climate Data Record (CDR) of AVHRR	Sentinel-2
Burnt area		300m 10day Copernicus v1 (pre-operational)	Sentinel-2
Water bodies	1km 10day Copernicus v2	300m 10day Copernicus v1	Sentinel-1
Soil moisture	SWI Surface 10km 10day Copernicus		
Soil erosion	25km Global Soil Erosion (2012, 2001) (ESDAC)		
Evapotranspiration	3km daily LSA-SAF DMET 5.6km monthly SSEBop v4 ET anomaly	500m 8day MOD16A2	Ethiopia, Ghana, Kenya, Mozambique, Rwanda, and Tunisia: 100m 10day FAO/WaPOR (2009-2016)
DEM			30-90m SRTM

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768 Table 3: List of the AfriCultuReS services per scale level.

	Product ID	**Product Name**	**Coarse**	**Medium**	**High**
Climate	AfriCRS-S1-P01	GAEZ Agro-Climatic Condition	✓		
	AfriCRS-S1-P02	Seasonal Climate Forecast and Early Warnings	✓		
	AfriCRS-S1-P03	Decadal Climate Change Predictions	✓		
	AfriCRS-S1-P04	Long term Climate Change Projections	✓		
Crop	AfriCRS-S2-P01	Crop Type Mapping			✓
	AfriCRS-S2-P02	Crop Condition Monitoring	✓	✓	✓
	AfriCRS-S2-P03	Crop Yield Forecast	✓		✓
	AfriCRS-S2-P04	Crop Calendar			✓
	AfriCRS-S2-P05	Crop Phenology Monitoring			✓
	AfriCRS-S2-P06	Crop Early Warning	✓	✓	✓
Drought	AfriCRS-S3-P01	Seasonal Drought Forecast	✓		
	AfriCRS-S3-P02	Drought Monitoring and Early	✓		

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		Warning			
Land	AfriCRS-S4-P01	Land Use & Land Use Change Monitoring	✓	✓	✓
	AfriCRS-S4-P02	Land Degradation	✓		
	AfriCRS-S4-P03	Disasters Mapping and Monitoring (Fire, Flood)		✓	✓
Livestock	AfriCRS-S5-P01	Grazing and Rangeland Mapping	✓	✓	✓
	AfriCRS-S5-P02	Grazing and Rangeland Condition Monitoring	✓	✓	✓
Water	AfriCRS-S6-P01	Water Bodies Mapping	✓	✓	✓
	AfriCRS-S6-P02	Lake Water Quality Monitoring	✓	✓	✓
	AfriCRS-S6-P03	Soil Moisture Monitoring	✓	✓	
	AfriCRS-S6-P04	Water Consumption Monitoring	✓	✓	✓
Weather	AfriCRS-S7-P01	Weather Forecast	✓		
	AfriCRS-S7-P02	Weather Extremes Early Warning	✓		

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Figures and figure legends:

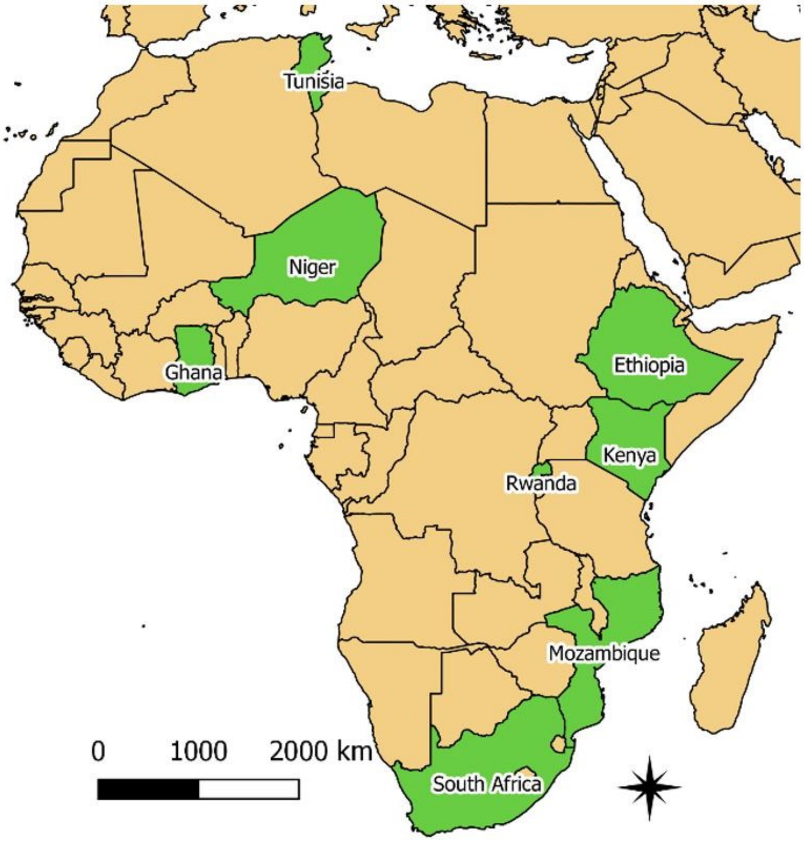

Figure 1: Distribution of the AfriCultuReS' pilot countries.

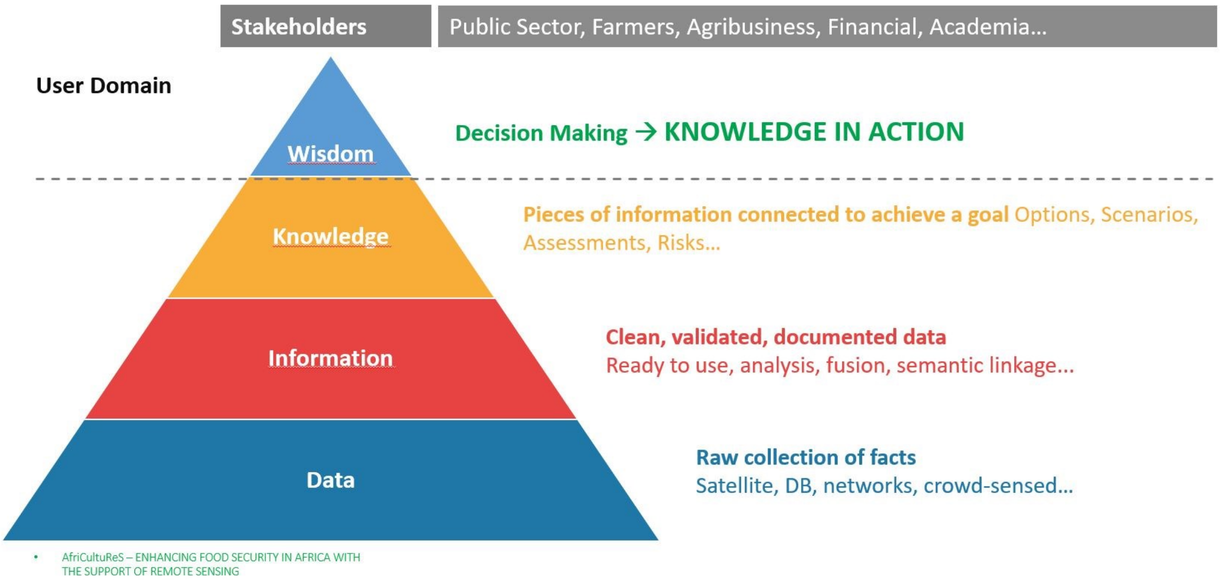

Figure 2: Mainstreaming data into decision making

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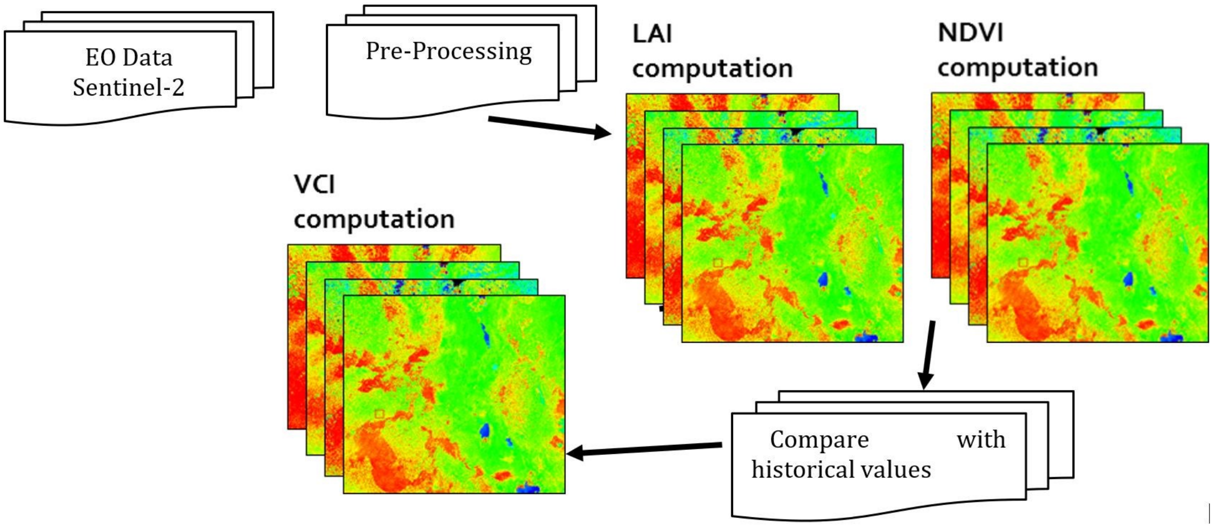

Figure 3: Schematic view of the procedure for computing the AfriCultuReS crop condition monitoring using VCI, NDVI or LAI.

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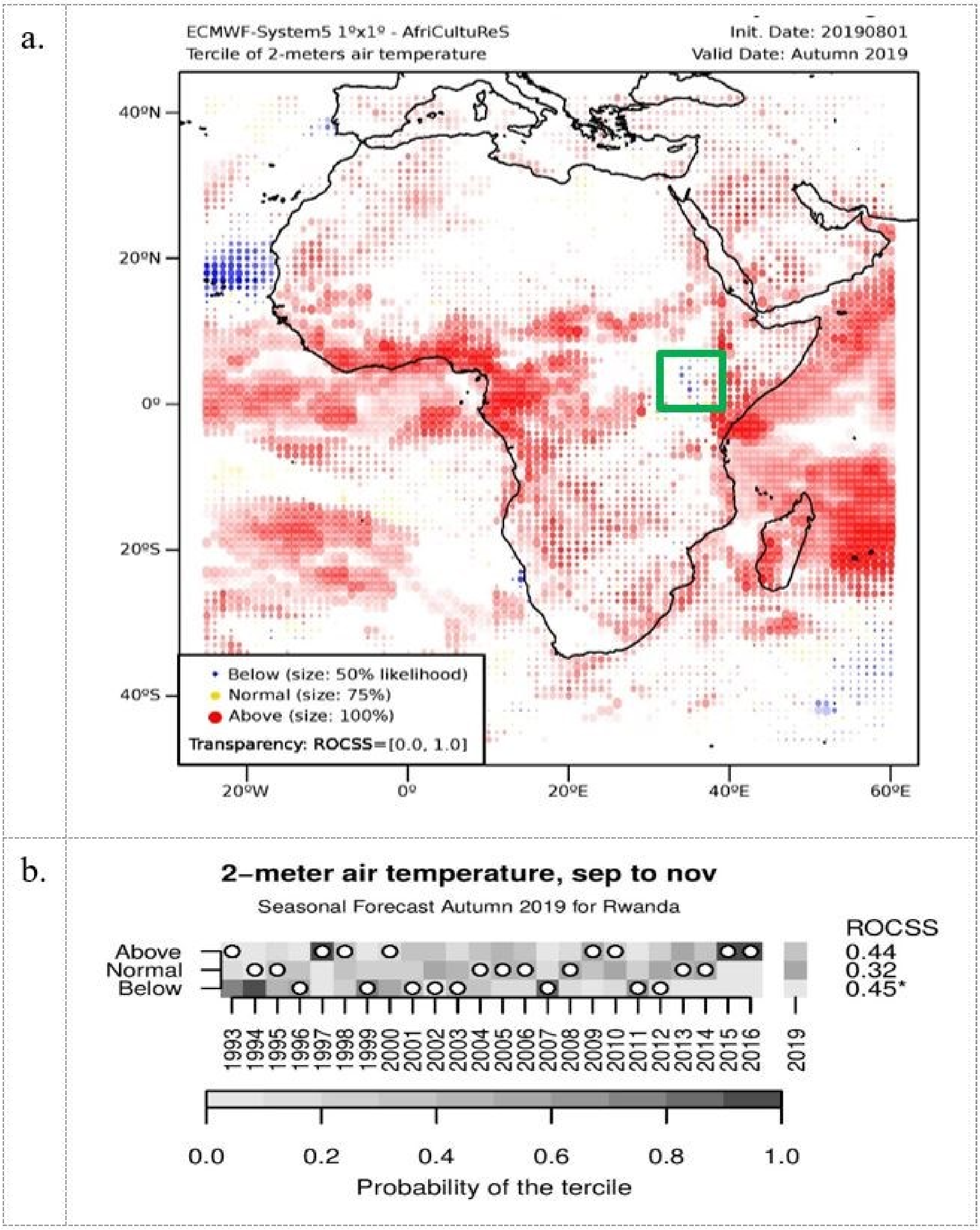

Figure 4: (a.) Overview of 2-meter air temperature from September-November 2019 (the study area of Rwanda is indicated with a green box) and (b.) seasonal forecast for the Rwanda study area for autumn 2019.

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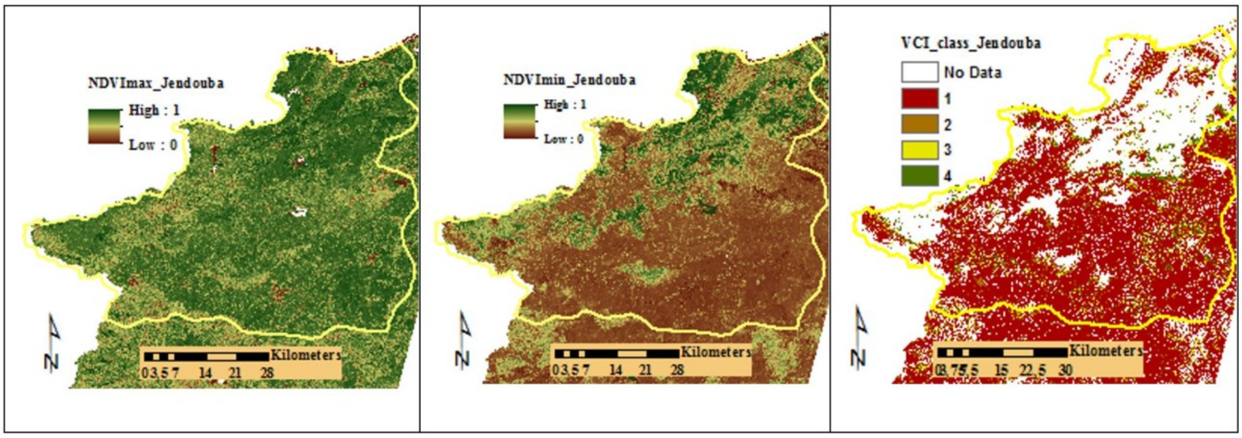

Figure 5: Example of crop condition maps computed for the Jendouba test area in Tunisia. Left: Historical max of NDVI, Centre: Historical min of NDVI, Right: VCI computed for day 23 July 2019. Note: white area refers to cloudy pixels.

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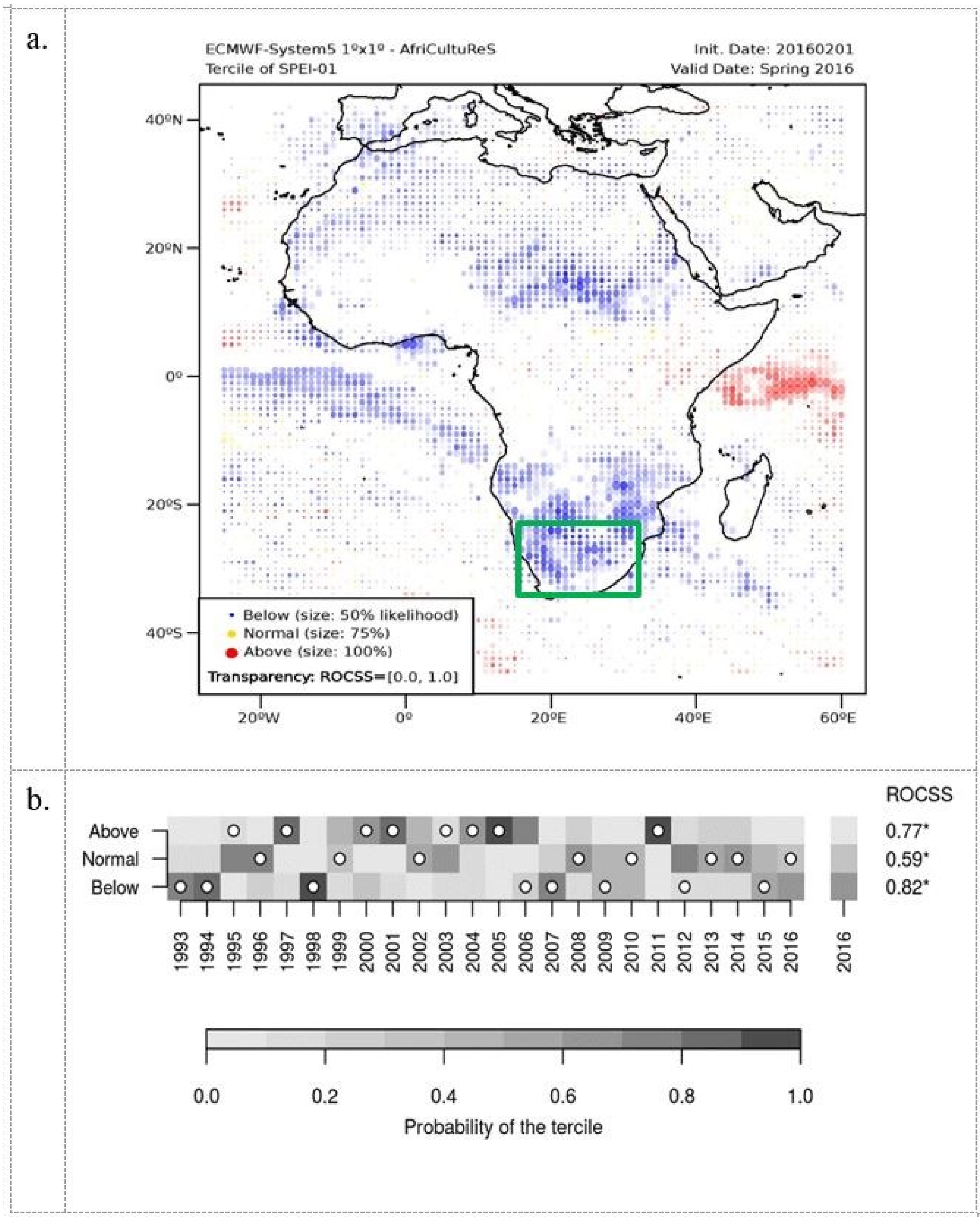

Figure 6: (a.) Seasonal Drought forecast for the African continent during spring of 2016 (the study area of South-Africa is indicated with a green box) and (b.) Standardized Precipitation-Evapotranspiration Index 1 from March-May 2016 in South Africa

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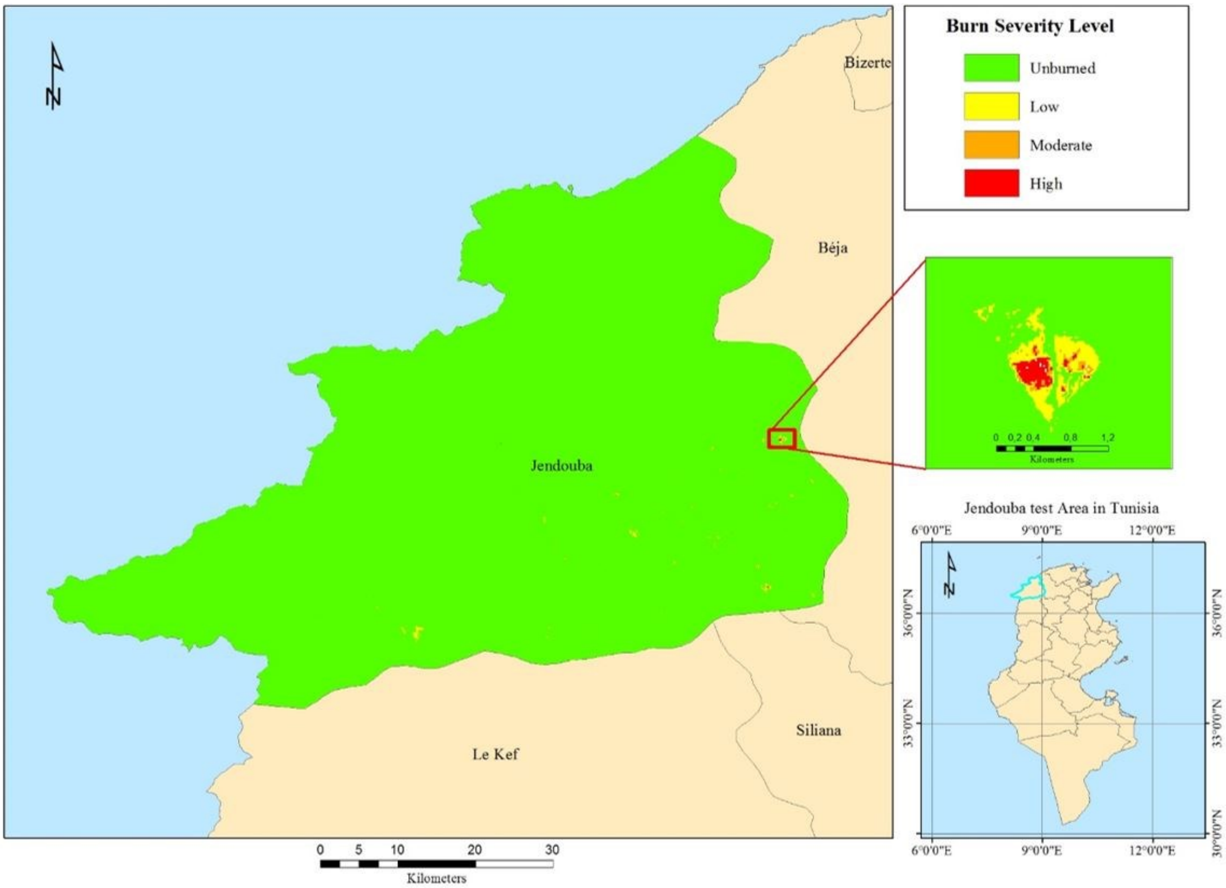

Figure 7: Example of high-resolution fire disaster mapping computed for the test area of Jendouba in Tunisia, between August 17th and August 22nd, 2019 by using the RBR index.

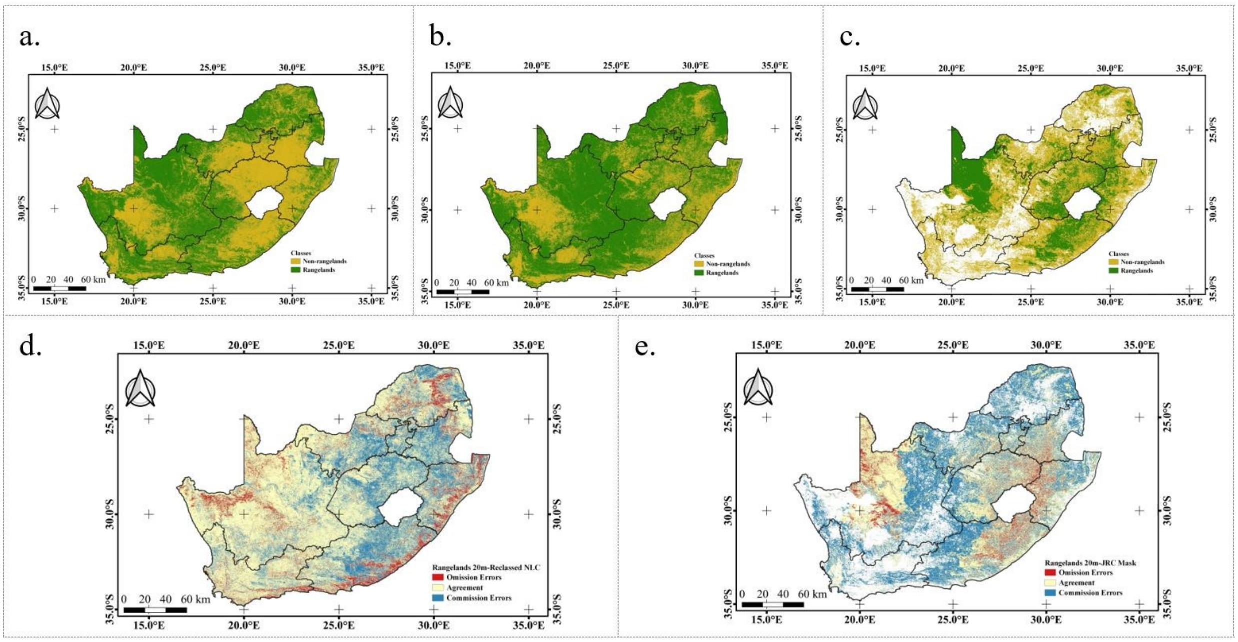

Figure 8: A comparison between a preliminary rangeland map from Sentinel-2 and ESA CCI LC (a), reclassified rangeland map from NLC (b) and JRC Global Rangeland Mask (c). Figures 8d and e indicate the differences between preliminary map and NLC, and JRC-Rangeland mask respectively.

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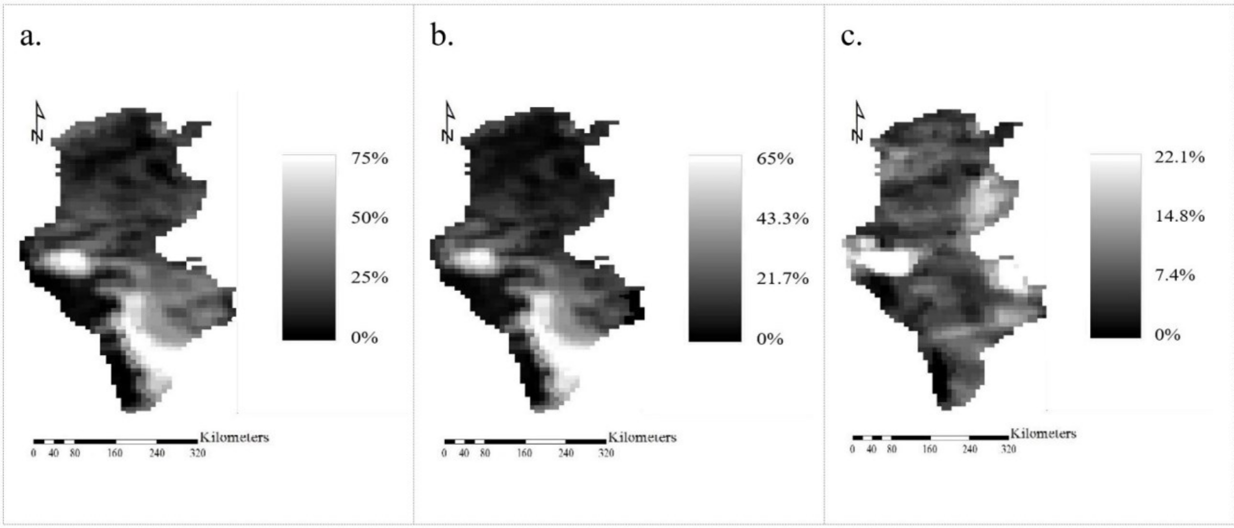

Figure 9: Example of soil moisture maps for Tunisia. SWI10 map of 01 July 2019 (a), the historical 10-year mean SWI10 value (b), and the historical 10-year standard deviation of SWI10 (c). The latter two were computed using Metop-ASCAT time series.

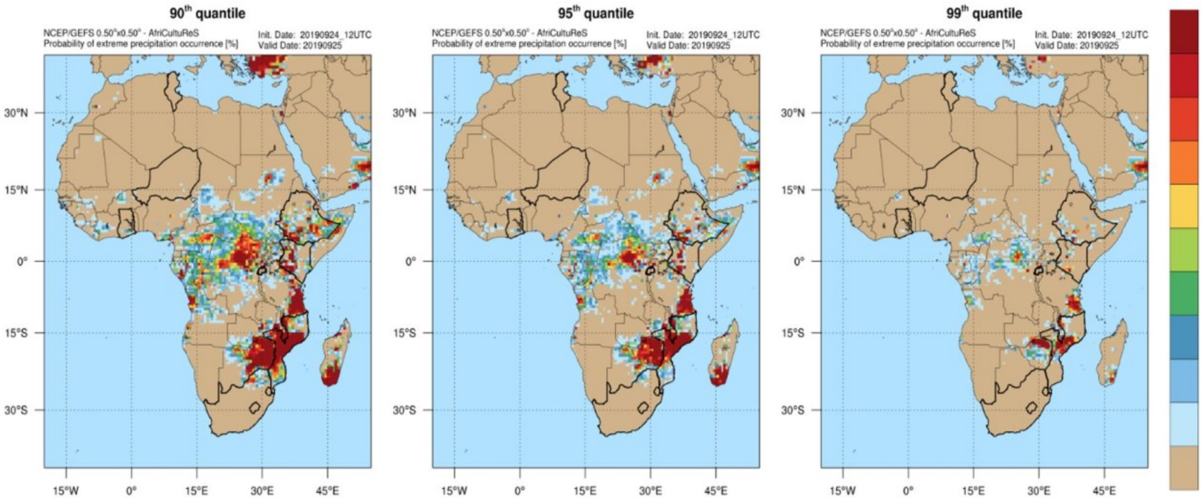

Figure 10: Probability of extreme precipitation occurrence (%, shaded contours), on 25th of September 2019, based on the GEFS/NCEP 12UTC prognostic cycle, on 24th of September 2019. The AfriCultuReS pilot countries are illustrated with bolder borderlines.

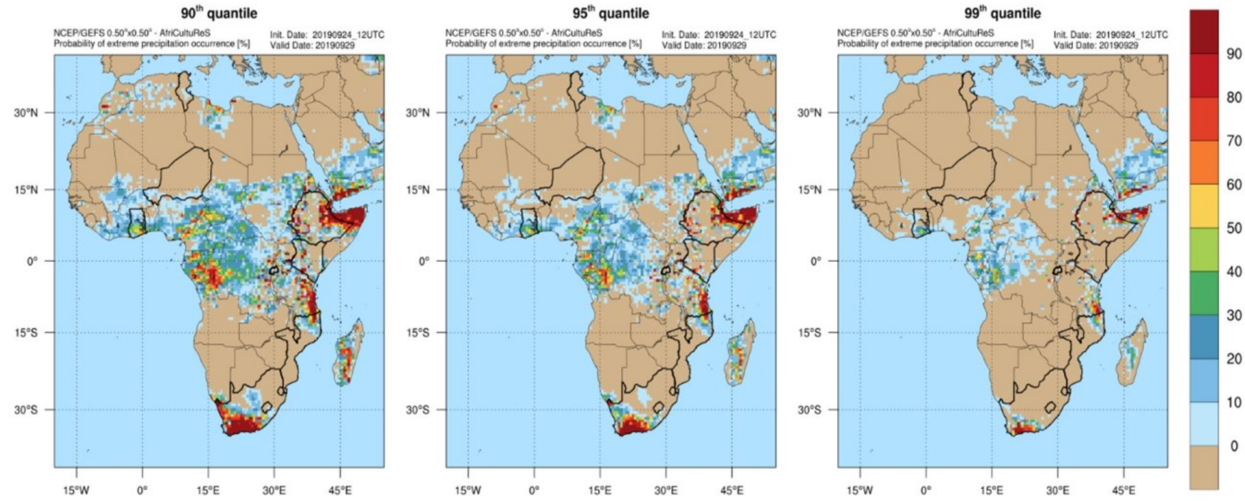

Figure 11: As in Figure 10, but on 29th of September 2019.