APPLICATION OF REMOTE SENSING TO EARLY WARNING FOR FOOD SECURITY AND ENVIRONMENTAL MONITORING IN THE HORN OF AFRICA

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ABSTRACT:

The horn of Africa includes the countries of Burundi, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania, and Uganda with a land area of more than 6million km^2 and a population in excess of 160 million people. Most of the countries in the sub-region are either semi-arid or arid with significant evidence of environmental degradation. The environmental and weather conditions in most of the countries are highly precarious, the sub-region experiencing frequent droughts and crop failures whose results are the ever recurring famines. The sub-region, therefore, requires a reliable and effective early warning system (EWS) for environmental monitoring and food security. The recent World Bank Workshop in Nairobi, Kenya, on Food Security situation in the Horn of Africa put emphasis on establishing reliable national and regional early warning systems for food security. The Regional Centre for Mapping of Resources for Development (RCMRD) has, over the years, implemented remote sensing based regional early warning systems for food security to supplement national early warning initiatives that are not so elaborately developed in the eastern Africa countries. Between 1995 and 2000, the RCMRD in collaboration with the Environmental Analysis and Remote Sensing (EARS) Consultants of Delft, The Netherlands with funding from the Netherlands Government carried out an early warning system project known as Regional Famine Early Warning System (REFEWS), which introduced new aspects in the early warning activities in the sub-region. The project developed a methodology for monitoring vegetation growth conditions as well as estimating end of season crop yields. The methodology estimates end of season crop yield forecasts half way the crop growing season and therefore if implemented gives a precise advance warning on the food situation before end of the season. Being a remote sensing based methodology, it has several advantages that include a wide and extensive coverage, regular data availability, timely data availability and dissemination as well as being highly cost-effective. This paper describes the early warning methodology developed for food security and environmental monitoring in the Horn of Africa.

1. INTRODUCTION

1.1 Background

Among the many environmental issues facing African populations, majority of whom derive their livelihood from subsistence farming and pastoralism are droughts and desertification, and their subsequent socio-economic effects among them famine and starvation. According to the Centre for Research in the Epidemiology of Disaster (Blaikie et al., 1994), the frequency of occurrence of droughts has been increasing and whereas only 62 droughts were reported in the 1960s, the number rose to nearly 240 in the 1990s. However, according to Drought Volume I – A Global Assessment (Wilhite, 2000), these figures are misleading because drought is one of the most under-reported natural disasters because the sources of most of these statistics are international aid or donor organizations. Unless countries afflicted by drought request assistance from the international community or donor governments, these episodes are not reported.

Some of the most affected are the Sahelian and Sub-Saharan countries. The droughts of the mid 1980s directly adversely affected more than 40 million people in Sub-Saharan Africa (Wilhite, 2000). The eastern Africa sub-region has been significantly affected as evidenced by the frequent famines and starvation that have attracted world attention in the recent past. One of the main resulting consequences of droughts has been the escalating poverty due to diminished means of economic production such as the cases where pastoralists' livestock have been wiped out during a drought (Oroda, 2001). Like most of the regions of Africa, the economies of all the countries of eastern Africa are highly dependent on rain-fed agriculture – both crop and livestock production. Besides determining the quality and quantity of agricultural production, rainfall is also a major factor determining water availability for the various socio-economic uses.

The eastern Africa sub-region comprises Burundi, to some extent the Democratic Republic of Congo, Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Somalia, Sudan, Tanzania and Uganda. Of these, seven form the IGAD sub-region and include Djibouti, Eritrea, Ethiopia, Kenya, Somalia, Sudan and Uganda. According to the 1995 estimates by the World Resources Institute (World Resources Information, 1996), the IGAD sub-region has an estimated human population of more than 146 million and a land surface area of more than 6 million Km^2. Ecologically and environmentally the area is highly precarious, more than 60% of the sub-region being classifiable as semi-arid or arid. Other countries such as Sudan experience real desert like conditions with less than 250 mm annual rainfall.

1.2 Status of Early Warning Systems in the Horn of Africa Countries

The sub-region experiences very frequent droughts as exemplified above, rainfall distribution and intensity varying considerably, both spatially and temporally. The frequent droughts often lead to crop failures and lack of grazing and browse with frequent occurrence of famines in the sub-region. The famines often result into hunger, starvation, malnutrition, mass-migration of populations and in many cases death. These negative impacts of famine, resulting from environmental factors, are often compounded by several socio-econo-political factors that have over the years impacted negatively on the general production of the area. Generally, famine is realised late when it has taken its toll on the population. Hence the sub-region greatly needs an EWS for monitoring environmental conditions as well as crop yield forecasts.

Besides Ethiopia, however, none of the countries of eastern Africa has established a system that can be used reasonably to monitor droughts that are so common in this part of the world. No reasonable early warning systems have been established and even the existing national early warning systems are not adequately elaborate which is probably why the fight against famine in eastern Africa has not been successful. The inadequacy can be attributed to several factors among them lack of facilities and equipment and limited well-trained personnel. The sub-region is, therefore, quite unable to predict, counter or manage the aftermaths of the frequent droughts.

Although the economic, social and environmental costs and losses associated with droughts and desertification have been increasing dramatically in the Horn of Africa, it is difficult to quantify their trends precisely because of lack of reliable historical estimates as a result of lack of systematic assessments, monitoring and recording and neither has there been systems that have specifically mapped the extent and trend of drought and desertification. This lack of reliable and operational EWS has all along caused inadequacy in food supply information, a situation significantly exploited by unscrupulous and speculative traders thereby denying a reasonable population size access to food and compounding the food insecurity situations.

The above scenario calls for setting up systems, Early Warning Systems (EWS), to continually provide reliable data and information on drought, desertification and the resulting consequences useful for decision-making.

1.3 Early Warning Activities at the Regional Centre for Mapping of Resources for Development (RCMRD)

The Regional Centre for Mapping of Resources for Development (RCMRD) has, for a long time, been the only source of early warning information for food security covering the entire sub-region. The first early warning project for the IGAD countries was initiated at the Centre in 1988 with financial assistance from the Government of Japan through the Food and Agriculture Organization (FAO) of the United Nations. The project that used METEOSAT Cold Cloud Duration (CCD) and NOAA-NDVI data in its activities ended in 1993. A similar project was started in 1996 when FAO secured funding from the French Government. This project, which ended in 1997 also used both METEOSAT CCD and NOAA-NDVI data in its early warning projections.

Between 1995 and 2000 the RCMRD in collaboration with the Environmental Analysis and Remote Sensing (EARS) Consultants of Delft, the Netherlands, secured funding from the Netherlands Government through the Netherlands Remote Sensing Board (BCRS) to carry out an early warning system project in eastern Africa. The project was known as the Regional Famine Early Warning System (REFEWS) and the methodology used in this project is the basis of this paper.

2. THE REFEWS METHODOLOGY

The REFEWS project introduced new aspects in early warning in eastern Africa. It brought in quantified early warning data by providing end of season crop yield forecasting, estimated halfway the crop-growing season. Shown in figures 1 and 2 are a schematic data derivation representation overview of the system (fig. 1) and energy water balance at the earth surface (fig. 2).

2.1 Generation of Meteosat Data and the Simulation of Crop Early Warning Products

Early warning system: The early warning system is based on monitoring of the earth surface with METEOSAT, a geo-stationary weather satellite owned by Eumetsat (See fig.1 above). The Environmental Analysis and Remote Sensing (EARS) Consultants run a Primary Data User Station that receives Meteosat data every half hourly. The received data is pre-processed using the EARS Energy Balance Mapping Software (EARS-EBMS), stored and every 10 days (meteorological dekad) the data are processed to generate several products (Rosema and Fiselier, 1990). For this project the following image products were generated and used:

Level 1
- Rainfall estimation
- Actual evapotranspiration
- Sensible heat flux
- Global and net radiation

Level 2
- Relative crop yield (end of season estimated crop yields)
- Relative crop yield difference (images comparing the current year from the previous one)

Energy and Water balance: Figure 2 below shows the energy and water balance measurements. An important part of the methodology used is based on the surface energy balance. The energy balance implies that the energy provided to the surface by radiation (net radiation I_n) is on average used in two ways: (a) to heat the atmosphere (sensible heat flux H) and (b) to evaporate water (latent heat flux LE).

$$I_n = H + LE \quad (1)$$

LE is the energy equivalent to the actual evapotranspiration (E = LE / L, where L is the heat of evaporation). The latent heat flux or actual evapotranspiration is a direct measure of water availability at the surface. However, the actual evapotranspiration depends also on the radiation input. Therefore drought is best characterised by the energy sharing ratio's

$$1 = H / I_n + LE / I_n \quad (2)$$

The last term is called the relative evapotranspiration. The simplified methodology of information extraction is as follows. From the Meteosat visible and thermal infrared imagery the planetary albedo (reflectivity) and planetary temperature are obtained. Subsequently clouds are discriminated from cloud-free pixels. For cloud free pixels the planetary albedo and temperature are converted to surface albedo and surface temperature by means of atmospheric correction procedures. Subsequently the boundary layer air temperature is mapped. The albedo and surface temperature are used to calculate the net radiation (I_n) at the earth surface. From the surface-air temperature difference the sensible

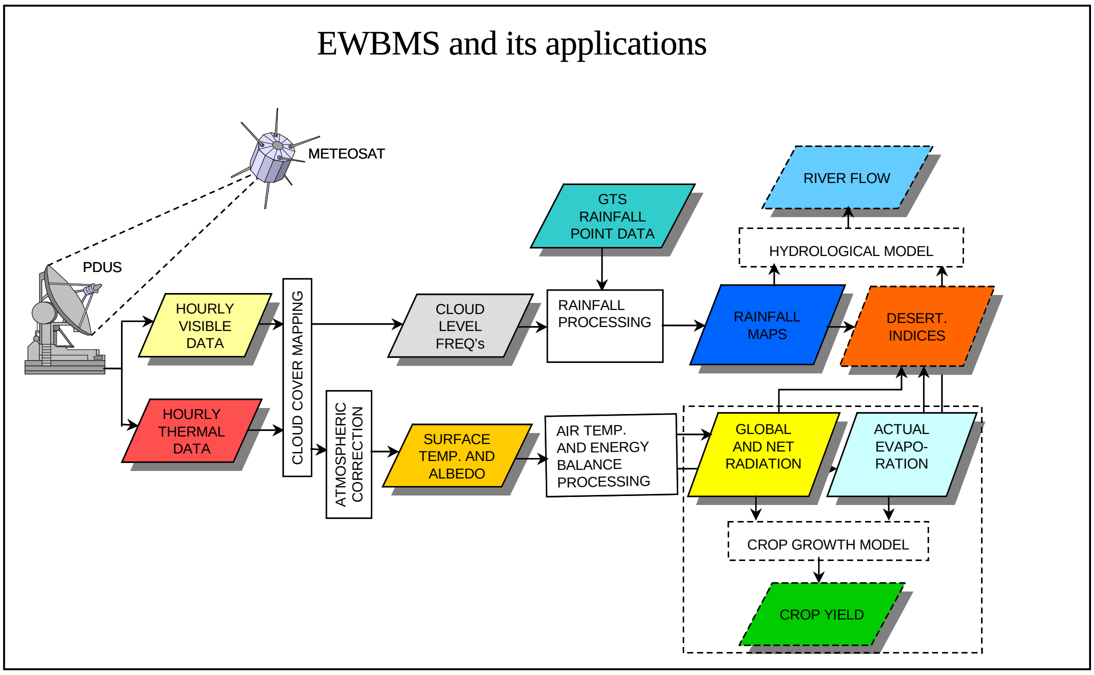

Figure 1. METEOSAT data derivation scheme

heat flux (H) is obtained. Finally the actual evapotranspiration is found as the difference between these two i.e. $LE = I_n - H$.

In case pixels are cloudy, adapted radiation calculations are made and unchanged energy sharing is assumed to estimate the energy balance components. In this way continuous energy balance data in both space and time is obtained.

The actual evapotranspiration is also a part of the surface water balance. The water balance states that precipitation (rainfall) (P) can be used in three ways: for evaporation (E), for infiltration into the ground (I) and for surface run-off (R). The difference between rainfall and actual evapotranspiration is called the effective rainfall. This is the basic input for regional water budget studies and rainfall-runoff models at catchment scale are generated on a 10-day basis. A statistical method is used which is based on the dwelling time of clouds at different heights and on readily available global transmission stations (GTS) rainfall data from rainfall stations in the region.

Crop yield forecasting: In order to relate relative evapotranspiration data to crop growth, a special crop growth model, the exponential- linear model has been developed by EARS hence the model is known as EARS-EL (Roebeling et al., 1999). EARS-EL model was used to simulate the development of a crop using the satellite-derived values of radiation and actual evapotranspiration as input. This model is run twice: one time with the actual evapotranspiration and the second time assuming optimum water supply (potential evapotranspiration). The ratio of the two simulated biomass values is called the relative biomass. The relative biomass has been demonstrated to be a good predictor of the relative crop yield already halfway the growing season. An actual crop yield forecast is usually obtained by multiplying the relative yield with the highest reported yield during the past 10-20 years. Once longer time series have been built regressions between the reported and calculated relative yields may be used.

For comparison with reported crop yields the image products are integrated within the limits of administrative boundaries and main cropping zones.

2.2 The Relationship between METEOSAT Derived Products and Crop Growth

It is well known that water is required for crops to grow and that rainfall has been the most used input parameter in crop yield models. However, not all rainfall is available to a crop and a considerable amount is lost by run-off and by deep percolation. Models for estimating water availability to the crop, such as the water satisfaction index approach exemplified by Frere and Popov (1986), and crop growth models such as WOFOST developed by van Diepen et al. (1989) use rainfall as input to simulate the water availability to the crop. These require many input data such as topography and micro-relief of the terrain, soil type and rooting depth, permeability at the surface, and coverage by vegetation. This information is normally not readily available nor is it accurately known.

Evapotranspiration is, however, a more direct indicator of crop growth since it is a measure of the amount of water actually used by the crop. Its utility is illustrated by the following citation: "it has been demonstrated that for annual crops the difference between the potential and actual crop evapotranspiration will be proportional to the loss in biomass and, finally, the loss of economic yield (Frere and Popov, 1986). For a long time, however, spatial data on distribution of actual evapotranspiration were not available and were only recently introduced on the basis of meteorological satellites. The advantage of using METEOSAT derived actual evapotranspiration for crop yield prediction is its directness. No information on soil, topography and surface conditions is required nor soil water budget calculations. It is important to note, however, that present meteorological satellites do not resolve individual crop yield estimation but rather give information on the general water availability in an area.

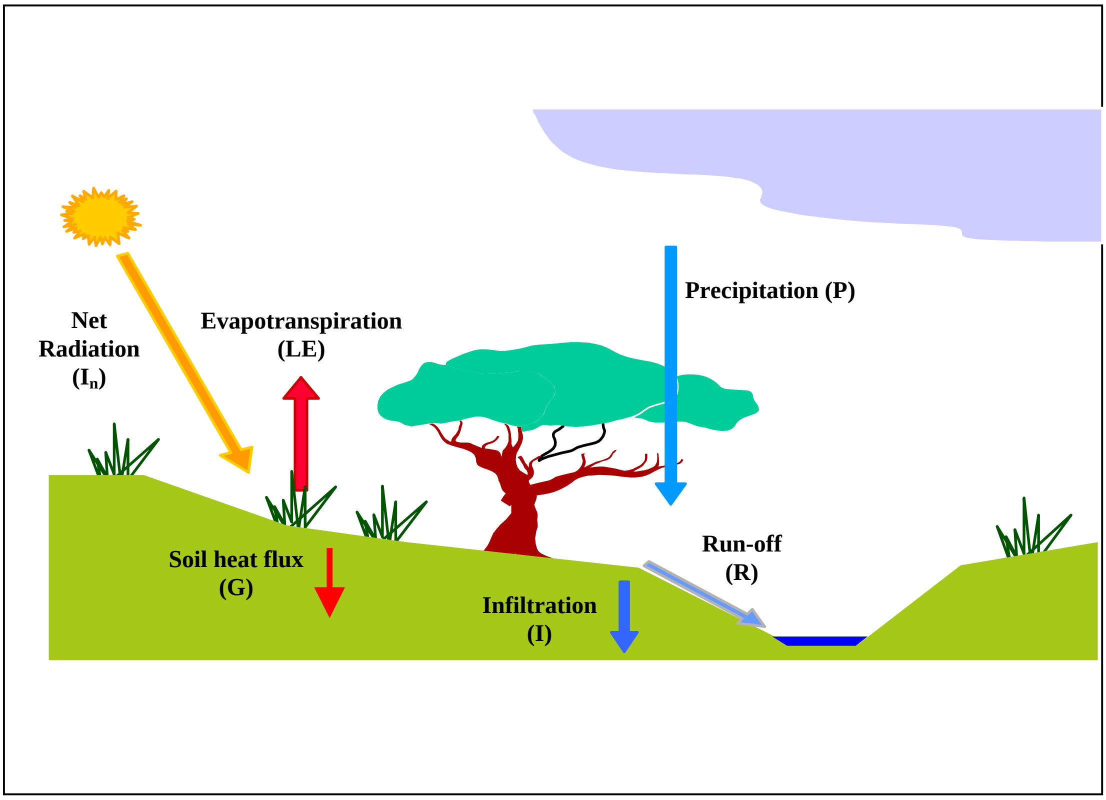

Figure.2. Energy and Water Balance at the surface of the earth

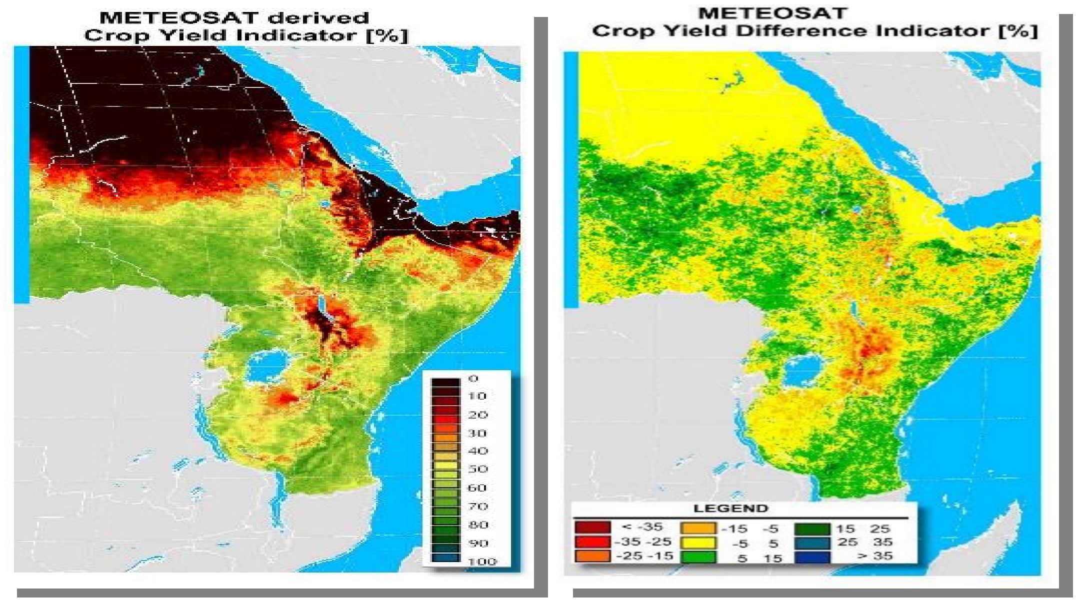

Figure 3. Crop yield forecast images

Physiological background: There is a strong relationship between evapotranspiration and crop growth, which has a plant physiological background. Water used by the crop is transpired though the leaf stomata while at the same time the plant assimilates carbon dioxide from the atmosphere through the stomata. When water is, insufficiently available, the stomata will close during which time both transpiration and Carbon dioxide assimilation are (almost) proportionally reduced. Figure 4 shows this relationship. Transpiration (LE) and Carbon dioxide assimilation (F) fluxes may be formulated as in the equations below:

$$LE = (vI_n + LE_i)/\{v+ (r_a + r_c/r_a)\} \ldots \quad (3)$$

$$F = \text{Change in } CO_2/(r_a+1.8r_c + r_m) \ldots \quad (4)$$

where:
v = 2.4
r_a = atmospheric resistance
r_c = crop (stomatal) resistance
r_m = crop mesophyll resistance

The first expression, $LE=(rI_n + LE_i)/[r+(r_a+r_c)/r_a]$ is the Penman - Monteith equation (Monteith, 1977). Maximum transpiration (LE_{max}) and maximum assimilation (F_m) occur when stomata are completely open, for which case we will assume the crop resistance to be negligible ($r_c = 0$).

Relative evapotranspiration (Q) can be defined as $Q=LE/LE_{max}$, and Relative assimilation (R) as $R=F/F_{max}$, and by substitution and elimination of crop resistance (r_c):

$$R=Q/\{Q + a (1 - Q)\} \quad (5)$$

where:
$a= 1.8 (1+v) *r_a/(r_a + r_m)$

The relation above (relative evapotranpiration and relative yield) is dependent on wind speed resistance (r_a), stomatal resistance (r_c) and also on the mesophyll resistance (r_m), which depends on crop type and crop development stage. Normally a factor of 1.8 is adopted for r_m to cater for the lower diffusion velocity of CO_2.

If soil water supply to the plant roots becomes insufficient, the leaf stomata will close. This minimizes water loss while at the same time reducing Carbon dioxide uptake from the atmosphere needed for photosynthesis. Growth is, therefore, dependent on the availability of soil water that is provided by rainfall and depleted by evapotrnaspiration. Vegetation growth and evepotranspiration are, as a matter of fact, therefore, positively related. In fact, according to Frere and Popov, for annual crops the difference between potential and actual crop evapotranspiration is proportional to the loss in biomass production and, finally, the loss of economic yield (Frere and Popov, 1986).

2.3 The Relationship between Crop Growth and Yield

As discussed above evapotranspiration is a good measure of primary production and crop growth. The derivation of crop yield is consistent with theoretical derivation given in the section above as presented by the Doorenbos and Kassam (1979), as an approach to the calculation of irrigation water requirements. The method is based on the work by Stewart et al. (1977) who, from experimental data, found that the relative crop decrease is linearly proportional to the relative evapotranspiration deficit averaged for the growing season.

$$1-Y/Y_m = k_y(1-LE/LE_m) \quad (6)$$

or since,

$$1 - Y/Y_m = 1-F/Fm = 1-R \quad (7)$$

then,

$$(1-R)= k_y(1-Q) \quad (8)$$

where k_y is the yield response factor, which is depended on crop type and the phenological stage of the crop.

Given below are k_y factors for some common crops.

Maize	1.25
Sorghum	0.9
Wheat	1.00

The lower the ky value, the more drought resistant is the crop whereas k_y value of 1.0 represents an average crop whose average yield is

$$R=Y/Ym = LE/LEm = LE/In. \quad (9)$$

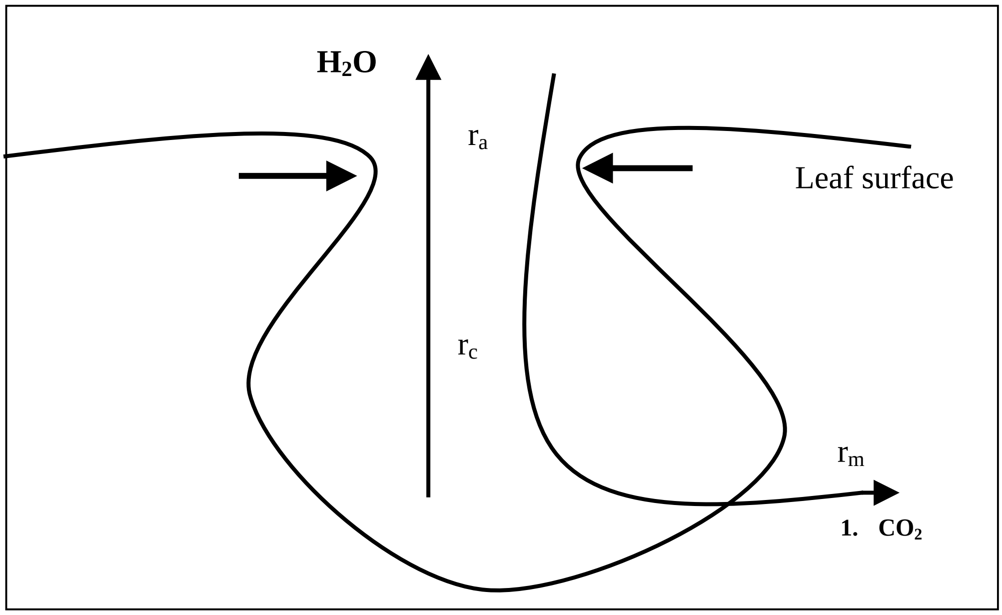

Figure 4. Illustration of the leaf stomata and the related physiological activities. In the figure, r_a is the atmospheric resistance, r_c is the stomatal or crop resistance and r_m the mesophyl resistance.

2.4 Gross Primary Production and Net Primary Production

Gross Primary Production (GPP) corresponds to the sum, for a given surface, of photosyntheses, which occur during a defined elapsed period (time) whereas Net Primary Production (NPP) is the Gross Primary Production less the production used in respiration.

NPP =GPP - (Rc+Re+Rp) ……………….. (10)

where:
Rc = growth respiration
Re = maintenance respiration
Rp = Photorespiration

In theory, under optimum living conditions, the NPP should represent the quantity of plant matter that can really be observed on the ground for annual plants. Some quantity of the plant is, however, consumed or disappear as a result of ageing. The quantity of plant matter really observable on the ground is, thus, called plant biomass or phytomass

Phytomass = sum from day 1 to day t (GPP - (Rc + Rc + Rp +C+S) ………….(11)

where:
C = losses by annual consumption
S = losses by ageing

For perennial crops, production and biomass mean different situations. Production represents quantity of matter accumulated per unit surface and per unit time whereas biomass designates the total mass of matter on a given surface. For example a forest may have a net production of 10 tones/ha/year while its biomass is about 300 tonnes/ha

2.5 Potential Yield and Actual Yield

Yield designates the quantity for matter exploited by man from a crop per unit area. Potential Yield is the yield obtained when plants are grown in unlimited conditions of media (optimum availability of water and nutrients, without extremes of condition). Under natural conditions and in large crops, however, plants always suffer, to a greater or less degree, from stresses such as water stress, high temperatures, annual consumption, diseases etc. that induce losses. The yields obtained are thus referred to as actual yields

One of the main purposes of REFEWS Project was to estimate crop yields in eastern Africa countries. The estimations are modelled based on the derived evapotranspiration since evapotransipiration is proportional to crop growth. Actual evapotranspiration is an indicator of the actual crop performance based on the fact that it is influenced by the many environmental parameters that influence plant growth such as moisture availability, temperatures, ambient sun, wind conditions, etc. The project applied simple crop models, *namely the ExponentialLinear growth model* developed by EARS Consultants, which is a modification of the Stewart model (1977).

The model is given as:

1-Y/Ym = k_y(1-LE/LEm) ………….. (12)

This model was developed by Stewart et al. (1977) but was widely applied by Doorebos and Kassam (1979) in their calculation for crop irrigation water requirement. The relationship is applied to whole or part of the growing season. k_y is the yield response factor. For average crop, k_y = 1 and, thus:

$Y/Y_m = LE/LE_m = cLE/I_n$ ………. (13)

where c=1.25

The Exponential Linear Growth model assumes that biomass increase is proportional to the amount of light intercepted by the crop which, is influenced by factors such as the standing biomass (Bi) if the ground cover is incomplete (Bi < Bc) and relative evapotranspiratin (Q = cLE/I_n). The model has two growth phases, the exponential growth phase

day1: B1 = B0(1=rQ1)
day2: B2 = B1(1+rQ2) = B0(1+rQ1)(1+rQ2)

and, the linear growth phase expressed as below:

day c+1: Bc +1 = Bc + BcrQc+1
day c + 2: Bc +2 = Bc+1 + BcrQc +2

3. POLICY FOR FOOD SECURITY FOR THE HORN OF AFRICA

A true food security can only be facilitated by an early warning system (EWS) that is closely linked to the policy making and the response arms of governments, as well as potential donors and outside assistance sources. A regional EWS that gives all countries access to similar timely and accurate early warning products at the scale of the region would provide a good tool for decision-making. Depending on national requirements, the countries can then decide whether the regional products provide sufficient information or if they want to include these products in their national EWS for more detailed analyses. The need for a policy framework to encourage the member States of the Horn of Africa to establish, an operational Regional Early Warning Systems for food security is, therefore, quite necessary. The countries of the Horn of Africa can also benefit from the fast developing information technologies in establishing satellite-linked networking for faster communication and linkages. Such exchange of information will assist to alleviate disasters, famine and poverty.

4. INDICES OF DESERTIFICATION

Rainfall and evapotranspiration are not necessarily the best indicators of aridity and desert like conditions. In regions with high solar irradiation plant life needs more water to survive hence Budyko's index, which gives the information and characterizes the climatic aridity (Hare, 1977):

$AI = I_n/LR$ ……. (17)

where:
AI = Aridity Index
I_n = net radiation
L = heat of evaporation
R = rainfall

The index gives information on the climatic aridity. Since net radiation and the heat of evaporation are automatically derived from the METEOSAT Satellite by the EARS-EBMS, the methodology can be used to monitor desertification because rainfall data are often readily available from rainfall stations in most countries.

5. FUTURE PLANS

The war against famine is, however, far from over, and the RCMRD together with its partners in Europe and within the IGAD sub-region are pursuing the operational implementation of the system and the introduction of the system to a wider group of end-users in the interest of a better preparedness for drought and food emergencies in the sub-region. Currently the Centre, in collaboration with of a number of organisations in the sub-region, is pursuing the establishment of an operational EWS for the Horn of Africa. Among the organisations are the Regional Drought Monitoring Centre in Nairobi, Famine Early Warning System (FEWS) of the United States Agency for International Development (USAID) and the Environmental Analysis and Remote Sensing (EARS) Consultants of Delft, The Netherlands.

The project being developed, particularly, responds to some of the United Nations Commission to Combart Desertification (UNCCD) related funding priorities, which call for:

- Establishment of Sub-Regional Action Programmes (SRAP) to address the drought and desertification problems – which have not been adequately addressed in the eastern Africa sub-region. One of the implementation strategies of the SRAP is the Establishment of early warning systems to monitor drought and desertification. Other complementary actions envisaged in the convention, for inclusion in the SRAP, are technical and scientific cooperation, capacity building, education and public awareness; all intended to be addressed in this project.
- In executing this project, the RCMRD also intends to meet the need of enhancing sub-regional opportunities for mutual benefits through more effective use of already existing and available technical, human and other relevant resources such as existing facilities and technical know-how at the RCMRD as well as sub-regional information with regard to early warning systems.
- Dissemination of research results and appropriate modern technology

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