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Agron. Sustain. Dev. 25 (2005) 63–77

DOI: 10.1051/agro:2004056

Research article

Real-time agrometeorological crop yield monitoring in Eastern Africa

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(Received 24 March 2003; accepted 7 September 2004)

Abstract – The Joint Research Centre (JRC), in collaboration with the Food Agriculture Organization (FAO), has developed for East Africa an operational crop yield monitoring and forecasting system (CYMFS). The CYMFS integrates into a Geographical Information System (GIS): the meteorological information of the European Centre for Medium-Range Weather Forecast (ECMWF), the Crop-Specific Water Balance (CSWB) model, and the Crop Production System Zones database (CPSZ). Additional and independent real-time satellite data from SPOT VEGETATION were analyzed using a specific crop mask to concentrate the analysis only on agricultural areas. This approach gives to the food analyst a qualitative picture of crop yield expectation for rain-fed crops at different stages of the growing season. The proposed methodology was applied to the first crop season of 2001 and 2002 and demonstrated a clear potential in crop monitoring and yield forecasting. The results obtained during the extremely dry year of 2002 proved that the crop monitoring system was timely and geographically precise. A new crop cycle progress index (CCPI) was developed to take into consideration the agro-ecological heterogeneity of the region.

crop monitoring / yield forecast / MARS project / early warning / food security

1. INTRODUCTION

1.1. Institutional background

The Monitoring Agriculture with Remote Sensing project (MARS) of the Joint Research Centre, European Commission, has developed a system for the early assessment of the main crops in Europe. The objective of the activity is to provide timely, independent and objective yield estimates to the European Commission services in charge of the Common Agricultural Policy (Directorate General Agriculture) and of the European Union agricultural statistics (Eurostat).

More recently, MARS-FOOD has focused on countries outside Europe. The activities are aimed at improving methods and information on crop yield prospects in countries where food insecurity problems exist or may arise. This activity mainly supports the Food Aid and Food Security policy of the European Commission (Directorate General EuropeAid). The CYMFS activity in Eastern Africa is carried out in close collaboration with the Food and Agriculture Organization (FAO) of the United Nations, where the main FAO services concerned are the Environment and Natural Resources Services (SDRN) and the Global Information and Early Warning System (GIEWS).

Objective

This paper presents a methodological approach on real-time crop yield monitoring in Eastern Africa. The approach is based on the agrometeorological FAO water balance model using the meteorological information of the European Centre for Medium-Range Weather Forecast (ECMWF). The main purpose is to develop a tool that routinely informs the food analyst about the yield expectation in the region. At the first stage the tool will give more qualitative than quantitative information, describing the impact of climate on the crop yield. In the second stage, the tool will be calibrated against historical yield series in order to get more quantitative information. A complementary analysis of the satellite data from SPOT VEGETATION contributes to the description of the current crop situation.

1.2. Eastern Africa, IGAD Sub-region

"The seven East African states (Fig. 1) which make up the Intergovernmental Authority on Development (IGAD sub-region), Djibouti, Eritrea, Ethiopia, Kenya, Somalia, Sudan and Uganda, cover an area of 5.2 million square km and have a total population of more than 160 million people. The average population growth ratio, of 2.5%, is one of the highest population growth rates in the world and nearly half of the population is under 14 years of age (Tab. 1).

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Figure 1. Intergovernmental Authority on Development (IGAD) countries: Djibouti, Eritrea, Ethiopia, Kenya, Somalia, Sudan and Uganda.

Table I. Comparative physiographic and demographic data of Intergovernmental Authority on Development (IGAD) States.

Country	Population Millions	Population Growth (annual in %)	Area (km^2)	GNP/ Inhab. (US$)	Rural Pop. (%)
Djibouti	0.6	4.0	23 200	880	16.7
Eritrea	4.1	2.7	117 600	170	81.3
Ethiopia	64.3	3.0	1 100 000	100	82.4
Kenya	30.1	3.6	580 400	350	66.9
Somalia	8.8	1.6	637 760	110	72.5
Sudan	31.1	2.9	2 500 000	310	63.9
Uganda	22.2	3.5	241 000	300	85.8
Total	161.2	Av. 2.5	5 199 960	Av. 317	Av. 67.1

Source: The World Development Indicators Database of the World Bank as of April 2002.

The sub-region is prone to recurrent severe droughts which hamper crop and livestock production, and coupled with rampant insecurity and other natural and man-made disasters, has resulted in food deficits each year, thus making the IGAD sub-region one of the most food-insecure regions. About 80 percent of the IGAD sub-region is classified as arid and semi-arid lands (ASALs) and sub-humid lowlands, which receive on average less than 400–880 mm of rainfall per year, and more than 40 percent of the total area is unproductive because of severe environmental degradation resulting from both natural conditions and human actions"[1].

In addition to climate hazard in many areas of the IGAD, conflict and political factors constitute sources of vulnerability and risk of food insecurity. Repeated occurrences of drought and high variability in precipitation; distorted prices for agricultural inputs; and rapid population growth have contributed to food insecurity.

The main food crops in the region are: maize, sorghum, millet, wheat, barley, rice and teff. Nevertheless, maize and sorghum are the most significant in a context of regional food security. Both together represent above 70% of the total IGAD cereal production. The 96% of the regional maize is produced by Ethiopia (44%), Kenya (37%) and Uganda (15%). On the other hand, the 87% of sorghum is produced by Sudan (61%) and Ethiopia (26%).

Some countries have a bi-modal rainfall distribution, giving the opportunity to have two crop seasons per year. The climate variability goes from desert conditions in Sudan (hyper-arid

[1] Source: IGAD Website, http://igadregion.org.

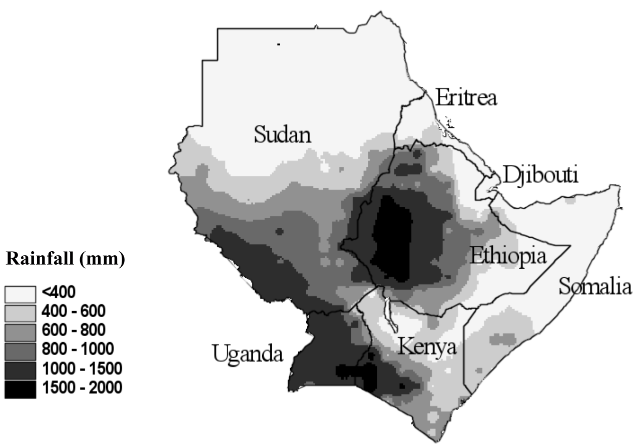

Figure 2. Annual average rainfall in millimeters (mm). Rainfall goes from 50 mm per year in the hyper-arid zones of Sudan to more than 2000 mm per year in the highlands of Ethiopia.

zones of less than 50 mm per year) to humid conditions (more than 2000 mm per year) in the highlands of Ethiopia (Fig. 2).

Another important point to keep in mind is that the IGAD countries are not homogenous from the agro-ecological point of view, which implies a high temporal variability in crop seasons. Therefore it is more complex to monitor one crop at the same time for the whole region (for example, in one country the crop cycle could be nearly completed while in another country the same crop had just started).

Due to internal conflicts and political factors, little progress has been made in the establishment of a regional structure in charge of crop monitoring and yield forecasting to support the activities of supervision and field intervention to guarantee the food security in the IGAD countries. This situation contrasts with other regions of Africa where the regional structure of crop monitoring is institutionalized, such as in southern and western Africa.

The Southern African Development Community (SADC) was established in 1980. The SADC is promoting regional cooperation in economic development. It has adopted a Programme of Action covering cooperation in various sectors, including food security and natural resources management. In order to enhance food security in the whole region, the SADC established a Food Security Programme. Its secretariat is formed by the Food, Agriculture and Natural Resources (FARN) Development Unit in Harare, Zimbabwe. Another example of a crop monitoring system is the Early Warning and Crop Production Forecast Project established in 1995 with the agreement of the Agriculture-Hydrology-Meteorology Regional Center in Niamey, Niger (AGRHYMET), the Italian Cooperation and the World Meteorological Organization (WMO) to monitor western Africa. The two systems mentioned regularly produce crop production reports during the crop season.

Finally, a well-known problem for the establishment of a CYMFS in the IGAD sub-region is that there is a low number of meteorological stations reporting in real time and scarce crop background information. Recent improvements in the quality of meteorological estimates such as rainfall, temperatures, etc., in real time by the general atmospheric models open the possibility of developing a system based on these estimates instead of meteorological stations. MARS-FOOD in collaboration with the FAO is making efforts to integrate all available data, tools, software and databases for the implementation of a CYMFS for the region. The proposed methodology is presented in the flowchart, Figure 3.

2. METHODOLOGY

Model description

The core of real-time information is based on VEGETATION images from the SPOT-4 satellite and meteorological information derived from the European Centre for Medium-Range Weather Forecast (ECMWF model). The background crop data mainly come from the Crop production system zones (CPSZ) database [14]. A water balance model was selected to evaluate the climatic impact on crop yield, because water deficit is the main limiting factor in semi-arid areas such as the IGAD region. Amongst the existing water balance models, the FAO Crop-specific water balance model (CSWB) was chosen because it has already been proved to work properly when forecasting the yield in semi-arid conditions, and for the reason that it is the most common model in African countries thanks to FAO projects. The choice of this model respects the homogeneity of analysis in the continent, making possible the comparison of results between countries. A similar methodological approach was tested by Reynolds et al. [12] in Kenya with very positive results for maize production estimates. MARS-FOOD activities are more concentrated on developing and improving tools for yield estimation and monitoring.

Tools

Additionally, early warning software such as Windisp4 [11] and Agromet Shell[2] was selected for the same reasons (well spread in early warning projects). Windisp4 is very flexible software for spatial and temporal analysis of remote-sensing images. Finally, some commercial software such as SURFER 3.2 and ArcView 3.2 were necessary to transform the information and to express it in maps.

Products

The products obtained thanks to this methodology can be divided into 4 groups:

(1) the CPSZ-NDVI profiles that are used as a crop yield indicator due to the properties of irradiance of healthy vegetation;

(2) the crop planting date analysis and the crop cycle progress index both give an indication of the evolution of the ongoing crop season;

(3) the water satisfaction index (WSI), that gives an indication of the water stress suffered by the crop and

(4) the yield estimate in tons per hectare.

[2] Agromet Shell is software that integrates the main tools used in the EWS such as SUIVI (agrometeorological database), FAOINDEX (Crop-specific water balance), the most common tools of agrometeorological data interpolation, etc. Agromet Shell has been developed by the Agrometeorological Group at FAO and programmed by Peter Hoelsloot.

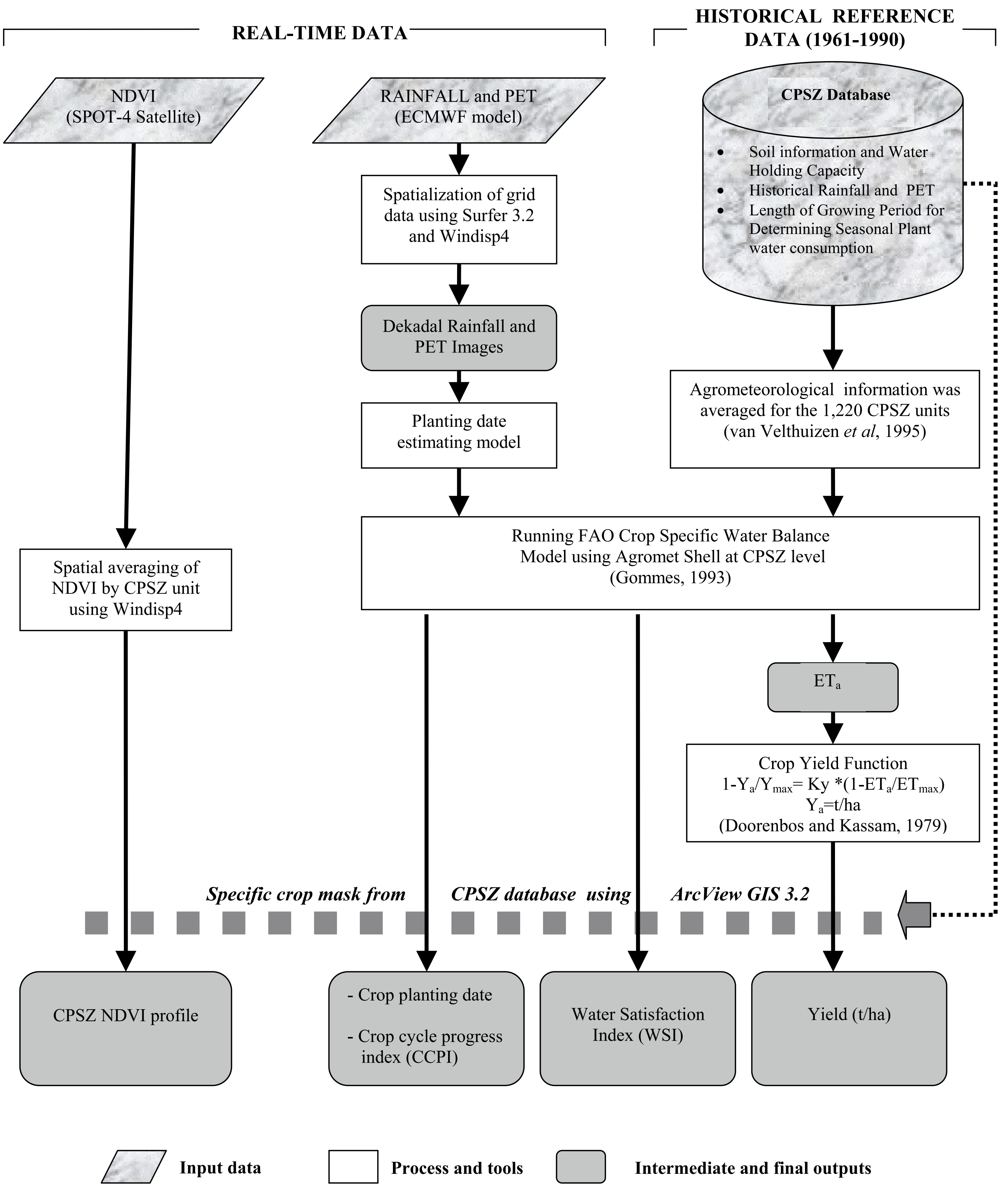

Figure 3. Flowchart illustrating the monitoring and yield forecasting methodology for Eastern Africa.

Table II. Data availability and reliability per country.

	Djibouti		Eritrea		Ethiopia		Kenya		Somalia		Sudan		Uganda	
	A	R	A	R	A	R	A	R	A	R	A	R	A	R
Crop occurrence data	–	g	+	m	++	g	+	m	–	p	+	m	+	m
Physical environment data	++	g	++	g	++	g	++	g	++	g	++	g	++	g
Agronomic data	–	p	+	m	++	g	+	m	–	p	+	m	+	m
Livestock	–	p	+	m	+	m	+	m	–	p	+	m	+	m
Environmental hazard data	– –	n.a.	–	m	+	m	–	m	– –	n.a.	+	m	+	m
Pest and disease hazard data	– –	n.a.	–	m	+	m	+	m	– –	n.a.	+	m	+	m

A = data availability R = data reliability

++: complete –: incomplete g: good p: poor
+: almost complete – –: no data m: moderate n.a.: not applicable.

Source: Van Velthuizen et al. (1995). Crop production system zones of the Intergovernmental Authority on Development.

Another important sub-product is a derived database that includes: 10-day rainfall and PET images, historical planting dates and a series of WSI and yield estimates; all this information will become invaluable reference data for improving the future crop monitoring activities in the region.

2.1. Reference data

Most of the ground-based reference data was provided by the spatial CPSZ database for the IGAD sub-region, developed by van Velthuizen et al. [14]. This database includes:

- 1220 homogeneous map units which correspond to administrative units, or subdivisions thereof whenever steep ecological gradients occur.
- For each of the map units, up to 502 variables describing the physical and biological environment, as well as the prevailing agricultural practices have been assembled.
- 44 relatively homogeneous CPSZs were defined using mainly statistical clustering techniques.

The CPSZs represent homogeneous zones in terms of agro-ecological conditions and current distribution of agricultural land use.

The CPSZ database gives the background information to assess crop conditions and food production prospects. It also provides the appropriate agronomic data and basic information for crop monitoring activities. Amongst other things, the CPSZ database provides the following crop information:

- Current distribution of crops
- Agricultural systems under which crops are grown
- Crop management calendars
- Crop phenology
- Average crop performance in terms of achieved yields
- Ecological condition under which the crops are grown
- Frequency of occurrence and severity of environmental hazards
- Frequency of occurrence and severity of invasion/infestation by pests and diseases.

Availability and quality of the data in the CPSZ database vary greatly between countries (Tab. II).

2.2. Real-time input data

2.2.1. Meteorological data

MARS at the JRC receives 10-day meteorological information produced by Meteoconsult (Nl). The company derives and processes the following data from the European Centre for Medium-Range Weather Forecast (ECMWF model) in Reading in the UK: Rainfall, Potential evapotranspiration (PET), Minimum, Maximum and Mean Temperature, Cumulated mean temperature, Climatic water balance and Global Radiation. The original data delivered to JRC are stored as a one-degree grid (ground spatial resolution). A window from –6° to 28° Latitude and 20° to 54° Longitude was produced to analyze the IGAD region. Rainfall and PET data were then interpolated from the original 1-degree grid to a final resolution of 0.083 degrees (approximately 10 km) in order to make the use of these data possible with the relatively small CPSZ units (about 100 km^2). A nearest neighbor[3] interpolation method was applied, avoiding extra modifications of the ECMWF estimates. There is no spatial refinement in this process, but the final product simplifies considerably both the interpretation by the analyst and the extraction of average values for small polygons. Finally, the 0.083-degree grids were converted into images to allow processing with the WINDISP software

Dekadal rainfall and ETP were then spatially averaged for each CPSZ unit and the agrometeorological information of each CPSZ was imported into Agromet-Shell using the longitude and latitude of the center of the polygon[4] as spatial reference. The crop information needed to run the water balance model (WHC, average yield, cycle length) was taken from the CPSZ database. The current planting date which represents the start

[3] The Nearest Neighbor gridding method assigns the value of the nearest datum point to each grid node. This method is useful when data is already on a grid, but needs to be converted to a grid with smaller cells, or, in cases of data with only a few missing values, this method is effective for filling in the holes in the data.

[4] Agromet-Shell was designed for storing agrometeorological information based on meteorological stations. In the present study the information from the CPSZ units (spatially averaged for each polygon) was inserted in lieu of meteorological stations with the objective of running the water balance model.

of the simulation process is calculated using an agrometeorological planting date-estimating model described in 2.4.

2.2.2. Remote-sensing data

The VEGETATION instrument was launched onboard the SPOT 4 satellite in March 1998. This instrument offers a global coverage almost daily (90% of the globe covered every day and the remaining 10% the following day) at a spatial resolution of 1 km at nadir. Compared with the existing instruments of the same kind, and in particular NOAA-AVHRR, SPOT VEGETATION provides an enhanced radiometric resolution and, above all, a limited local distortion of about 0.3 km [13]. On May 4th 2002 the SPOT 5 satellite with the VEGETATION 2 sensor was launched successfully. SPOT VEGETATION 2 S10 images became regularly available from the 1st of January 2003.

The SPOT VEGETATION data are purchased by MARS and delivered by the Centre Traitement des Données Végétation (CTIV) of Vito (the Flemish Institute for Technological Research) in Mol, Belgium. The products acquired by MARS are 10-day NDVI (Normalized Difference Vegetation Index) synthesis (S10) images, obtained through Maximum Value Compositing (MVC). The images are corrected for radiometry, geometry and atmospheric effects. The 10-day images are delivered to the JRC with a delay of around 2–3 days.

2.3. The CSWB model

The FAO CSWB is a very simple but physically sound soil water balance model which is used to assess the impact of weather conditions on crops [4, 6]. The water balance of the specific crop is calculated in time increments, usually 10 days. The equation of the water balance is:

$$W_t = W_{t-1} + R - ET_m - (r + i) \qquad (1)$$

where,

W_t: amount of water stored in the soil at the time t

W_{t-1}: amount of water stored in the soil at the end of the previous period (t–1)

R: cumulated rainfall during the dekad or t-period of time

ET_m: maximum evapotranspiration in the t-period time

r: represents the water losses due to runoff in the t-period time

i: represents the water losses due to deep percolation in the t-period time.

Extensive research has been conducted for each term in equation (1), and various methods can be used to measure or calculate their values. No account is typically taken of effective rainfall in the CSWB model, because deep percolation and runoff are initially assumed to be equal to zero. However, after the plant's root zone has reached water-holding capacity, the remaining rainfall is considered as runoff or deep percolation. Therefore, the effective precipitation is typically assumed to be 100% of the actual precipitation and equation (1) can be reduced to:

$$W_t = W_{t-1} + R - ET_m \qquad (2)$$

The maximum evapotranspiration, in equations (1) and (2), is the water requirement for the crop, defined as:

$$ET_m = K_c \times PET \qquad (3)$$

where,

K_c: crop coefficient

PET: Potential Evaporation and Transpiration in mm/dekad.

The potential evapotranspiration (PET) is the maximum quantity of water that is transpired and evaporated by a uniform cover of short grass [10]. PET is calculated from the EMCWF model outputs using Penman's formula. The crop coefficient values are estimated by Agromet-Shell as a percentage of the cycle length as described by Doorenbos and Pruitt [3]. The soil moisture content, W_t and W_{t-1} terms from equation (2), is the water stored in the plant's root zone. The pre-season K_{cr} is a dummy "crop coefficient" used to compute initial soil moisture. Using this, a water balance is computed in the usual way starting 10 dekads before the planting dekad. From the planting dekad onwards, the crop-specific coefficients are used. A pre-season K_{cr} of 0 (zero) instructs the programme to assume an initial soil water storage of 0. If W_t is greater than the readily available water-holding capacity of the soil, then the soil has a water surplus. If W_t is less than 0, the soil has a water deficit, D.

Two main outputs of the CSWB model are demonstrated to be positively correlated with the crop yield: the Actual evapotranspiration (ET_a) and the Water Satisfaction Index (WSI). ET_a has the advantage of including radiation, which is an important climatic variable susceptible to influencing the crop yield in the region. The influence of factors other than water stress which can reduce crop yields such as waterlogging, mechanical damage produced by strong winds, or biological factors, such as locusts, birds, insects or plant diseases are not considered by the CSWB model.

The WSI is an index of the CSWB model to assess the amount of water received by the crop during any time of the season. Normally, the WSI is used for defining qualitative yield classes (i.e. good, average, poor) or in relative figures (percent of an optimal yield crop). The WSI expresses the percentage of the crop water requirements which has been met. It is calculated as follows:

$$WSI = 100\ [1 - (\Sigma\ |D|/WR)] \qquad (4)$$

where,

WSI = Water Satisfaction Index expressed as percentage

D = Soil water deficit, mm/dekad

WR= Maximum plant water requirement, mm/dekad.

The water deficit, D, is set equal to zero whenever W_t from equation (2) is zero or positive, and D is set equal to W_t whenever W_t is negative. The values of D are then summed and divided by the total seasonal water requirement of the plant to calculate the WSI. When the WSI is equal to 100, it indicates no water stress and good crop yields, while a WSI of 50 corresponds to poor crop yield or crop failures.

2.4. Planting date-estimating model

To start the simulation the CSWB model needs the current planting date of each crop season. The criterion followed to define the planting dekad was the 1st dekad with at least 20 mm

Table III. K_{max} coefficient for maize for each country.

Country	Kenya	Eritrea	Ethiopia	Somalia	Sudan	Uganda
K_{max}	1.24	1.62	1.12	1.41	1.24	1.22

K_{max} = Maximum Yield/Average Yield from FAO-STAT (reference period: 1990–2000).
Source: FAO-GIEWS Website: http://www.fao.org/waicent/faoinfo/economic/giews/

of rainfall followed by two dekads with at least 20 mm of total rain. This criterion was developed at the Agriculture-Hydrology-Meteorology Regional Center in Niamey, Niger [1] and adapted[5] to the IGAD region. It is possible to analyze the information of the actual planting dekad in relation to the normal planting dekad included in the CPSZ database. This analysis is interesting because late planting is likely to be linked to yield reduction/failure due to insufficient water availability at the end of the crop cycle.

2.5. Crop cycle progress index (CCPI)

Another output derived from the CSWB model is an index of the crop cycle progress. It is expressed as a percentage of the total crop cycle duration. For example, if the crop cycle length is 100 days and at the moment of analysis there are 30 days (3 dekads) left, the index will be 70%, indicating that 70% of the crop cycle has been reached. Values of 0% indicate areas where the conditions for planting do not subsist or have not been fulfilled yet, while a 100% value indicates that the crop has already reached the maturity stage and could be harvested. This is a useful indicator due to the variability of the planting period in the IGAD countries. The "crop cycle progress index" adds more meaning to the spatial-temporal analysis done with the vegetation index and water satisfaction index

2.6. Crop yield functions

The CSWB model output can be changed from relative figures to absolute figures (kg/ha) using crop yield functions [2]. Crop yield functions are based on empirical water balance studies and are useful for estimating yields because they relate water stress to yield reduction, as follows:

$$1 - (Y_a / Y_m) = K_y (1 - [ET_a / ET_m]) \quad (5)$$

where,

Y_a = actual yield expressed in kg ha^{-1}

Y_m = maximum yield expressed in kg ha^{-1}

ET_a = actual evapotranspiration, mm $dekad^{-1}$

K_y = yield reduction factor.

Empirical experiments indicate that seasonal K_y values for equation (5) range from 1.2 [2] to 1.5 [7]. A seasonal K_y value of 1.5 was chosen for equation (5) based on recommendations by Gommes and Houssiau [6] for maize in East Africa. Therefore, quantitative yields from the crop yield function were calculated for the CSWB model by solving equation (5) in terms of Y_a and assuming $K_y = 1.5$:

$$Y_a = 1.5\ (ET_a / ET_m)\ Y_m - 0.5\ Y_m \quad (6)$$

The maximum reference yields, Y_m from equation (6), will in an indirect way account for other local farm factors which affect yield, such as agricultural and soil management practices. Average yield values from the CPSZ database were multiplied by the coefficient K_{max} to obtain an estimate of maximum yield (Y_m). K_{max} was obtained by the ratio of maximum maize yield and Average maize yield of the FAO-STAT yield series (reference period 1990–2000) available online[6] (Tab. III).

The maximum and actual evapotranspiration, ET_m and ET_a from equation (6), were calculated in the first stage of the CSWB model by cumulating dekadal water requirement and actual evapotranspiration for different stages of the growing season or for the whole period. When the growing season has not reached its end, the CSWB model is run using the historical average rainfall for the following dekads. This means that at any time during the growing season it is possible to have an estimate of the crop yield based on the assumption of having "average rainfall" for the rest of the crop growth cycle. The final crop yield estimate will be obtained as soon as the total crop growth cycle has been completed.

2.7. CPSZ-NDVI Profile

In addition to the CSWB model, the MARS-FOOD CYMFS relies on remote-sensing data. At the moment of writing the model is still used in a completely independent way from the remotely observed parameters, but this could change in the future. Reynolds et al. [12] have already tested the use of NDVI for detecting the planting date, and the same parameter has proved its usefulness for establishing K_c values during the crop season [8]. In the MARS-FOOD CYMFS the remote-sensing-derived parameters are mainly used as additional independent data, which are compared with the model outputs in order to verify whether the final results of the system are supported by a convergence of the single parameters.

The Normalized Difference Vegetation Index (NDVI) is the most frequently used within agrometeorological analysis. It is defined as:

$$NDVI = (NIR - VIS)/(NIR + VIS) \quad (7)$$

NIR and VIS are, respectively, the reflectance (%) in the near-infrared and in the red channels. It is easy to understand the index when the characteristics of absorption and reflection of

[5] AGRHYMET considers 25 mm of rainfall during the first dekad, which is too high for some of the IGAD countries; in lieu of that, a threshold of 20 mm of rainfall seems to be more appropriate for this region.

[6] FAO-GIEWS website: http://www.fao.org/waicent/faoinfo/economic/giews/

the radiation by green leaves is studied. The chlorophyll of the plant absorbs the majority of the radiation in the visible part of the spectrum, principally the red portion (0.6–07 µm), and is highly reflective in the near-infrared. Thanks to this property of green vegetation, NDVI is a direct indicator of the plant's photosynthetic activity and variations due, for example, to moisture stress are among the typical phenomena that can successfully be monitored by NDVI.

The MARS project has had a lot of experience of the use of this parameter and methods such as the CNDVI method [5] have been developed to extract NDVI profiles from low resolution satellite imagery based on higher resolution land cover maps in Europe. In Eastern Africa this method is currently in use for some countries where enough land cover data are available such as, for example, in Somalia (Nègre et al. [9]), but has not been implemented yet at the level of all the IGAD countries. Therefore at the IGAD level, a simplified approach based on the CPSZ database was followed. The method foresees the simple averaging of the NDVI values for each CPSZ unit and is in line with the rainfall data processing. The profiles extracted for each CPSZ unit are called CPSZ-NDVI. Temporal profiles and difference images are the main NDVI-derived products used in the MARS-FOOD CYMFS.

3. RESULTS

3.1. Vegetation index analysis

The absolute NDVI difference between the third dekad of July 2002 and the same dekad of the previous year was calculated (Fig. 4). The NDVI difference shows a decrease in the vegetation activity, mainly in central Ethiopia and the western part of southern Sudan. Nevertheless, the meaning is different depending on the stage of the crop cycle in each country (main justification of the introduction of the "crop cycle progress index"). For Sudan, where the agricultural activity has just started, the negative difference is linked to the delay of the rainy season. A different situation is present in Ethiopia where most of the areas have already been planted. The reduction in vegetation activity implies a decrease in maize yield expectation. Finally, for Uganda and Kenya this reduction is supposed to have less impact on the final yield because the crop cycle is almost complete at the end of July.

These CPSZ-NDVI profiles are presented as an illustration of the three types of NDVI differences (*increase, no change* and *decrease* in vegetation) and compared with the profile of the precedent year (they could be compared with some historical statistical profiles too). As it would be difficult to extract and to interpret NDVI profiles for every unit, it is planned to select some specific key areas or CPSZs according to their agronomic pattern and their food security situation. The involvement of national and international institutions working in this field will be crucial for the selection procedure mentioned. Rainfall is shown in the same graph to facilitate the profile interpretation.

Due to the scarce rain during the crop season, the CPSZ-NDVI profile of unit ET-224 in Ethiopia shows a relevant decrease in vegetation index compared with 2001. At the same time, the unit UG-57 in Uganda exhibits similar behavior to the year before. The situation is more favorable for the unit SO-72 in Somalia, which shows a positive difference of NDVI.

3.2. Planting dekad and crop cycle progress index (CCPI)

Figure 5 shows the planting date analysis for maize during the first crop season of 2002. It is possible to appreciate that for most of the units that were already planted, a normal to early planting took place (Fig. 5b). On the other hand, for the CPSZ units that were not yet planted, there is a delay in relation to the normal planting dekad (Fig. 5c). In Sudan the delay is 1 or 2 dekads. The longest delay takes place in some units in western Ethiopia (6 to 8 dekads of delay); these units could face problems of water availability at the end of the crop cycle. In this case, late planting should be considered as an early warning of possible yield reduction, and subsequently, these units should be monitored with special attention. Figure 6 gives an example of a "crop cycle progress index" up to the third dekad of July 2002.

3.3. The CSWB model

3.3.1. Qualitative analysis of yield prospects

Figure 7 shows the results of the CSWB model expressed by the Water Satisfaction Index (WSI). The index was classified into 3 qualitative classes (*crop failure*, *poor to mediocre* and *average to very good* yield expectation). The outputs describe the crop situation for maize during the first crop season, 2002. Maize yields are forecasted to be below 2001 levels for the IGAD countries during the main crop season of 2002, except for Kenya, where indicators show a better yield expectation. From a food security point of view, the forecasted yield reduction in Ethiopia will have a negative impact in the region due to the fact that the Ethiopian production represents around 40% of the region's total maize production. In a country context analysis the food security situation would be critical in Ethiopia and Eritrea.

The total area that falls into each class was extracted using a GIS tool available in ArcView. Then the percentage represented by each class of yield expectation at a country level was calculated and reported in a graph in Figure 7. It is important to highlight, however, that this analysis does not take into account the percentage of area not planted in each CPSZ unit; therefore it is only an indirect way to assess the impact at a country level. As the error is approximately constant it is possible to compare the present situation with the anterior crop season.

In Sudan, a reduction of around 26% is expected in the class "average to very good" yield due to late planting. In Eritrea crop failure is forecasted for 95% of the units cultivated with maize. In Ethiopia the crop situation is below 2001, with a decrease of 22% of the class "average to very good". In Uganda the maize situation seems slightly below 2001 with an increase of 11% of the class "poor to mediocre". Kenya presents a better situation than 2001, with an increase in maize yield expectation in the class "poor to mediocre" (20%). The rain-fed maize situation is not good in Somalia. For the whole region the maize situation is forecasted below the level of 2001, producing food security problems mainly in Ethiopia and Eritrea.

Figure 8 shows the final situation of maize during the first crop season, 2002. This thematic map combines the results of the WSI inferior to 50 (crop failure) with the differences between WSIs in 2002 and 2001; showing the differences

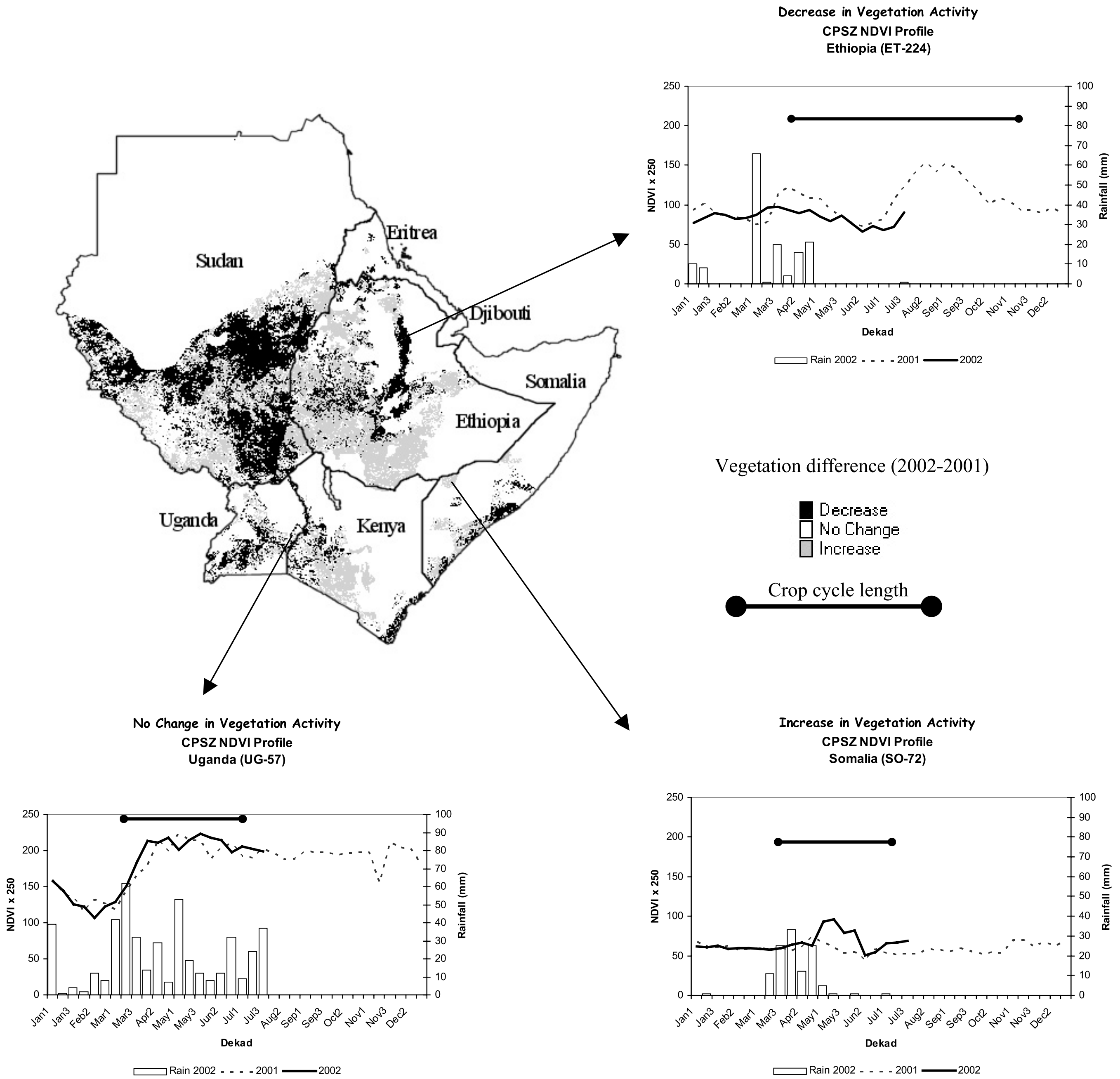

Figure 4. Normalized Difference Vegetation Index (NDVI). Absolute difference between the third dekad of July 2002 and the same dekad of the previous year. The CPSZ-NDVI profiles shown in this figure represent three typical situations of NDVI difference (decrease, no change and increase). Most of the "black" areas of Sudan are due to a delay of the rainy season. For the rest of the countries they are due to the poor rainfall during the first crop season.

greater than 10% of WSI reduction. In this way it is possible to identify the geographic location of the areas affected by the drought in 2002.

3.3.2. Quantitative analysis

To show how it will be possible in the near future to pass from a qualitative to quantitative yield estimation, the crop yield functions presented in 2.4 were applied to both crop seasons. The results for the crop season 2002 are presented in Figure 9. As compared with the WSI outputs, quantitative yield forecasts are a fraction of the maximum yield. That implies that areas falling into the same WSI class can have different yield expectations in terms of tons/ha. For example, it is possible to appreciate that a *very good* yield class (WSI = 100) represents different potential yield in terms of tons per hectare in Ethiopia (1.2 to 1.5 t/ha) compared with Somalia (0.5–0.8 t/ha).

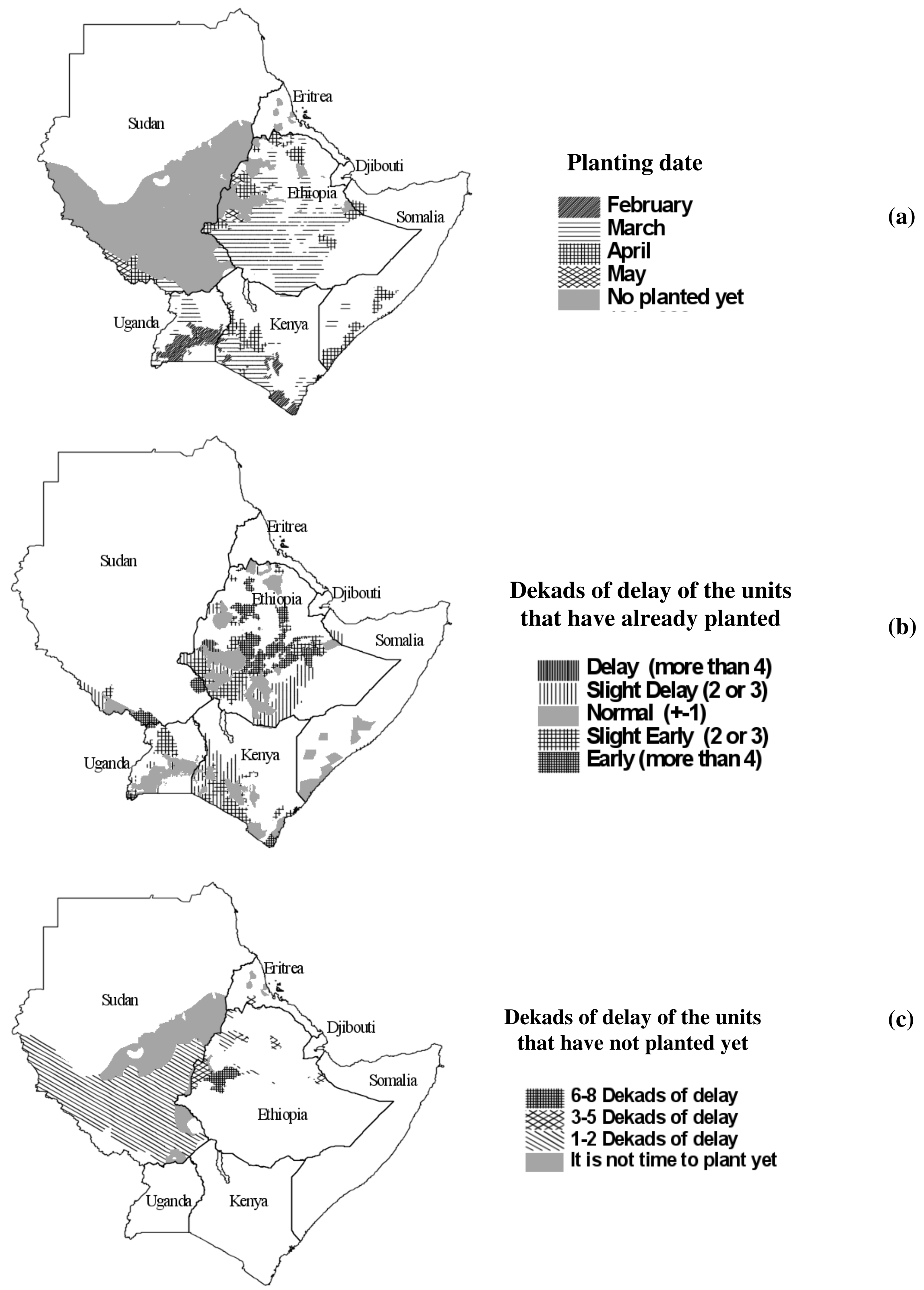

Figure 5. (a) Planting situation for Maize at the end of May during the first crop season 2002. (b) Difference of planting dekad with normal for the units that have already planted. (c) Difference of planting dekad with normal for the units that have not planted yet.

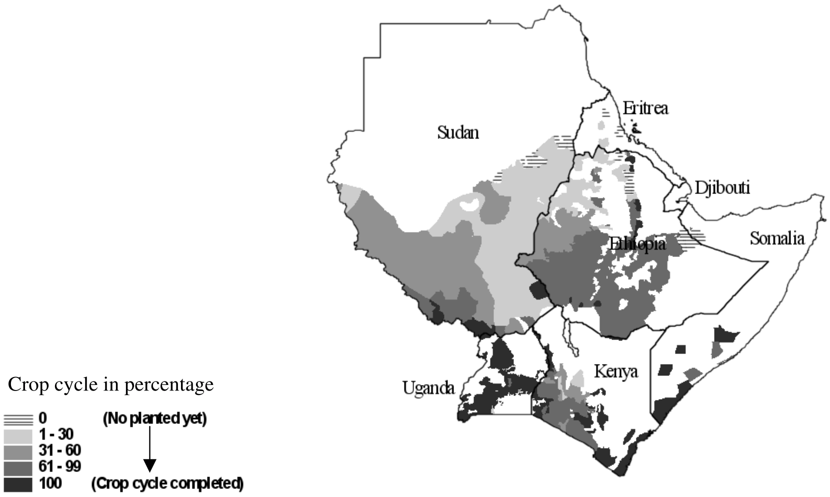

Figure 6. Crop cycle progress index expressed in percentage of the total length of the Maize cycle, up to the 3rd dekad of July 2002. For Uganda, Kenya and Somalia the index indicates that the crop cycle of the first crop season, 2002, is almost finished. In northwestern Ethiopia, Sudan and Eritrea the agricultural activity has just started.

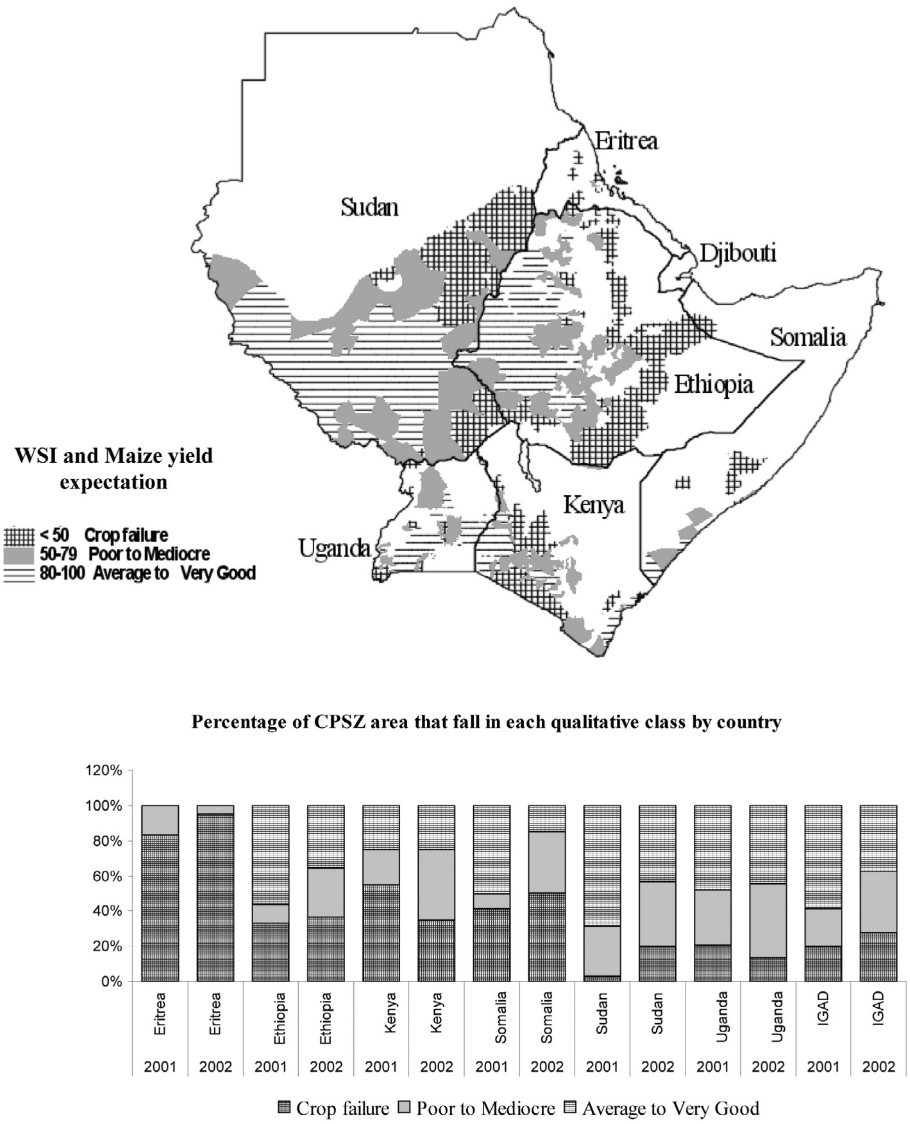

Figure 7. Water Satisfaction Index (WSI) and qualitative maize yield expectation for the Intergovernmental Authority on Development (IGAD) countries up to the 3rd dekad of December 2002. First crop season. In the graph the comparison between WSIs in 2001 and 2002. For the whole region the maize situation seems worse than 2001 (2001 was not good in terms of crop production). Kenya is the only country that shows a better situation compared with 2001.

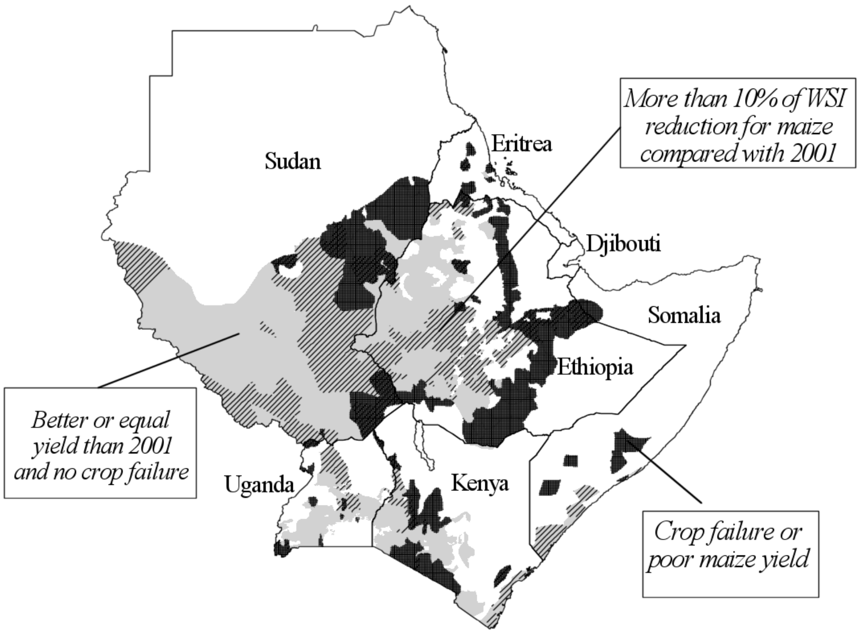

Figure 8. Maize: areas shaded with lines present more than 10% of Water Satisfaction Index reduction as compared with 2001 and in dark the areas with crop failure or very poor maize yield. Most parts of Ethiopia, Eritrea and Somalia present a poor situation for rain-fed maize during the first crop season of 2002. In Uganda the situation for maize seems similar to 2001. Kenya is the only country that presents a better situation compared with last year. Sudan and Eritrea represent around 1% of the regional maize production. The major maize producers in the region are: Ethiopia (44%), Kenya (37%) and Uganda (15%). Ethiopia and Eritrea present a serious food security problem due to crop failure during 2002.

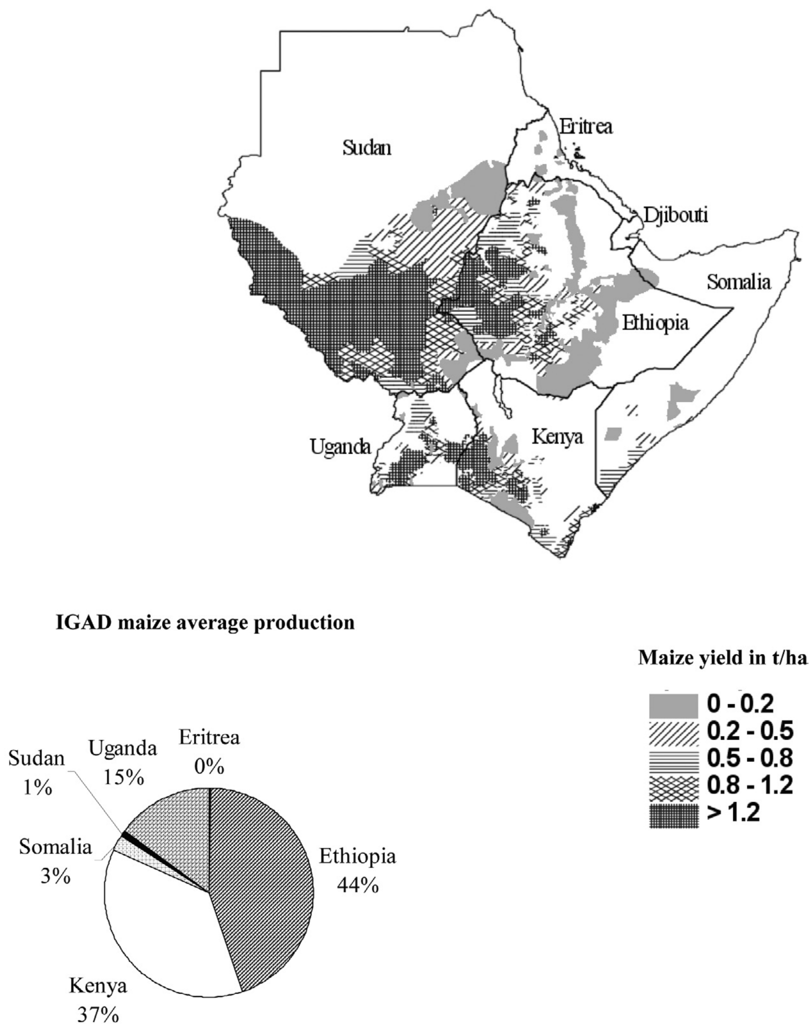

Figure 9. Maize yield estimates in tons per hectare for the Intergovernmental Authority on Development (IGAD) countries. First crop season 2002. Please note that even though Sudan presents a big maize area, the average crop density is low and the country's contribution to the total regional maize production is only 1%.

Table IV. Percentage of Crop Production System Zone (CPSZ) area that fall into each quantitative class. 2002 yield estimates compared with the final yield estimates of 2001. First crop season.

Yield expectation	Eritrea		Ethiopia		Kenya		Somalia		Sudan		Uganda	
(t/ha)	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002
Crop failure	56	92	30	34	41	21	50	50	3	10	10	7
0.1–0.2	12	8	3	4	9	6	0	5	6	6	3	3
0.21–0.5	33	0	7	11	8	21	5	11	10	17	11	12
0.51–0.8	0	0	9	14	11	8	11	32	11	9	18	22
0.81–1.00	0	0	6	6	0	12	34	2	7	12	10	8
1.01–1.20	0	0	11	9	4	6	0	0	8	9	10	9
1.21–1.50	0	0	14	13	9	5	0	0	35	23	18	13
1.51–2.00	0	0	19	7	3	10	0	0	8	3	19	17
2.00–4.00	0	0	2	1	14	14	0	0	4	7	2	10
> 4	0	0	0	0	1	0	0	0	8	4	0	0
Average yield*	0.30	0.15	1.20	0.98	1.33	1.21	0.80	0.55	1.35	1.19	1.10	1.21

* The average yield is the result of multiplying the percentage of area of each class by the average of range of the yield espectation.

Table IV shows the percentage of CPSZ area that falls into each quantitative class. The following method has been applied to obtain a first forecast at a country level, which can easily be compared with the existing yield time series, often available on a national scale only. The average yield is the result of multiplying this percentage by the average of the yield expectation range. Units with less than 0.1 t/ha are considered in the class of “crop failure” and are not used in the calculation of national average yield. The present values of both indexes, WSI and Yield, have to be considered as relative indicators and not as absolute figures. The yield forecasts still have to be properly calculated and calibrated using a historical time series.

4. CYMFS CHARACTERISTICS

The proposed CYMFS provides to the food analyst a series of crop yield indicators for assessing the crop yield variation due to agronomic aspects mainly. The analyst usually compares the indicators with the precedent crop season and historical values. The previous crop season is a very useful point of reference because it is very “fresh” in the mind of farmers and agricultural officers. After a dry or wet season it is very easy for everyone involved in agriculture to asses the current crop situation, comparing it with the recent past experience. The analyst also uses secondary sources of information such as newspapers or field reports, for enriching his own analysis of the current crop situation. The final result of the analyses is usually published in the early warning bulletins. Based on these bulletins and with other social and economic information the decision-makers can estimate the local production and calculate the food importation needs. These results should be considered as a contribution to a more complex food security system that integrates nutrition, politics, economical and security aspects.

The CYMFS has some important characteristics that make it suitable for a preliminary food security assessment such as:

- objectivity
- multi-scale analysis
- homogeneity
- timeliness
- determination of the areas with a potential problem.

Objectivity

The method is objective, there are no intermediates in the process to avoid any kind of subjectivity or political bias. Moreover, the proposed system has an independent source of information to ensure a minimum of convergence of the analysis. The system comprises results of remote-sensing and agrometeorological information, but both remain independent in the analysis.

Multi-scale analysis

Two scales are involved in the process of crop production: the temporal scale and the geographical one. Both scales are encompassed by the SPOT VEGETATION profiles and the water balance model analysis. The different agro-ecological characteristics of the geographical units in the region and the variation over time of the weather parameters are taken into account.

Homogeneity

The ensemble of the units (around 1,220 CPSZ units) are treated with the same methodology to ensure consistency from year to year and from place to place. This characteristic permits the comparison of results obtained in one country with results achieved in another (regional scale); the same applies at a subnational level (national scale). In other words, the proposed methodology attains geographical and temporal “inter-comparability”.

Timeliness

The information is available in a very short time (4 to 9 days), as compared with the traditional statistical approaches that can take months.

Determination of the areas with a potential problem

The results of the process give to the food analyst a preliminary picture of the crop situation, indicating the zones in which

Table V. Summary of the support products for crop monitoring and yield forecasting in Eastern Africa.

Product	Derived product	Type of analysis	What is it used for?
Vegetation Index (NDVI)	NDVI difference.	Spatial distribution of biomass production. (Map)	NDVI images describe the amount of green vegetation present. The difference in vegetation types results in different values, hence the dekadal NDVI images are compared with the long-term average (or the previous year) of the same dekad to give an indication of the status of the potential biomass production of the growing season.
Vegetation Index (NDVI)	CPSZ-NDVI profile ongoing year with reference year.	Temporal evolution of crop biomass. (Profile graph)	The CPSZ-NDVI profile represents the spatialy averaged NDVI values for a specific administrative level from a series of images. This analysis gives the temporal aspect of the behavior of the vegetation and agricultural area. Overview of the campaign (start, growing, senescence, water stress).
Planting date	Comparison (delay or advance planting dekad).	Spatial-temporal planting front. (Map)	Comparaison of the current planting dekad with the normal one can be a good indicator of possible yield reduction or crop failure when a long delay is observed from the onset of the rainy season.
Crop cycle stage	Indicator of crop cycle progress.	Spatial analysis of crop stage. (Map)	The crop cycle progress is an index expressed in percentage derived from the CSWB model. The index gives an indication of the percentage already completed of the crop cycle length.
Water Satisfaction Index (WSI)	Comparison with previous year or long-term average.	Geographical and temporal distribution. (Map + Profile graph)	The WSI is a crop water stress indicator. It expresses the percentage of the crop water requirements which has been met. The difference in WSI with the long-term average (or previous year) gives an indication of the current crop yield situation.
Yield estimates	Comparison (better or below than reference yield).	Spatial distribution of yield. (Map)	The yield forecast is obtained by using the crop yield functions. Comparison with historical estimates gives an assessment of the present growing season.

some potential food insecurity problem may arise. The CYMFS summarizes the basic information and determines the critical places, reducing the amount of information that the local analyst has to evaluate in the field. Moreover, the monitoring system contributes to an optimization of the field efforts and field interventions that aim to resolve the food insecurity problem. Finally, Table V presents the main characteristics of the support products of the crop monitoring and yield forecasting system for Eastern Africa.

5. CONCLUSION AND PERSPECTIVES

This paper presented the real-time CYMFS which has been developed in JRC Ispra, in cooperation with the FAO SDRN Agrometeorological Group. The system permits one to perform monitoring in real time and provides to the food security analyst an early assessment of the crop situation. During the 2002 crop season, MARS-FOOD started warning about the food crisis in Ethiopia and Eritrea from July (4 months before the international press!) through its pilot bulletins. Feedback and comments from FAO colleagues and users in DG-AIDCO, EU delegations and FAO-Global Early Warning and Information System (GIEWS) will help to improve and refine the system. Contacts with the regional and national food security units in the region would be another way to improve the products proposed. Access to a historical archive of meteorological data will make it possible to test and calibrate the absolute figures of yield forecast against a statistically valid series. It is intended to use the vegetation index (NDVI) time series to estimate the planting dates in the near future. The present paper shows the results for maize but it will be possible to apply the same approach to other crops by changing the crop coefficients (K_c, K_y, etc.). Moreover, it is intended to extend the analysis to other countries such as Rwanda, Burundi and Tanzania. Finally, it will be necessary to develop an "automatic" data production chain to simplify the process of bulletin elaboration and to develop an interactive user interface to facilitate access and interpretation of the information produced.

Acknowledgements: The authors would like to thank Dr. R. Gommes and Dr. M. Bernardi of the FAO Agrometeorological Group, for their useful suggestions and ideas during the conception phase of the crop yield monitoring and forecasting system.

APPENDIX: LIST OF SYMBOLS AND ACRONYMS

AGRHYMET	Agriculture-Hydrology-Meteorology Regional Center
ASAL	Arid and semi-arid lands
AVHRR	Advanced Very High Resolution Radiometer
CTIV	Centre Traitement des Données Végétation
CCPI	Crop Cycle Progress Index
CNDVI	CORINE land cover Normalized Difference Vegetation Index
CPSZ	Crop Production System Zone
CSWB	Crop-Specific Water Balance
CYMFS	Crop Yield Monitoring and Forecasting System
D	Soil water deficit, mm/dekad
DG-AIDCO	Direction General for Aid and Cooperation Office
ECMWF	European Centre for Medium-Range Weather Forecast
ET_a	Actual crop evapotranspiration, mm/dekad
ET_m	Maximum crop evapotranspiration, mm/dekad
EU	European Union
EuropeAid	Food Aid and Food Security of European Commission
Eurostat	European Union Agricultural Statistics
EWS	Early Warning Systems
FAO	Food and Agriculture Organization of United Nations
FARN	Food, Agriculture and Natural Resources
GHA	Greater Horn of Africa
GIS	Geographical Information System
GIEWS	Global Information and Early Warning System
i	Water losses due to deep percolation
IGAD	Intergovernmental Authority on Development
IPSC	Institute for the Protection and Security of the Citizen (JRC)
JRC	Joint Research Centre of European Commission
K_c	Crop coefficient
K_{max}	Ratio between maximum yield and average yield
K_y	Yield reduction factor
MARS	Monitoring Agriculture with Remote Sensing project
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration (USA)
PET	Potential evapotranspiration, mm/dekad
r	Water losses due to runoff
R	Cumulated rainfall during the dekad, mm/dekad
SADC	Southern African Development Community
SDRN	Environment and Natural Resources Services (FAO)
VITO	Flemish Institute for Technological Research
W	Amount of water stored in the soil, mm
WHC	Water Holding Capacity, mm
WMO	World Meteorological Organization
WSI	Water Satisfaction Index
WR	Plant Water Requirement, mm
Y_a	Actual yield, kg/ha
Y_m	Maximum yield, kg/ha

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