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The warning classification scheme of ASAP – Anomaly hot Spots of Agricultural Production

Technical description of warning classification system version 1.0

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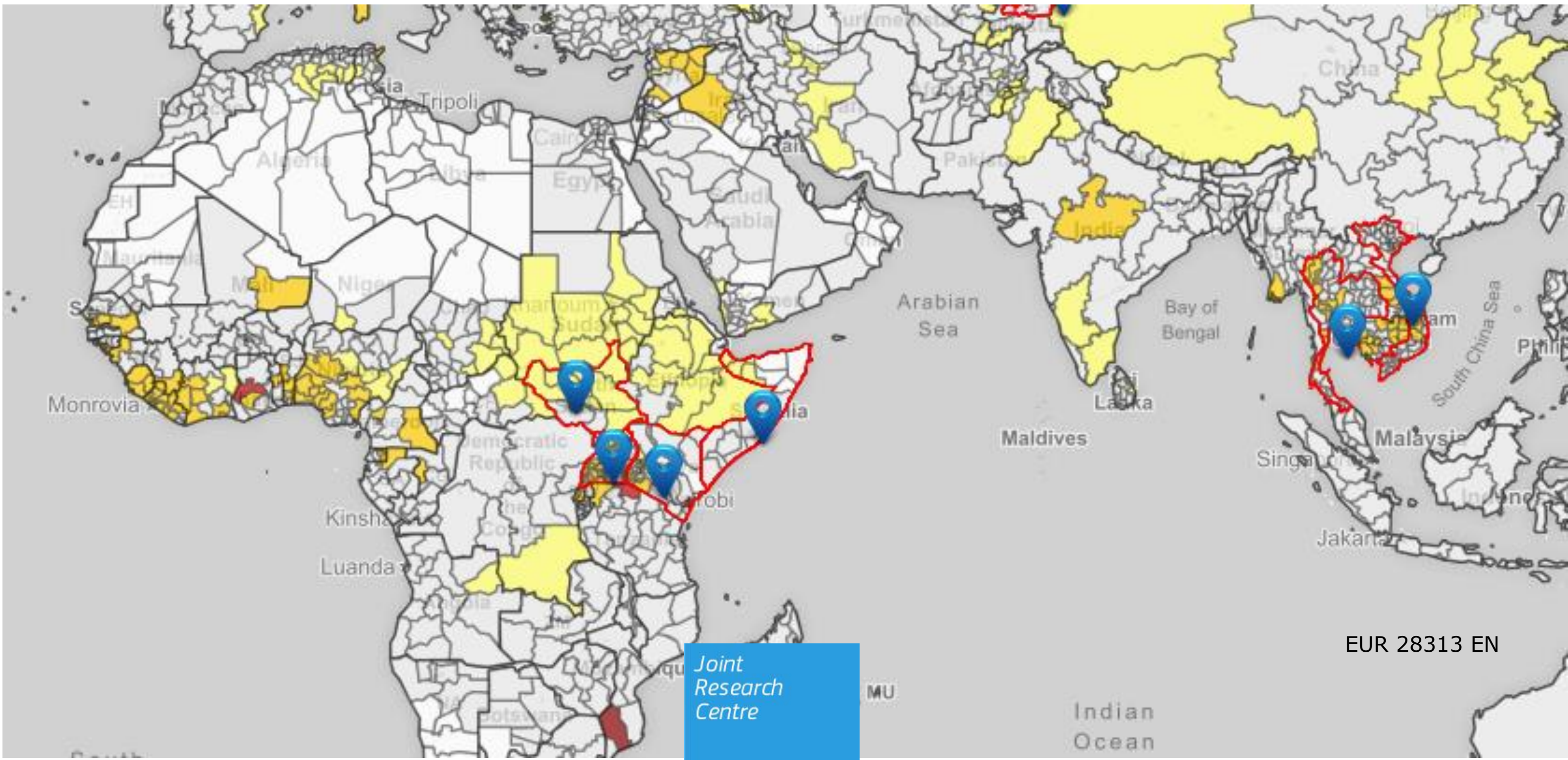

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Table of contents

Summary

Agriculture monitoring, and in particular food security, requires near real time information on crop growing conditions for early detection of possible production deficits. Anomaly maps and time profiles of remote sensing derived indicators related to crop and vegetation conditions can be accessed online thanks to a rapidly growing number of web based portals. However, timely and systematic global analysis and coherent interpretation of such information, as it is needed for example for the United Nation Sustainable Development Goal 2 related monitoring, remains challenging.

With the **ASAP** system (**Anomaly hot Spots of Agricultural Production**) we propose a two-step analysis to provide timely warning of production deficits in water-limited agricultural systems worldwide every month.

The first step is fully automated and aims at classifying each sub-national administrative unit (Gaul 1 level, i.e. first sub-national level) into a number of possible warning levels, ranging from "none" to level 4++. Warnings are triggered only during the crop growing season, as derived from a remote sensing based phenology. The classification system takes into consideration the fraction of the agricultural area for each Gaul 1 unit that is affected by a severe anomaly of two rainfall-based indicators (the Standardized Precipitation Index computed at 1 and 3-month scale), one biophysical indicator (the anomaly of the cumulative Normalized Difference Vegetation Index from the start of the growing season), and the timing during the growing cycle at which the anomaly occurs. The level (i.e. severity) of the warning thus depends on: the timing, the nature and number of indicators for which an anomaly is detected, and the agricultural area affected. Maps and summary information are published on a web GIS.

The second step, not described in detail in this manuscript, involves the verification of the automatic warnings by agricultural analysts to identify the countries (national level) with potentially critical conditions that are marked as "hot spots". This report focusses on the technical description of the automatic warning classification scheme version 1.0.

1 Introduction

Agricultural drought, with its negative effects on agricultural production, is one of the main causes of food insecurity worldwide. Extreme droughts like those that hit the Sahel region in the 70's and 80's, the Ethiopian drought in 1984 and the recent Horn of Africa drought in 2010/2011 have received extensive media attention because they directly caused hunger and death of hundreds of thousands of people (Checchi and Robinson, 2013). With the increased food prices in the first decade of the century (more than doubled according to Food and Agricultural Organization Food Price Index) and a continuously increasing demand for agricultural production to satisfy the food needs and dietary preferences of an increasing world population, drought is one of the climate events with the highest potential of negative impact on food availability and societal development. Droughts aggravate the competition and conflicts for natural resources in those areas where water is already a limiting factor for agriculture, pastoralism and human health. Climate change may further deteriorate this picture by increasing drought frequency and extent in many regions of the world due to the projected increased aridity in the next decades (Ipcc, 2013).

Crop failures and pasture biomass production losses are the primary direct impact of drought on the agricultural sector productivity. Drought-induced production losses cause negative supply shocks, but the amount of incurred economic impacts and distribution of losses depends on the market structure and interaction between the supply and demand of agricultural products (Ding et al., 2011). These adverse shocks affect households in a variety of ways, but typically the key consequences are on assets (United Nations, 2009). First, households' incomes are affected, as returns to assets (e.g., land, livestock, and human capital) tend to collapse, which may lead to or exacerbate poverty. Assets themselves may be lost directly due to the adverse shocks (e.g., loss of cash, live animals, and impacts on health or social networks) or may be used or sold in attempts to buffer income fluctuations, affecting the ability to generate income in the future.

One way to mitigate drought impacts relies on the provision of timely information by early warning and monitoring systems that can be used to ensure an appropriate response (Rembold et al., 2016). Obviously, even if the impact of a drought can be timely assessed, having an operational early warning systems in place is only a first step towards ensuring rapid and efficient response (Hillbruner and Moloney, 2012).

The Joint Research Centre (JRC) of the European Commission has a long standing experience in monitoring agriculture production in food insecure areas around the world by using mainly remote sensing derived and geospatial data. The first remote sensing based crop monitoring bulletin was published in 2001 for Somalia and was followed by similar products for other countries in East, West and Southern Africa over the following years. However, while this work addressed well country level information needs, the full potential of global data sets of remote sensing and weather information for monitoring agricultural production in all countries affected by risk of food insecurity, remained largely underexploited. Also, recent extreme climatic events with their impact on crop production in food insecure areas around the globe, such as for example the 2015/2016 El Nino, have confirmed how important it is to dispose of global early warning system. Finally the JRC is getting progressively more involved in global multi-agency networks for agricultural monitoring such as for example the Global Agriculture Monitoring Initiative (GEOGLAM), promoted by the G20 international forum as part of Group on Earth observations (GEO). This requires regular information to be made available for the two GEOGLAM flagship products, the Agricultural Market Information System (AMIS) crop monitor for main food producing countries and the Crop Monitor for Early warning for food insecure countries.

In order to fulfil the information needs of the Directorate General for International Cooperation and Development (DG DEVCO) of the European Commission for programming their food security related assistance and for making available timely early warning information to the international community, the JRC is developing an information system called ASAP (Anomaly hot Spots of Agricultural Production). ASAP addresses users with no expertise in processing remote sensing and weather data for crop monitoring and aims at directly providing them with timely and concise decision support messages about agricultural drought dependent production anomalies.

With ASAP we propose a two-step analysis to provide timely warning of production deficits in water-limited agricultural systems worldwide every month.

The first step consists in an automatic warning classification system aimed at supporting a more detailed agricultural analyst assessment at country level.

The goal of the warning classification algorithm is to quickly produce a reliable warning of hydrological stress for agricultural production at the first subnational administrative level (GAUL1), with a homogeneous approach at the global scale. This is achieved performing an automatic standard analysis of rainfall estimates and remotely sensed biophysical status of vegetation, based on the assumption that these indicators are closely linked to biomass development and thus, to crop yield and rangeland production. The result is summarised into a warning level ranging from none to 5. The system is mainly based on the time series analysis software SPIRITS (Software for Processing and Interpreting Remote sensing Image Time Series; Eerens et al., 2014) developed by the Flemish Institute for Technological Research (VITO) and JRC.

The second step involves the verification of the automatic warnings by agricultural analysts to identify the countries (national level) with potentially critical conditions that are marked as “hot spots”. In their evaluation, the analysts are assisted by graphs and maps automatically generated in the previous step, agriculture and food security-tailored media analysis (using the Joint Research Centre Media Monitor semantic search engine), and the automatic detection of active crop area using high resolution imagery (e.g. Landsat 8, Sentinel 1 and 2), processed in Google Earth Engine. Maps and statistics, accompanied by short narratives are then made available on the website and can be used directly by food security analysts with no specific expertise in the use of geo-spatial data, or can contribute to global early warning platforms such as the GEOGLAM, which perform a multi-institution joint analysis of early warning information.

In this contribution we describe the main features of the ASAP warning classification system version 1.0, currently at the operational test level[1]. Section 2 describes the spatial framework at which the classification system works. Section 3 lists the base information layer used for the classification. The method used is described in Section 4, introducing the reader to the pixel-level analysis (4.1) and the aggregation at the administrative level used to identify the warning level (4.2). Conclusions are drawn in Section 5 whereas near-future and long-term improvements of the classification methods are outlined in Section 6.

[1] At the time of writing (October 2016)

2 Data

Global early warning monitoring systems require timely and synoptic information about vegetation development (Rembold et al., 2015). Satellite products used for these purposes mostly refer to vegetation indices (e.g. the Normalized Difference Vegetation Index, NDVI) and biophysical variables (e.g. the Fraction of Absorbed Photosynthetically Active Radiation, FAPAR; the Leaf Area Index, LAI). Such products are mainly derived from space measurements in the visible to near infrared domain. Rainfall, a key driver of vegetation development especially in the water limited ecosystems targeted by ASAP, are often analysed to anticipate the effect of water shortage. In order to draw conclusions about the development of crops during an ongoing growing season, such key variables are analysed in near real-time and often compared with reference years (for instance, a past year known for having had abundant or poor crop production) or with their historical average (here referred to as the Long Term Average, LTA). The use of remote sensing time series for crop and vegetation monitoring typically requires a number of processing steps that include the temporal smoothing of the cloud-affected remote sensing signal, the computation of LTA and associated variability, the computation of anomalies, the detection of plant phenology and the classification of the productivity level on the basis of seasonal performances.

Data should therefore have a global coverage and high acquisition frequency. In addition a consistent archive of data records should be available to allow the computation of the LTA.

The automatic warning classification of ASAP V1.0 is based on 10-day rainfall estimate (RFE) products of the European Centre for Medium-Range Weather Forecasts (ECMWF) at 0.25° spatial resolution and observations of the Normalized Difference Vegetation Index (NDVI) from the MetOp mission at 1 km spatial resolution. Both sources are acquired with a 10-day frequency. ECMWF and MetOp time series are available from years 1989[2] and 2008, respectively. Satellite-based phenology is computed over a 16-year time series (1990-2014) of NDVI observations from the SPOT-VEGETATION (VGT) mission (same spatial and temporal resolution of MetOp). Both VGT and MetOp NDVI products are temporally smoothed with the Swets algorithm (Swets et al., 1999).

While the retrospective smoothing of past NDVI observations (with data points before and after the value to be smoothed are always available) is straightforward, near real-time (NRT) smoothing require special processing as no (or few) observations are available after the image of interest. Two main differences with respect to retrospective smoothing were implemented for the NRT smoothing.

First, differently from retrospective smoothing that is applied once and for all on the time series, NRT smoothing is repeated on the same image when a new observation is made available. With the employed Swets settings, five observations before and after the value to be smoothed are involved. This means that, being X the index of the current dekad (i.e. ten-day period, 36 dekads in a year), all the images from X-5 to X are subject to changes because of the smoothing operated at time X. This also imply that 5 smoothed versions of each dekad are generated and stored, and that each subsequent calculation made using the images subjected to changes is recomputed at each time step.

Second, some adaptation of the smoothing was implemented to deal with the possibility of having, as last observation, a non-valid value (i.e. the pixel is flagged cloudy or missing). In this case the smoothed value is not available or largely unreliable (if the extrapolate tails option is used). Both outcomes are suboptimal. The following procedure is applied to avoid the shortcomings described. We introduce an educated guess about the current missing value by adding to the previous valid observation (i.e. at X-1) the

[2] Original ECMWF data are available for a longer time span. We are referring only to the data used by the MCYFS (Mars Crop Yield Forecasting System)

LTA variation between X-1 and X. In other words, we assume average behaviour (increase vs decrease and magnitude) but we don't force absolute magnitude of NDVI.

Croplands and rangelands are identified using masks generated from the harmonized land cover/land use dataset of Vancutsem et al. (2013) and the FAO GLC-SHARE global land cover (Latham et al. 2014), respectively. The masks, derived from an original resolution of 250 m, are expressed at the lower spatial resolution of RFE and NDVI data as Area Fraction Image (AFI, i.e. the percentage of the pixel occupied by the given target).

3 Geographic coverage

The automatic classification capitalizes on the global availability of the climatic and remote sensing indicators and is produced globally. At the sub-national level all classified warnings are made available at the global level in a web-GIS page named "Near Real Time Monitoring Tool".

Concerning the final hot spot identification at the national level only, the automatic warning information produced for ca. 90 countries worldwide is retained and evaluated further by the analysts. These countries were selected in accordance with:

1.) the need of food availability information of the European Commission (EC) for countries where food security is a priority sector for the European Development Fund (EDF) programming;
2.) the aim of contributing to the GEOGLAM Crop Monitor for Early Warning which provides information for countries with a high risk of food insecurity.

The list includes most of the African continent and selected countries in Central America, Caribbean region, and Central and South East Asia.

3.1 Spatial framework

3.1.1 Spatial unit of analysis

National and sub-national boundaries rely on the Global Administrative Units Layers (GAUL) of the Food and Agriculture Organization of the United Nations. The base layer used by the classification system is the GAUL level 1 representing the first sub-national level administrative units. This level was identified as a reasonable compromise with regards to the trade-off between the need of analysing units with homogeneous agro-ecological characteristics (ideally small units) vs. the need of summarizing the results for a global outlook (ideally large units). In addition, working with administrative units has the advantage that they are well known and analysts can easily compare with other data normally available at the administrative level (crop types, calendars, area and yield statistics, etc.).

This layer has been adapted to the specific needs of the early warning system to form an ASAP unit, as follows:

- Small GAUL1 units are aggregated at the GAUL0 level (country level). In particular, when the average size of GAUL1 units within a GAUL0 is less than 5000 km^2, all GAUL1 units are merged together and the GAUL0 polygon is used as the ASAP unit. An exception to this rule is applied in Africa to avoid oversimplification in the main ASAP countries: merging is not applied if the GAUL0 size is greater than 25000 km^2.
- Suppression/merging of negligibly small ASAP units. All the resulting single polygons with a total area smaller than 200 km^2 are considered too small to be relevant at the working scale of ASAP and are thus merged with the neighbouring polygons (if possible, of the same country) or excluded (in case of islands).

- Total crop and rangeland areas are calculated per ASAP unit. GAUL0 units with crop/rangeland area < 1000 km^2 and GAUL1 units with crop/rangeland < 100 km^2 are excluded. Note that crop and rangeland are considered separately. So a Given GAUL0/1 may be excluded from the cropland analysis but not for the rangeland analysis, and vice-versa.

Finally, different layers with simplified geometries have been created to optimize visualization at different scales, but this does not impact calculation: simplified polygons are used for visualization purposes only.

3.1.2 Identification of water limited regions

Water, temperature and radiation are the main limiting factors to vegetation growth at the global level (Nemani et al., 2003). All limiting factors are indirectly covered by ASAP that uses NDVI (an index related to vegetation growth) and rainfall. In fact, negative NDVI anomalies indicate sub-optimal vegetation growth, independently from limiting factors. Therefore both temperature and radiation stresses are indirectly monitored by ASAP even if the two indicators are not used as input data.

In ASAP we focus on drought-related production deficit. As a consequence, we monitor precipitation in water-limited ecosystems with the aim of anticipating biomass development problems. On the contrary, the interpretation of RFE-based anomalies in non water-limited areas is not straightforward and may be misleading. Therefore, RFE are only used in ASAP in water-limited regions of the globe.

As a rough indicator of water-limitation we use the simplified annual climatic water balance, represented by the difference between the mean cumulative annual values of precipitation and potential evapotranspiration (similarly to the aridity index of UNEP; UNEP, 1992). A positive water balance indicates regions where water in not limiting factor, i.e. the evaporative demand is met by the available water. We thus use both indicators (RFE and NDVI) in countries where the annual climatic water balance (i.e. precipitation – potential evapotranspiration) is negative (Figure 1). Elsewhere, we only consider NDVI.

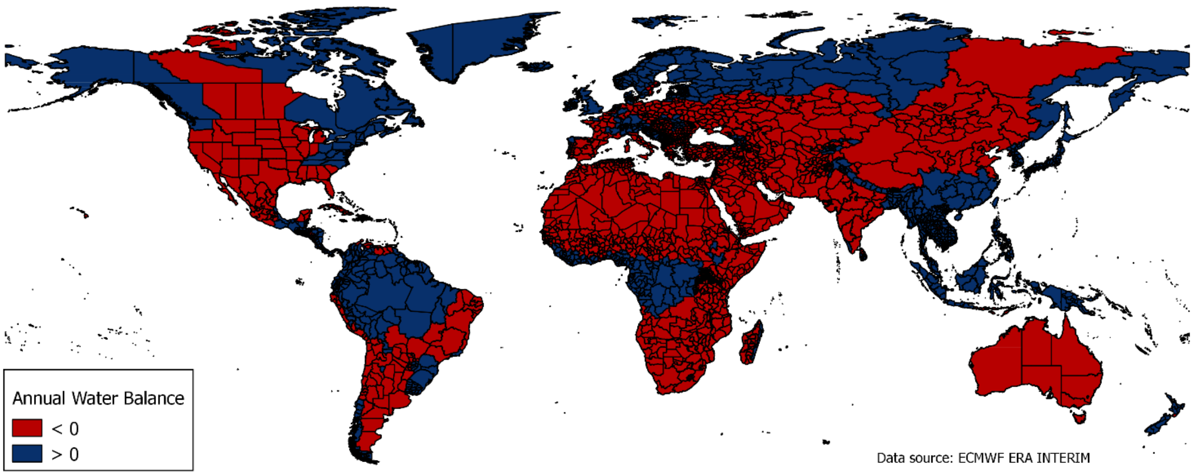

Figure 1. Annual climatic water balance. Data source: 10-day ECMWF ERA-INTERIM rainfall estimates and potential evapotranspiration, average computed over the period 1989-2014.

4 Methods

Although an ideal monitoring system would be crop specific, we recognize that crop specific global maps are not available. In addition, crop specific maps would need to be updated every year as crops location is not constant over time due to rotation practices, for instance. Therefore, our analysis is performed separately for cropland and rangeland areas. For simplicity and conciseness, in the following description we will refer to the cropland layer only.

As mentioned before, the warning classification is applied at the GAUL1 level. However, substantial processing is made at the pixel level to compute the indicators on which the classification is built upon. This processing is described in Section 4.1. Once the pixel-level indicators are computed, they are aggregated at the administrative unit and used in the classification for the warning (Section 4.2)

The ASAP software platform was developed using a combination of a large set of open tools, mainly PostgreSQL, PostGIS, SPRITS, Python, R, Geoserver, and OpenLayers.

4.1 Pixel-level analysis

The main indicators used by the classification system are computed at the pixel level whenever new observations become available (i.e. every 10-days). Indicators rely on the per pixel definition of the multi-annual average of phenology, described in the following section.

4.1.1 Computation of remote sensing phenology

The ASAP systems works with anomalies of basic indicators. Anomalies are simple statistics defined broadly as departure from the observed historical distributions. Obviously, at any place and any time of a time series, an anomaly can be computed. However, the interpretation of such an anomaly is relevant only in specific conditions. As mentioned, our analysis is restricted to cropland and rangeland areas using the appropriate masks. In addition, only anomalies occurring during the growing season should be retained. In fact, for instance, an NDVI anomaly during the winter dormancy of vegetation or in the period when fields are ploughed and bare soil exposed, carries little information. This is why we are interested in defining when vegetation grows.

To define the mean growing season period we use the satellite-derived phenology computed with the SPIRITS software on the long term average of SPOT-VEGETATION NDVI time series. The software uses an approach based on thresholds on the green-up and decay phase as described in White et al. (1997).

As a result of the phenological analysis, the following key parameters are defined for each land pixel: number of growing season per year (i.e. one or two); start of season (SOS, occurring at the time at which NDVI grows above the 25% the ascending amplitude); time of maximum NDVI; start of senescence period (SEN, when NDVI drops below 75% of the descending amplitude); and end of the season (EOS, when NDVI drops below 35%). Figure 2 provides a graphical representation of the phenological events.

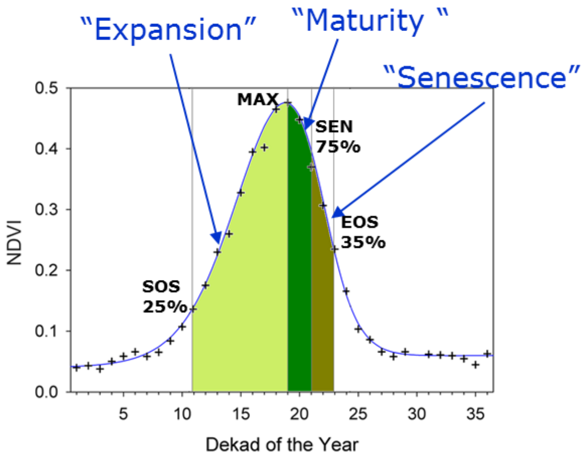

Figure 2. Graphical representation of the phenological events as derived by satellite data. Dekad stand for 10-day period. The period between SOS and MAX is referred to as "expansion", the one between MAX and SEN as "maturity", and the one between SEN and EOS as "senescence".

Using the phenological information we thus retrieve two phenological indicators that are then used in the classification: the progress of the season and phenological stage.

The progress of the season is expressed as percentage and represents the fraction of the length of the growing season that has been experienced at time of analysis. A progress of 50% thus indicate that at time of analysis, the pixel is half-way through the season. The phenological stage refers to the temporal location of the time of analysis within the succession of phenological events. The period between SOS and MAX is referred to as stage "expansion", the one between MAX and SEN as "maturity", and the one between SEN and EOS as "senescence".

4.1.2 Computation of indicators for the classification

The warning classification builds on anomaly indicators of RFE and NDVI products. All anomalies are expressed as standardized anomalies.

4.1.2.1 RFE-based

RFE data are used to compute the Standardized Precipitation Index (SPI, World Meteorological Organization, 2012), an index widely used to characterise meteorological drought at a range of timescales.

The SPI is a probability index that expresses the observed cumulative rainfall for a given time scale (i.e. the period during which precipitation is accumulated) as the standardized departure from the rainfall probability distribution function. The frequency distribution of historic rainfall data for a given pixel and time scale is fitted to a gamma distribution and then transformed into a standard normal distribution. We computed the SPI using data from 1989 to 2015 and two accumulation periods: one and three months. SPI1 and 3 (i.e. using 1 and 3 months accumulation period) are considered to account for a short and prolonged meteorological water shortage, respectively.

4.1.2.2 NDVI-based

Vegetation anomalies based on biophysical indexes (such as NDVI) can be computed by looking at the value of the index at the time of analysis or at its cumulative value from SOS to time of analysis. Both approaches have pros and cons (Table 1). In ASAP we do compute both type of anomalies but we restrict the analysis to the cumulative ones in the classification system.

Table 1. Pros and cons of using a single snapshot at time of analysis vs. integrated value from SOS

	Time of analysis	Cumulative value from SOS
Pros	Quick response in case of abrupt disturbance	Reduced sensibility to noise when the indicator when season progresses
	Easy computation	More robust to false alarms (anomalous NRT values, typically low because of undetected clouds)
		Proxy of seasonal productivity (Prince, 1991)
		Overall view of the season
Cons	Quick response to noise (present because of poor NRT smoothing)	Relatively insensitive to actual disturbances at large progress of season
	Temporal snapshot only	

Two NDVI-based indicators are computed:

- zNDVIc, the standardized score of the cumulative NDVI over the growing season
- mNDVId, the mean of the difference between NDVI and its long term average over the growing season

The two indicators are defined by the following equations.

$$NDVIc(t) = \sum_{SOS}^{t} NDVI(t) \qquad (1)$$

$$zNDVIc(t) = \frac{NDVIc(t)-\mu_{NDVIc}(t)}{\sigma_{NDVIc}(t)} \qquad (2)$$

$$mNDVId(t) = \frac{\sum_{SOS}^{t}(NDVI(t)-\mu_{NDVI}(t))}{n} \qquad (3)$$

Where t refers the time of analysis (current 10-day period), SOS is the start of season, $\mu_{NDVIc}(t)$ and $\sigma_{NDVIc}(t)$ are the mean and the standard deviation of NDVIc at time t, $\mu_{NDVI}(t)$ is the mean of NDVI at time t, and n is the number of 10-day periods from SOS to t. The values of the means and standard deviation are derived from the multi-annual archive of NDVI observations

4.1.2.3 Thresholding of indicators

Being interested in the area that is affected by a severe anomaly, we proceed as follows. Once the images the various indicators are computed, we produce three Boolean masks indicating per pixel if the indicator value is to be considered "critical". As the three indicators (SPI1, SPI3, and zNDVIc) are all standardized variables, we use a threshold of -1 (i.e. values smaller than this threshold are considered critical), corresponding the lowest 16% of observations (under assumption of normal distribution). In this way, each pixel in a given GAUL1 is classified as critical (or not) for SPI1, SPI3 and zNDVIc.

In order to avoid flagging as critical those vegetated pixels with reduced variability (i.e. small σ), where an anomalous zNDVIc may not represent a problem, we also consider the mean of the difference between NDVI and its long term average over the growing season (mNDVId). Thus, pixels having a zNDVIc value smaller than the threshold are flagged as critical only if also their mNDVId < -0.05.

In addition to that, we also consider large positive anomalies of zNDVIc (i.e. > 1) to flag the pixel as "exceptional conditions". Once again, a pixel is flagged only if the condition on mNDVId also holds (mNDVId > 0.05).

4.2 GAUL1-level classification

The information about the area affected by the various types of critical anomalies is summarised at the GAUL1 level for croplands and rangelands separately. For brevity and conciseness, when describing examples in the following, we refer to cropland only.

4.2.1 Operations in the spatial domain

We only consider cropland and rangeland areas, separately. Anomalies occurring outside such targets are neglected. All subsequent calculations are made on area fraction image (AFI) masks. Thus, for instance, the extent of the crop area exceeding a given threshold is not simply the total number of the crop pixel but the weighted sum of their AFIs. Note that to ensure consistency between the two different resolutions used (1 km MetOp NDVI and 25° ECMWF RFE), the coarser resolution data is resampled to the 1 km grid of MetOp using nearest neighbour resampling. This does obviously not create a higher resolution data layer, but allows for applying the same processing to the 2 data sources.

4.2.2 Time domain

4.2.2.1 Pseudo dynamic masks and active season

As mentioned, the crop and rangeland masks are used to aggregate the values of a given indicator at the administrative unit level. For instance, if we are interested in retrieving the mean crop NDVI value for a given GAUL1, we may compute the weighted mean of NDVI over the pixels belonging to the crop mask. The weighting factor will be the AFI of each single pixel involved in the calculation. However, in this way we would consider all the crop pixels, regardless the time of analysis *t*. This implies that we may consider the NDVI value of pixels that are located in an area used for crop production also in the periods of the year were the crop is not growing at all. To avoid such simplification we use the phenology information described in section 4.1.1. Therefore, although we use static crop and rangeland masks as base layers, we "switch on and off" the property of being an active crop (or a rangeland) at the pixel level according to the pixel mean phenology. In this way we obtain 36 pseudo dynamic crop masks, one per each dekad of the year, indicating per pixel the presence of crop (or rangeland) in its growing season period. An example on synthetic data of the evolution of pseudo dynamic masks is provided in Figure 3.

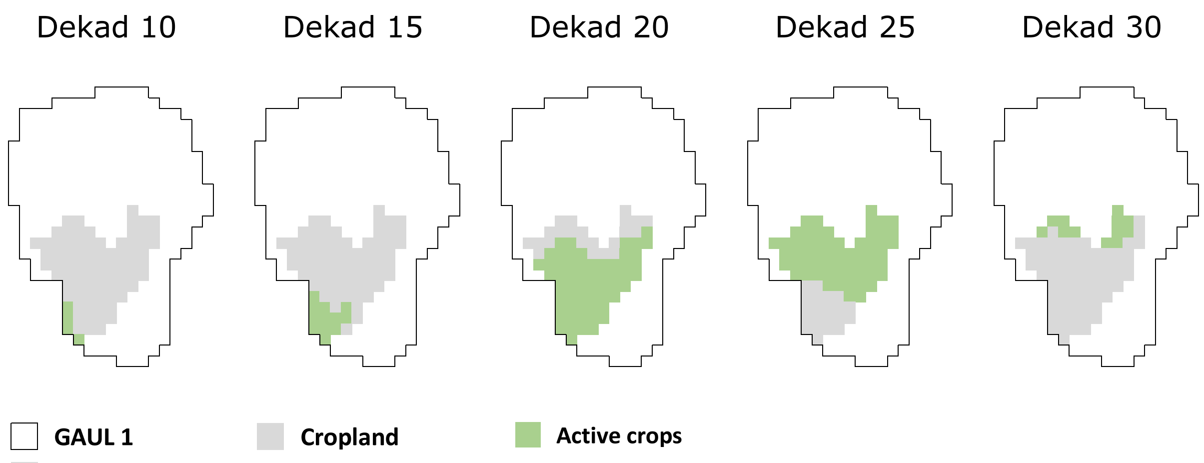

Figure 3. Graphical representation of pseudo dynamic crop masks. The panels show the static crop mask in grey and the temporal evolution of the pixels being labelled as active crop by the pseudo dynamic masks at selected dekads.

For a given GAUL1 and time *t* of analysis, the classification is started only when the time *t* is within the multi-annual average period of the growing season for at least 15% of the total crop area (Figure 4). This rule excludes that anomalies occurring outside the main growing season are considered to be relevant.

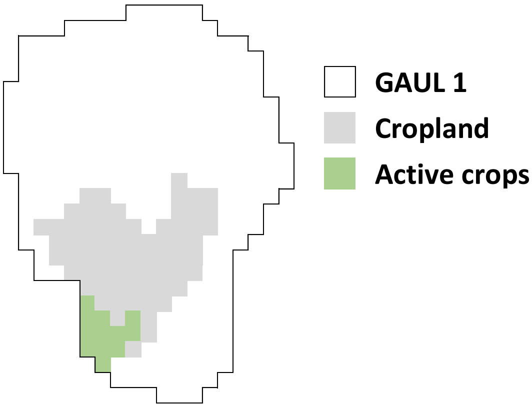

Figure 4. Graphical representation of the condition needed to start the classification at time t: 15 % of the cropland area is "active" (SOS<t<EOS).

For the whole period characterized by active pixels covering a fraction of more than 15% of the cropland area, the unit is considered active.

It is noted that, as a result of such rule, the active period of an administrative unit may be perceived to be longer than "expected", as the analysts reported.

The origin of this effect is explained in Figure 5 (based on synthetic data). Despite the fact that the mean season length is 15 dekads (the active period "expected" by the analyst), there is variability in SOS (and hence in EOS). As a results, 15% of the areas is active for a periods of 20 dekads.

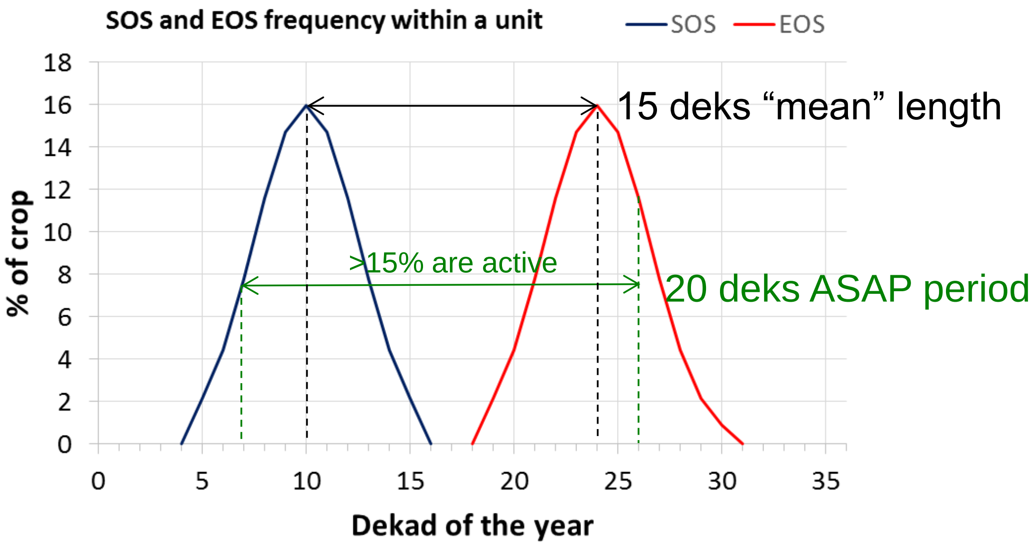

Figure 5.Frequency histogram of SOS and EOS for a hypothetical unit shown to explain the active period.

Finally, the presence of double growing season within the solar year (discussed in Section 4.2.2.2) may further increase the active period.

4.2.2.2 GAUL1 progress of the season and phenological stage

Mono- and bi-modal seasons (i.e. one and two growing cycles per solar year) may be present within the administrative unit. Although a dominance of one of the two modality can be expected, it cannot be excluded that, particularly for large ASAP units, both modality can be present at the same time.

As a reference for the entire unit we compute the median progress of the season of the administrative unit and the modal phenological stage (expansion, maturity and senescence). So, albeit two seasons with different modality may be present at the same time and with different progress (e.g. the mono-modal in maturity and the bi-modal in expansion), we will report the median progress (in %) and modal phenological stage. This timing will be thus related to most represented (in terms of area of active pixels) of the two. This "merging" of the two seasons was conceived in order to avoid treating mono- and bi-modal separately, with the consequence of having 4 targets by administrative unit, crop/rangeland, mono-/bi-modal.

The phenological stage has an effect on the warning level. In fact, during senescence, rainfall based indicators do not trigger a warning and only NDVI is used, as rainfall has little importance on crops during this phenological stage (although too much rainfall could cause high moisture in harvested grains).

In addition, a cumulative NDVI trigger during senescence is not a warning anymore, it is an ascertainment of a season failure.

4.2.3 Determination of critical area fraction by indicator

The warning level is based on the fraction of the area (of pixels having an ongoing growing season) being subjected to the different critical anomalies (SPI1, SPI3, and zNDVIc).

In this way we aim at detecting unfavourable growing conditions that may represent a food security problem. We thus trigger a warning only if two conditions on the anomaly are met: 1) the interested area is subjected to a severe negative anomaly in one or more indicators and 2) the area concerned by the anomaly is relevant.

It is noted that, by taking the overall mean of the anomaly we would instead mix the two components. For instance, a negative anomaly affecting 30 % when the other 70 % is rather positive, would result in a "normal" average.

We thus compute the critical area fraction (CAF) as the number of pixels flagged as critical over the total number of pixels with an active growing season at time of analysis:

$$CAF_x = critical\_area_x \,/\, active\_area \qquad (4)$$

The subscript x refers to the indicator considered (x = SPI1, SPI3, zNDVIc). Note that all calculation are made taking AFI into account.

4.2.4 Determination of exceptional area fraction for zNDVIc

As a positive anomaly in zNDVIc is univocally interpretable as favourable growth, we keep track of this possible event. In a similar way to CAF computation described in the previous section, we also compute an exceptional area fraction for zNDVIc only, i.e. area subjected to large zNDVIc positive anomaly (as defined in Section 4.1.2.3) divided by the total active area).

4.2.5 Warning level definition

A CAF_x > 25% (i.e. one quarter of the active area) will trigger a warning for that ASAP unit. In order to avoid triggering a warning when CAF is above the threshold but represents only a small area we suppress all the warning for which none of the various CAF_x exceed minimum area threshold (100 km^2). In other words, only warnings having at least one CAFx exceeding the minimum area are triggered. Table 2 summarizes all the thresholds used in the warning classification system.

Table 2 List of variables and thresholds used by the warning classification system.

Name	**Units**	**Meaning**	**Function**	**Value**
Pixel-level settings. Parameters used in the computation of the pixel-based phenology				
SOS_fract	[-]	The season starts when the NDVI profile crosses this fraction of the amplitude in the growing phase	Determine SOS. The current set of phenology related threshold values was empirically determined with a trial and error process.	0.25
EOS_fract	[-]	Season ends at this fraction in the decay phase		0.35
SEN_fract	[-]	The senescence period starts at this fraction in the decay phase		0.75
Pixel-level settings. Thresholds used to label a pixel as "critical" or "exceptional" on the basis of the value (original value and standardized value) of the selected indicator. SD stands for standard deviations.				
CT_zNDVIc	SD	Detection of anomalous negative condition	Below this threshold the pixel is flagged as "critical" for zNDVIc (standardised cumulative NDVI over the season)	< 1
CT_mNDVId	NDVI units	Detection of anomalous negative condition	Below this threshold the pixel flagged as "critical" for mNDVId	<-0.05
ET_zNDVIc	SD	Detection of anomalous positive condition	Above this threshold the pixel flagged as "exceptional" for zNDVIs	> 1
ET_mNDVId	NDVI units	Detection of anomalous positive condition	Above this threshold the pixel flagged as "exceptional" for mNDVId	> 0.05
CT_SPI	SD	Detection of anomalous negative precipitation	Below this threshold the pixel flagged as "critical" for SPI (Standardized Precipitation Index)	< 1
Administrative unit level settings. Thresholds on the fraction of the total and of the active area. They are used to determine the warning classification and to define Critical Area Fractions.				
RUN_ACT_PC	%	Percent of active pixels with respect to total (crop or rangeland mask ∩ active area from average phenology)	Above this fraction of active pixels, the warning classification is performed.	> 15%
CAFT1, CAFT2, CAFT3	%	Percent of active pixels labelled as "critical" over the total active pixels for indicators NDVI, SPI1, and SPI1	Trigger a warning level 2 to 5	25
AFTp	%	Percent of active pixels labelled as "critical" obtained by for the spatial union of all warnings	Trigger a warning level 1	25
MTAT1	km^2	Minimum total area being labelled as "critical" by an indicator to trigger a warning	Suppress the warning if the total area is below this threshold.	100

The level of the final warning depends on which indicators have a CAF exceeding the threshold and the modal phenological stage of the crop. To establish the final warning level, in our classification scheme we put emphasis on the relative importance of the various indicators and their agreement. We acknowledge that rainfall is the main driver of crop and rangeland growth and that NDVI is the result of such a driver (plus other perils other than drought), so we rank the RFE and NDVI anomaly events with increasing warning level (
Table 3).

Table 3. ASAP warning levels as a function of the warning source (i.e. indicator with Critical Area Fraction, CAF, exceeding the 25% threshold) and phenological phase at which the warning occurs. The symbol U *is to the spatial union operator while the symbol & is the logical* AND *operator.*

Warning source	**Warning level** by warning source and pheno-phase at which it occurs	
(Indicator with CAF > 25%)	***Expansion OR maturity***	***Senescence***
zNDVIc +	**Exceptional conditions**	**Exceptional conditions**
none	**-**	**-**
SPI1 U SPI3 U zNDVIc	**1**	**-**
SPI1	**2**	**-**
SPI3	**2+**	**-**
SPI3 & SPI1	**2++**	**-**
zNDVIc	**3**	**-**
zNDVIc & SPI1	**4**	**-**
zNDVIc & SPI3	**4+**	**-**
zNDVIc & SPI3 & SPI1	**4++**	**-**
zNDVIc	**-**	**5**

The warning level 1 can be considered as pre-warning as it is triggered when it is the spatial union (symbol U in the table) of the critical areas of all the three indicators that is exceeding the threshold of 25%. That is, none of the CAF_x exceeds the area threshold, but the total area affected by a critical indicator does. In other words, when the level 1 is triggered, the analyst knows that 25% of the crop area is affected by one or more critical indicators. The spatial union of the critical indicators is used to avoid double counting of areas being subjected to more than one critical indicator.

Levels from 2 to 2++ are issued by rainfall-based indicators. The lowest level in this group (level 2) is triggered by a deficit in the last month (i.e. SPI1) while the intermediate level (2+) is triggered by a more prolonged deficit (during the last three months, SPI3). The highest level of the group (2++) is assigned to the co-occurrence of the two conditions: a relatively long lasting deficit (SPI3) that is confirmed in the last month (SPI1).

An increased warning level (3) is assigned to the NDVI indicator as it shows that the growth of the vegetation has been affected, regardless of the causes.

It is recalled here that, as mentioned in Section 4.1.2.3, a critical zNDVIc is counted at the pixel level only if also mNDVId is critical.

The level 4 (ranging from 4 to 4++) is assigned to the co-occurrence of NDVI- and rainfall-based indicators with a similar logic that was used for the sub-levels of level 2 group.

The occurrence of a positive anomaly in zNDVIc is also represented in ASAP. As such occurrence does not represent a deficit, no numeric warning level is assigned to it and the event is simply labelled as "exceptional conditions". It is noted that the same ASAP unit may present simultaneously an "exceptional condition" and a warning.

Finally, the table shows that, during senescence, rainfall-based indicators do not trigger a warning and only NDVI is used because as rainfall deficit has little importance on crops during this phenological stage.

Concerning warning levels, it is interesting to observed that, besides the warning level issued for an ASAP unit at a given time of the year, additional valuable information may be extracted from the analysis of the evolution of the warning level in the preceding dekads. For instance, a persistency of warning of group 2 for some dekads may be regarded as more reliable than a first appearance of that warning level for the current dekad. Another example: a warning level 5 preceded by various warning levels in the previous dekads. In order to facilitate such analysis, when a warning is triggered, a matrix showing the temporal evolution past warnings is produced (an example is given in Figure 6).

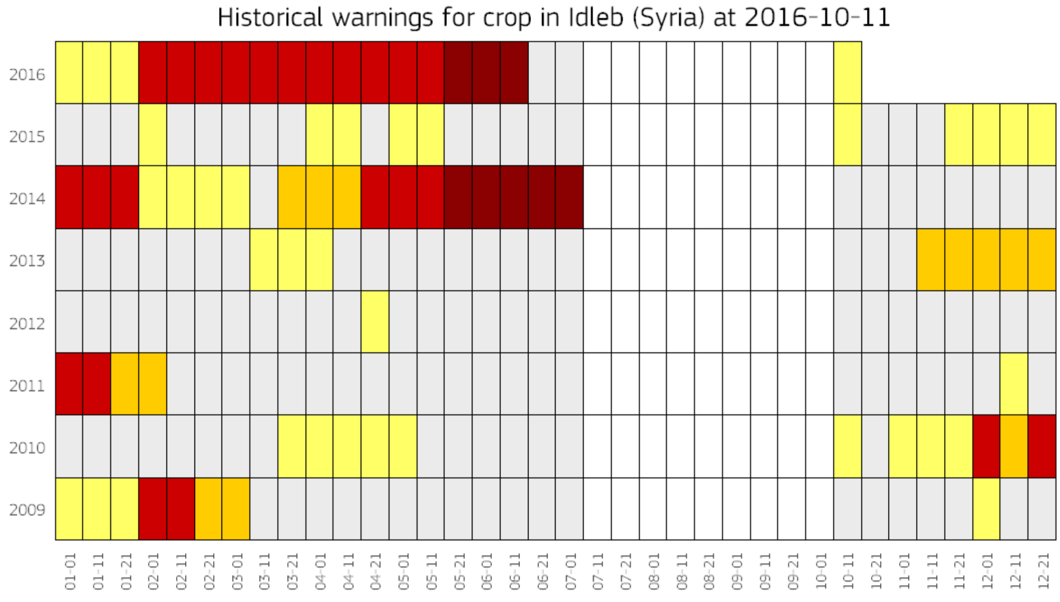

Figure 6. Example of historical warning matrix.

5 Results

An example of the result of the warning classification system is presented in Figure 7 for the time of analysis referring to 01/07/2016. ASAP units showing high levels of warnings are visible in southern Africa, affected by El Niño-related drought.

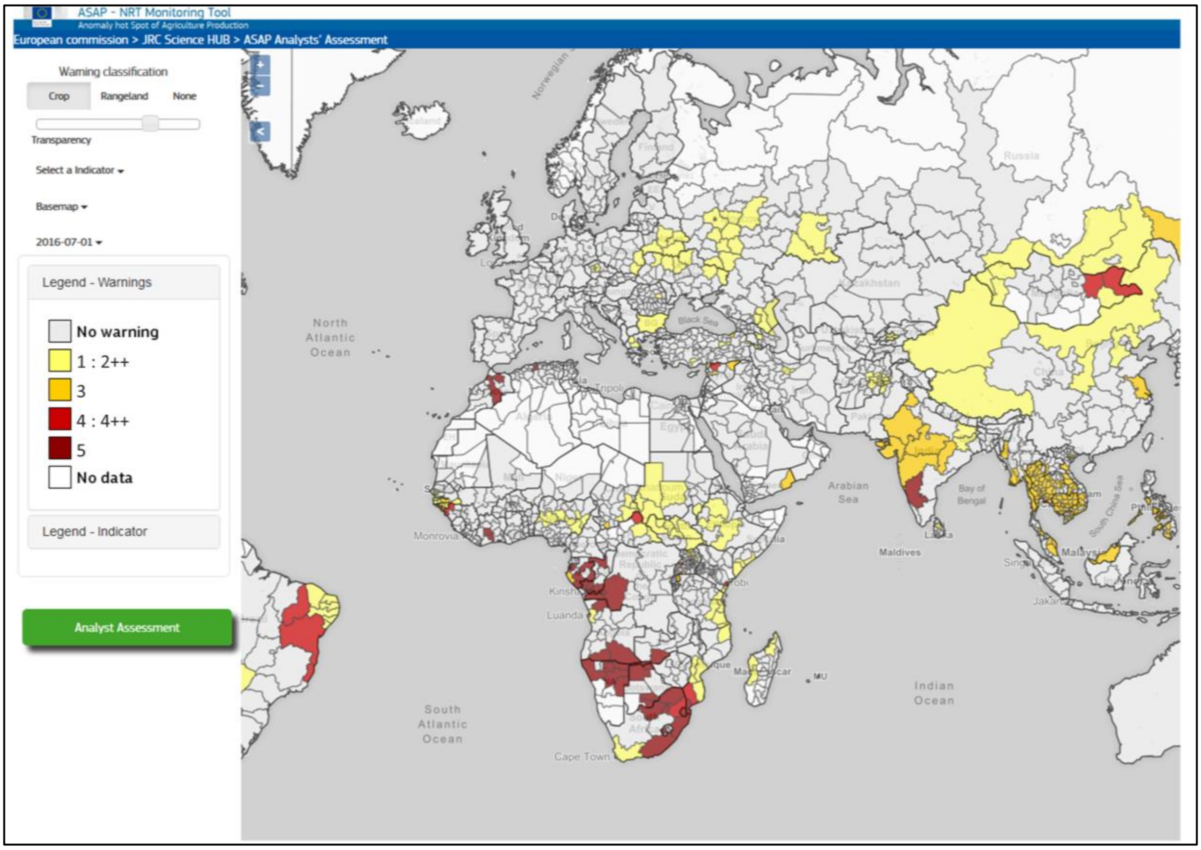

Figure 7. Example of warning classification referring to the time of analysis 01/07/2016.

Examples of different warning levels, as they are graphically represented in the web GIS, are given in Figure 8 to Figure 11.

Figure 8 shows an example of level 1 warning in Ethiopia (GAUL1 Amhara). At the time of analysis (01/07/2016) 77% of the crop area was active, 100% of the active crops were in the phenological stage of growth (right panel) with a median progress of the season of 15%. None of the critical areas concerned by the various indicators (left panel) is above the 25% threshold. The level 1 warning was originated by the spatial union of the critical areas that resulted in a 26% of the crop area affected by one or more indicators. Interestingly, a 20% of the total crop area showed a positive zNDVIc anomaly (> 1). This observation points out the difference between the ASAP approach (focussing on percentage area affected by a severe negative anomaly) and the traditional approach of averaging the anomaly over the unit of interest. Whereas a low level warning is issued by the classification system in this example, a compensation between the areas with positive and negative anomalies would have depicted with the average approach a normal condition for the administrative unit. Obviously the size of GAUL1 units inside and across countries is still highly variable, meaning that especially for large areas it remains difficult to get warnings if only a small part of the province is affected by a rainfall anomaly.

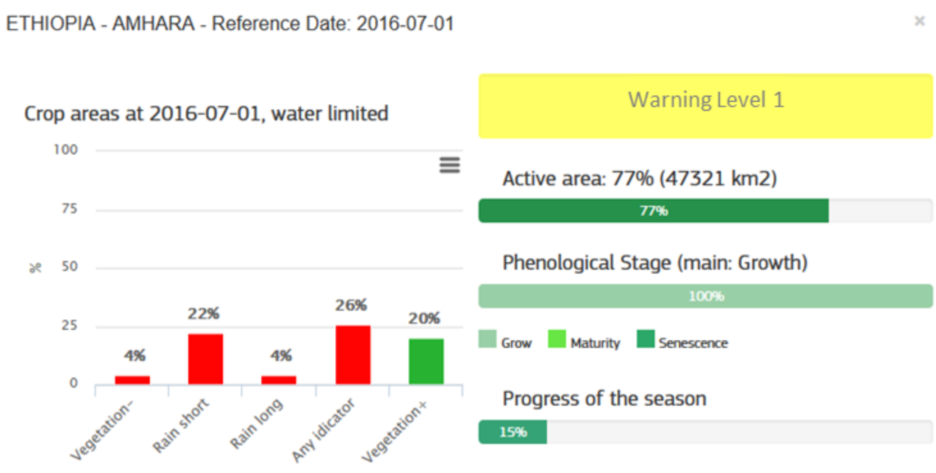

Figure 8.Example of a warning level 1 for crops. The left panel shows in red the critical area fraction for zNDVIc ("Vegetation-"), SPI1 ("Rain short"), SPI3 ("Rain long"), the spatial union of the previous three ("Any indicator"), and in green the exceptional area fraction ("Vegetation +"). The active area, the fraction of the active crops in each of the three phenological stages, and the mean progress of the season.

Figure 9 show an RFE-based warning (both SPI1 and SPI3 CAFs exceeding the threshold) for the GAUL1 unit Lindi in Tanzania. 98% of the crop area is in the maturity stage and already 80% of the growing season has passed. The analyst may thus consider that, although a large fraction of the crop area is presenting critical rainfall deficits (57% for the 3 month SPI and 31% for the 1 month SPI, thus with an improvement in the last month), the NDVI does not appear to be affected (only 2% of the area is critical for zNDVIc). This could mean for example that the rainfall deficit occurred at an advanced stage of maturation, when there was still a certain moisture reserve in the soil and the plants were therefore not strongly affected. This hypothesis is confirmed by the fact that the season later finished with no warning.

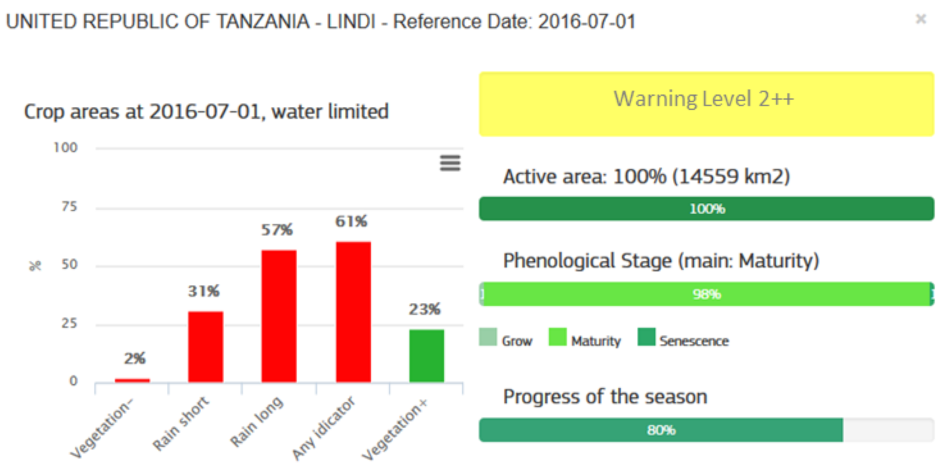

Figure 9. Example of a warning level 2++ for crops. For a description of the figure elements refer to Figure 8.

Figure 10 and Figure 11 show two warning levels (4+ and 5, respectively) for which both NDVI- and RFE-based critical area fractions exceed the 25% threshold.

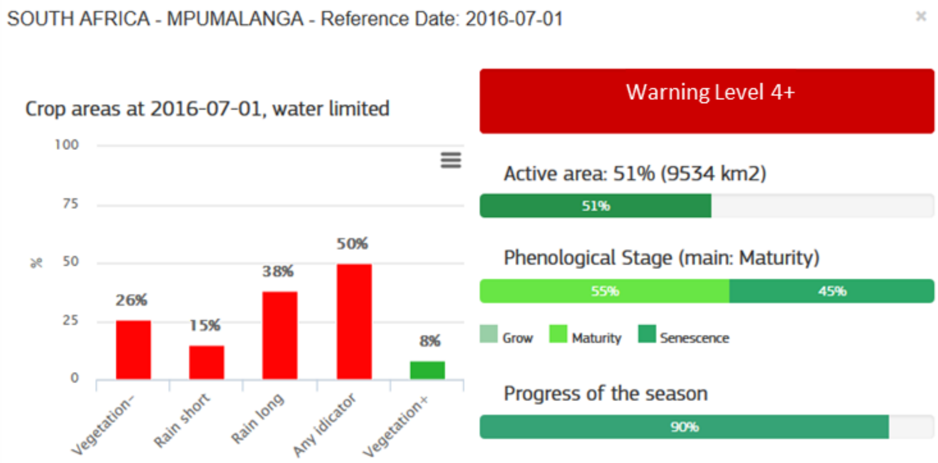

Figure 10. Example of a warning level 4+ for crops. For a description of the figure elements refer to Figure 8.

The main difference between the two is that the warning of Figure 11 is issued when the crops are mostly in their phenological stage of senescence. Thus, RFE-based indicators are not considered. Level 5 warning in fact informs the analyst that the season is turning to an end and that NDVI observations indicate a season failure (for 71% of the crops in this case).

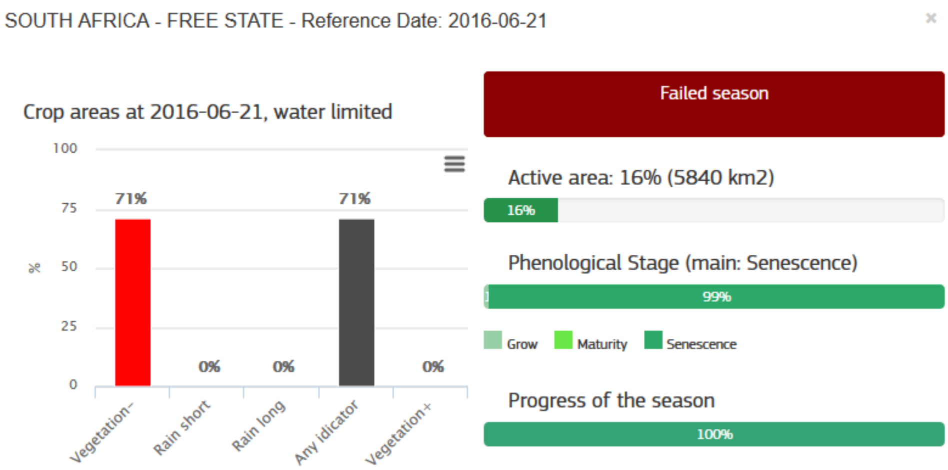

Figure 11. Example of a warning level 5 for crops. For a description of the figure elements refer to Figure 8. As the unit stage is senescence, the RFE indicators are not considered and greyed out in the left panel. Note that the warning classification is shown for this GAUL1 at time of analysis 21/02/2016.

It is noted that, when the warning is triggered and submitted to the analysist, the interpretation of the warning (and thus its suppression or promotion to global hot spot level status) is supported by other sources of information (see Section 1). In addition it is noted that global hot spots are identified at the GAUL0 level (the country level). Scaling from GAUL1 warning to GAUL0 hot spot is responsibility of the analyst that will consider several factors, including the severity of the warning, the crop calendars, the areas affected, and the number and importance of the GAUL1 units triggering a warning.

6 Conclusions

The classification system of ASAP V 1.0 automatizes the basic analysis of rainfall and NDVI data, with the goal of spotting - and highlighting to analysts - critical situations for crop and rangeland growth.

The classification system is currently fully operational and is being tested by agriculture analysts in the JRC. The hotspot map and overview based on analyst assessment will become regularly available from the beginning of 2017 and will be updated monthly between the 20th and the end of each month. At the same time the web GIS with the warning classification for each GAUL1 unit at the global level will also become publicly available. The more detailed information based on high resolution data processing for specific warnings will only become available at a later stage.

7 Way forward

Various modifications are currently being implemented to the automatic warning classification system V 1.0 These include: *i)* the update of the current cropland and rangeland masks using an optimal region-specific selection of available global and regional land cover products; *ii)* inclusion of the Global Water Requirement Satisfaction Index (a soil water balance models aligned to the ASAP phenology) as indicator; and *iii)* replacement of MetOp NDVI time series with Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI, filtered for optimal noise removal in NRT application (Klisch and Atzberger, 2016). The Water Satisfaction Index is expected to be more closely related water stress experienced by crop and rangelands, while the currently used SPI is only a climatic anomaly, not capturing rainfall deficit on vegetation. The improved NDVI provided by Klisch and Atzberger is expected to improve the early warning capacity of the system as opposed to the currently used NDVI, where the currently employed smoothing algorithm can still not completely remove cloud and atmospheric related noise.

Further developments of the ASAP system are envisaged for the near future. For example RFE based on infrared satellite measurements (e.g. Climate Hazards Group InfraRed Precipitation with Station data, CHIRPS) may be used to replace ECMWF model estimates. Anomalies of the Land surface temperature (LST) derived from satellite observations (e.g. MODIS) may be included to extend the range of limiting factors considered.

Additional and complementary information to be passed to the analysts together with the warning is also under test. Information about the delay of the start of the season, as derived from the NRT phenology retrieval, would complement the information provided by the NDVI anomaly, informing the analyst about the origin of observed anomalies (i.e. delay of the start vs. poor season started). Finally, the full automatization of the VHR analysis (now performed on ad hoc basis) would allow, thanks to the comparative analysis of the frequency distribution of NDVI values for different years, to disentangle the effect of a relatively poor season affecting all the area and those of a complete crop failure affecting partially the unit of interest.

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List of acronyms

AFI	Area Fraction Image
AMIS	Agricultural Market Information System
ASAP	Anomaly Hot Spot of Agricultural Production
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CTA	Critical Area Fraction
DG DEVCO	Directorate General for International Cooperation and Development
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EOS	End of Season
GAUL	Global Administrative Unit Layer
GEO	Group on Earth observations
GEOGLAM	Global Agriculture Monitoring Initiative
GIS	Geographic Information System
JRC	Joint Research Centre
LST	Land Surface Temperature
NDVI	Normalized Difference Vegetation Index
RFE	Rainfall Estimates
SD	Standard Deviation
SOS	Start of Season
SPI	Standardized Precipitation Index
SPIRITS	Software for Processing and Interpreting Remote sensing Image Time Series

List of figures

List of tables

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