Can. J. Remote Sensing, Vol. 29, No. 6, pp. 687–692, 2003

Characterization of yield reduction in Ethiopia using a GIS-based crop water balance model[1]

Gabriel B. Senay and James Verdin

Abstract. In many parts of sub-Saharan Africa, subsistence agriculture is characterized by significant fluctuations in yield and production due to variations in moisture availability to staple crops. Widespread drought can lead to crop failures, with associated deterioration in food security. Ground data collection networks are sparse, so methods using geospatial rainfall estimates derived from satellite and gauge observations, where available, have been developed to calculate seasonal crop water balances. Using conventional crop production data for 4 years in Ethiopia (1996–1999), it was found that water-limited and water-unlimited growing regions can be distinguished. Furthermore, maize growing conditions are also indicative of conditions for sorghum. However, another major staple, teff, was found to behave sufficiently differently from maize to warrant studies of its own.

Résumé. Dans plusieurs régions de l'Afrique sub-saharienne, l'agriculture de subsistance est caractérisée par des fluctuations significatives au niveau du rendement et de la production dues aux variations dans la disponibilité d'humidité pour les cultures de base. Des sécheresses à grande échelle peuvent conduire à la perte des cultures et, conséquemment, à une détérioration au plan de la sécurité alimentaire. Comme les réseaux de collecte de données au sol sont épars, des méthodes utilisant des estimations géospatiales de précipitation dérivées des observations satellitaires ou d'enregistreurs, lorsque disponibles, ont été développées pour calculer le budget saisonnier d'eau disponible pour les cultures. À l'aide des données conventionnelles de production de cultures pour quatre années en Éthiopie (1996–1999), il a été possible de déterminer des régions à ressources en eau limitées et des régions à ressources illimitées. De plus, les conditions de croissance du maïs constituent aussi un indice des conditions du sorgho. Toutefois, une autre culture de base importante, le teff, a été démontrée comme ayant un comportement suffisamment différent du maïs pour motiver ses propres analyses.
[Traduit par la Rédaction]

Introduction

Monitoring the establishment of the crop growing season and the subsequent performance of crops is an important process in the assessment of regional food security conditions in Africa. Tracking the spatial and temporal patterns of rainfall with respect to crop and soil characteristics can reveal situations of yield reduction due to water deficits. Ground observation networks often offer inadequate spatial coverage and suffer from problems of delay in reporting and uneven quality control. The use of remotely sensed data can help mitigate some of these problems. Derived geospatial climate monitoring products provide food security analysts with succinct and practical summaries of regional crop growing conditions.

Evaluation of the information content of output from a geospatial crop water balance model requires independent data on crop yield. Since the motivation for developing such monitoring products in the first place is the scarcity of conventional data, opportunities for evaluation are infrequent. We report on an opportunity to compare model results with crop data for 175 districts in Ethiopia over a 4-year period (1996–1999).

Background

A well-timed water supply is necessary for optimum crop production (FAO, 1986). When other factors (predominant variety, fertilizer use, salinization, pests, disease, mechanization) vary little from year to year, the single most important factor for crop production is water availability. The water requirement satisfaction index (WRSI) was developed by the Food and Agriculture Organization (FAO) (Frere and Popov, 1986) for use with station data to monitor water supply and demand for a rain-fed crop throughout the growing season. Although more robust and data-intensive physically based crop growth models are available, the WRSI model was adopted for geospatial implementation (Verdin and Klaver, 2002) because of its limited data requirements and simplicity for operational use.

Despite the generally observed qualitative agreement between seasonal WRSI updates and field observations, quantitative evaluation of WRSI and corresponding crop yield reports has not been possible in many countries in Africa owing to the lack of agricultural statistics. The primary objective of this study was to take advantage of an opportunity to examine the correspondence between WRSI values and reported maize

Received 10 May 2002. Accepted 24 January 2003.

G.B. Senay.[2] Earth Resources Observation Systems (EROS) Data Center, Science Applications International Corporation (SAIC), U.S. Geological Survey, Sioux Falls, SD 57198, U.S.A.

J. Verdin. Earth Resources Observation Systems (EROS) Data Center, U.S. Geological Survey, Sioux Falls, SD 57198, U.S.A.

[1]SAIC work performed under U.S. Geological Survey Contract 03CRCN0001.

[2]Corresponding author (e-mail: senay@usgs.gov).

yield to identify "water-limited" regions. In addition, the relationship between trends in maize yield and those of other cereal crops was investigated.

This study has focused on Ethiopia, located in northeastern Africa. Because of the wide range of altitude, climate, and soils in Ethiopia, a large variety of crops can be grown there. However, Ethiopia's agriculture is predominantly subsistence farming, which is vulnerable to excessive rainfall variability. There are two major crop growing seasons in Ethiopia: the long "meher" (May–October) and short "belg" (February–April). The meher season accounts for 90%–95% of the annual crop production of the country (FEWS NET, 2001).

Data

The Famine Early Warning System Network (FEWS NET) uses data from two operational remote sensing products to monitor agricultural areas for signs of drought on a near-real-time, spatially continuous basis. These include dekadal (10-day) advanced very high resolution radiometer (AVHRR) normalized difference vegetation index (NDVI) images (Los et al., 1994) produced by the National Aeronautic and Space Administration (NASA), and rainfall estimate (RFE) images (Xie and Arkin, 1997) prepared by the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA). Blended satellite rain gauge RFE images for the African continent are prepared by NOAA at 0.1° (~10 km) spatial resolution. The images are produced using an interpolation method that combines data from Meteosat cold cloud duration (CCD), the Special Sensor Microwave/Imager (SSM/I) of the Defense Meteorological Satellite Program, the Advanced Microwave Sounding Unit (AMSU) on board the NOAA-15 polar orbiter, and reporting rain gauge data from Global Telecommunication System (GTS).

One of the RFE derivative products currently in use by FEWS NET is the geospatial WRSI. The most important inputs are the RFE and potential evapotranspiration (PET). FEWS NET at the U.S. Geological Survey calculates daily PET values for Africa at 1.0° resolution from 6-h numerical meteorological model (Kanamitsu, 1989) output using the Penman–Monteith equation (Shuttleworth, 1992). In addition, the WRSI model uses relevant soils information from the FAO (1988) digital soils map and topographical parameters derived from the GTOPO30 digital elevation model (DEM) (Gesch et al., 1999).

Crop production data were obtained from the Ministry of Agriculture of Ethiopia through the FEWS NET office, Addis Ababa, Ethiopia. The production data included values for planted area in hectares and production in tonnes at the Woreda Administrative Unit, with an average district area of about 1600 km^2. Production data were available from 1996 through 1999. Only the meher production data on maize, sorghum, and teff were analyzed in this study.

To perform spatial analysis on the data in a geographic information system (GIS), the production data were related with district boundary map files using the Woreda administrative name in ArcView (ESRI, 2000). Some districts that did not have matching district–name between the map boundary file and production table could not be used for further analysis with the WRSI images.

Yield (t/ha) per district was calculated as the ratio between production in tonnes and planted area (ha). Plots and the coefficient of variation (CV; temporal variation in the 4-year period for a district) were used to identify large deviations that were considered to be data-entry or reporting errors. Districts whose yield statistics had a CV greater than 100% were removed from the analysis. In addition, districts reporting more than 5 t/ha were removed from the analysis, since 85% of the districts had maize yields of less than 2 t/ha.

A difference in agricultural practice between the two district groups was observed in the dominant crop type in the region. In the water-unlimited districts, the area planted with maize or teff was more than twice the area planted with sorghum in all 4 years. In the water-limited districts, the area planted with sorghum was the highest, followed by teff and maize in all years. This is consistent with the generally high water requirement of maize and the drought resistance of sorghum and the flexibility of teff in growing under both dry and water-logged conditions (Ketema, 1987).

Methods

Model description

The WRSI is an indicator of crop performance based on the availability of water to the crop during a growing season. Studies by the FAO (Doorenbos and Pruitt, 1977; FAO, 1986) have shown that WRSI can be related to crop production using a linear yield-reduction function specific to a crop. More recently, Verdin and Klaver (2002) demonstrated a regional implementation of the FAO WRSI in a grid-cell-based modeling environment for southern Africa.

WRSI calculation requires a start-of-season time (SOS) and an end-of-season time (EOS) for each modeling grid cell. Maps of these two variables are needed to define the spatial variation of the timing of the growing season and, consequently, the crop coefficient function, which defines the crop water use relative to a standard reference crop. The model determines the SOS using onset-of-rains based on simple precipitation accounting. (The time step of analysis is the dekad (WMO, 1992), whereby a month is divided into three parts, the first two of which are 10 days long and the last one completes the month.) The onset-of-rains is determined using a threshold amount and distribution of rainfall received in three consecutive dekads. In this study, SOS was established when there was at least 25 mm of rainfall in an initial dekad followed by a total of at least 20 mm of rainfall in the two consecutive dekads. The crop modeled was 120-day maize, giving 12 dekads for the length of the growing period (LGP). The EOS dekad for each grid cell was obtained by simply adding 11 dekads to the SOS dekad.

At the end of the crop growth cycle, or up to a certain dekad in the cycle, the respective sums of crop actual evapotranspiration (AETc) and crop potential evapotranspiration (PETc) are used to calculate WRSI (Equation (1)). A case of "no deficit" will result in a WRSI value of 100, which corresponds to the absence of yield reduction related to water deficit. A seasonal WRSI value less than 50 is regarded as a crop-failure condition (Smith, 1992).

WRSI is the ratio of seasonal AETc to the seasonal crop water requirement, which is the same as PETc, and is calculated as follows:

$$\mathrm{WRSI} = \frac{\sum \mathrm{AETc}}{\sum \mathrm{PETc}} 100 \qquad (1)$$

PETc denotes crop specific potential evapotranspiration after an adjustment is made to the reference crop PET by the use of appropriate crop coefficients (Kc). Kc values define the water use pattern of a crop. Published values (FAO, 1998) are available for critical points in a crop phenology, and intervening values are linearly interpolated. For example, maize Kc values are given as 0.30, 0.30, 1.20, 1.20, and 0.35 for the times corresponding to 0%, 16%, 44%, 76%, and 100% of LGP, respectively.

The water requirement of the crop (PETc) at a given time in the growing season is calculated by multiplying standard reference crop PET by Kc:

$$\mathrm{PETc} = \mathrm{KcPET} \qquad (2)$$

AETc represents the actual amount of water withdrawn from the soil water reservoir ("bucket"), where shortfall relative to PETc is calculated by a function that takes into consideration the amount of available soil water in the bucket.

Soil water content (SW) is estimated through a simple mass balance equation where the total volume is defined by the water holding capacity (WHC) of the soil. SW is the amount of soil water present at a given time step. The value of SW varies from a minimum of 0 to a maximum equal to WHC (in mm). Each time step's new SW is obtained after determining the actual extraction by the crop (AETc). To determine AETc, dekadal rainfall (PPT) is first added to SW to produce a plant-available-water (PAW) value:

$$\mathrm{PAW}_i = \mathrm{SW}_{i-1} + \mathrm{PPT}_i \qquad (3)$$

where i is the time step index. Depending on the PAW in the bucket, the value of AETc is determined by the following set of functions (see **Figure 1** for a schematic diagram of model components):

$$\mathrm{AETc} = \mathrm{PETc} \qquad \text{when PAW} \geq \text{SWC} \qquad (4)$$

$$\mathrm{AETc} = \frac{\mathrm{PAW}}{\mathrm{SWC}} \mathrm{PETc} \qquad \text{when PAW} < \text{SWC} \qquad (5)$$

$$\mathrm{AETc} = \mathrm{PAW} \qquad \text{when AETc} > \text{PAW} \qquad (6)$$

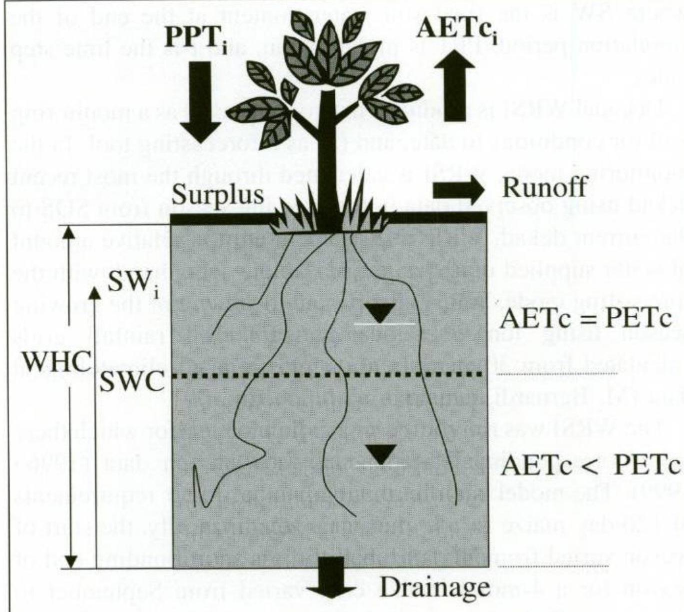

Figure 1. Components of a crop water balance model. See text for definition of terms.

SWC (in mm) is the critical soil water level in the bucket below which AETc will be less than PETc. SWC varies by crop and growth stage according to the following equation:

$$\mathrm{SWC} = \mathrm{WHC} \times \mathrm{SW_f} \times \mathrm{RD_f} \qquad (7)$$

where SW_f is the fraction of WHC that defines the available soil water level below which AETc becomes less than PETc during the mature stage of the crop (when root depth fraction, or RD_f, is equal to 1). For corn the SW_f is 0.45; the literature reports that this value can be estimated as one minus the allowable depletion fraction (FAO, 1998).

The root depth fraction, RD_f, varies between 0 and 1 during the growing season. The effective root depth increases linearly from emergence until the middle of the growing season when it attains effective depth for the remainder of the season. For maize, the effective root depth grows from a value of 0.1 m at emergence to a maximum of 0.9 m beginning in mid-season (after 44% of the growing season). The effective root depth is defined as 70% of the maximum crop root depth (Driessen and Konijn, 1992). The use of the root depth fraction is meant to simulate a young crop withstanding dry soil profiles (smaller SWC) thanks to light rain showers that replenish the upper root zone where the young crop's roots are concentrated.

$$\mathrm{SW}_i = \mathrm{SW}_{i-1} + \mathrm{PPT}_i - \mathrm{AETc}_i \qquad (8)$$

$$\mathrm{SW}_i = \mathrm{WHC} \qquad \text{when SW} > \text{WHC (upper limit)} \qquad (9)$$

$$\mathrm{SW}_i = 0.0 \qquad \text{when SW} < 0.0 \text{ (lower limit)} \qquad (10)$$

where SW is the final soil water content at the end of the simulation period, PPT is precipitation, and i is the time step index.

Dekadal WRSI is produced in two modes: (*i*) as a monitoring tool for conditions to date, and (*ii*) as a forecasting tool. In the monitoring mode, WRSI is calculated through the most recent dekad using observed data in the growing season from SOS to the current dekad. WRSI values represent the relative amount of water supplied until that dekad. On the other hand, with the forecasting mode, WRSI is projected to the end of the growing season using long-term average PET and rainfall grids calculated from 30 years (1961–1990) of FAO climatological data (M. Bernardi, personal communication).

The WRSI was run for the 4-year time period for which there were corresponding Ethiopian crop production data (1996–1999). The model was run to simulate the water requirements of 120-day maize for the meher season. Typically, the start of season varied from May to July, and the corresponding end of season for a 4-month maize crop varied from September to November. End-of-season WRSI images for 20 November of each year were used for this study.

Discrimination between districts that generally do not experience water shortage from those that do was performed using 4-year average WRSI values. Display of these images showed most of the western highlands of Ethiopia with an average WRSI value of 100. Based on this inspection, those districts with an average value of 100 were designated as water-unlimited, whereas those districts with averages less than 100 were designated as water-limited (**Figure 2**). There were 61 and 114 districts in the water-unlimited and water-limited groups, respectively.

The objective was to distinguish districts where yield variation is associated with water from those where yield variations are associated with other factors, like fertilizer input or plant disease.

Some of the factors that can affect the relationship between WRSI-based and reported data are: (*i*) inaccuracy in the reported data, (*ii*) imperfect spatial correspondence between district-wide average WRSI and crop production data that represent only a fraction of the district area, and (*iii*) model simplifying assumptions and flawed data inputs in the model.

The temporal patterns of yield for three cereal crops (maize, sorghum, and teff) were also investigated to explore the potential of using maize WRSI as an indicator of the performance of other cereals growing in the same region. The three crops were chosen as representatives, since in practice they can be grown simultaneously and (or) in succession. Stallknecht et al. (1993) reviewed the work of Ketema (1987), in which he reported that in some parts of the country farmers first plant maize in early April. If this crop fails because of drought, they will replant with sorghum, and if that fails, they will replant the field with teff.

The temporally pooled data set of all districts was used to determine the correlation in yield among teff, maize, and sorghum over the 4-year period. The significance of the correlation was tested using a t test for a correlation coefficient (r) at a significance level of 0.05.

Results

The year-to-year variation of reported yield and the corresponding WRSI values are shown in **Figures 3a** (water-limited districts) and **3b** (water-unlimited districts). **Figure 3a** shows that the WRSI values followed a trend similar to that of reported maize yield. It is clear that 1997 was a drought year in Ethiopia, producing notably the lowest yield during the 4-year period. Although the limited number of years precludes a proper statistical analysis of the correlation between WRSI and yield, an encouraging r value of 0.92 was obtained from the four data points.

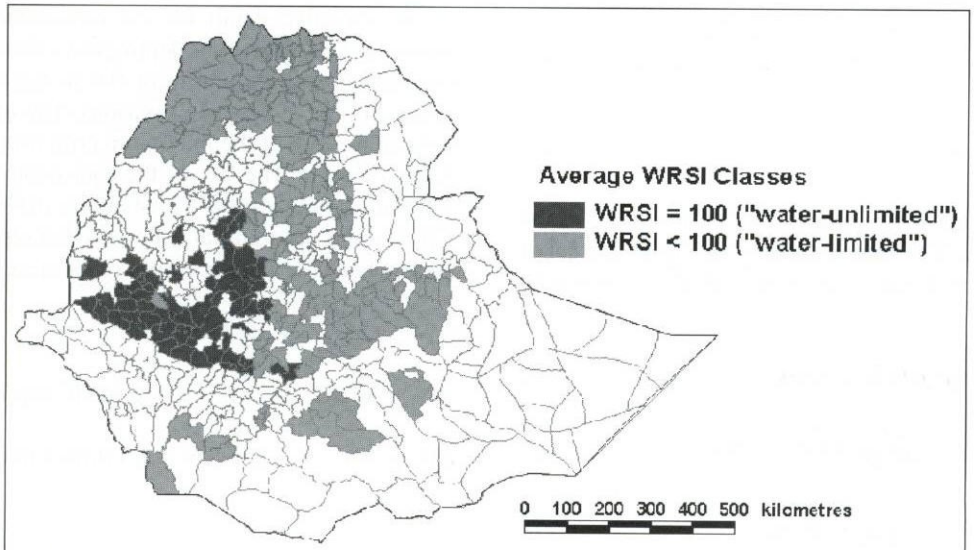

Figure 2. Broad district groups showing water-unlimited and water-limited regions in Ethiopia.

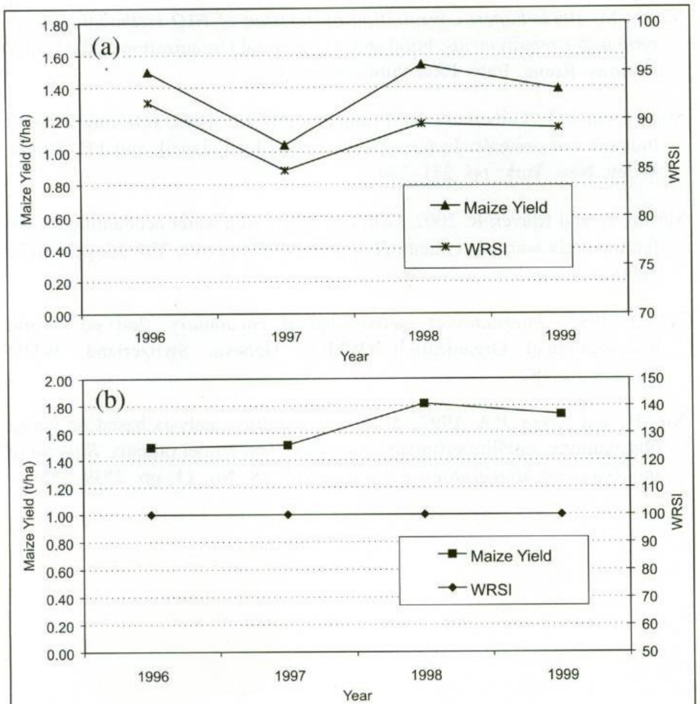

Figure 3. Maize yield and WRSI trends in (a) water-limited and (b) water-unlimited districts in Ethiopia.

Figure 3b shows yield changes for the water-unlimited districts. As expected, there was no marked yield change from 1996 to 1997. This supports the notion that WRSI can be used to distinguish between water-limited and water-unlimited regions. It is interesting to note that there was a marked increase (20%) in yield from 1997 to 1998. We attribute this change to the widespread introduction of an improved maize variety and fertilizer in 1998 (FEWS NET, Addis Ababa, personal communication).

The comparison between water-limited and water-unlimited districts was extended to include sorghum and teff cereals. **Figures 4a** and **4b** show the trends in average yield for the water-limited and water-unlimited districts, respectively (to avoid clutter in the charts, the WRSI values are not shown in **Figure 4**; they are the same as in those in **Figures 3a** and **3b**). The trends for sorghum and teff yields for the water-limited districts were similar to that of maize, in which 1997 is marked by low yield. For the water-unlimited districts (**Figure 4b**), sorghum behaved as expected, with little change from year to year. Teff yield dipped in 1997, however, although not as much as in the drought-prone districts (0.3 t/ha compared with 0.2 t/ha).

Discussion and conclusions

Generally, yield variability of the water-unlimited districts can be characterized by moderate change from year to year compared with the more dramatic changes in the water-limited districts. A large part of the yield variability in the water-limited districts is attributed to crop water stress.

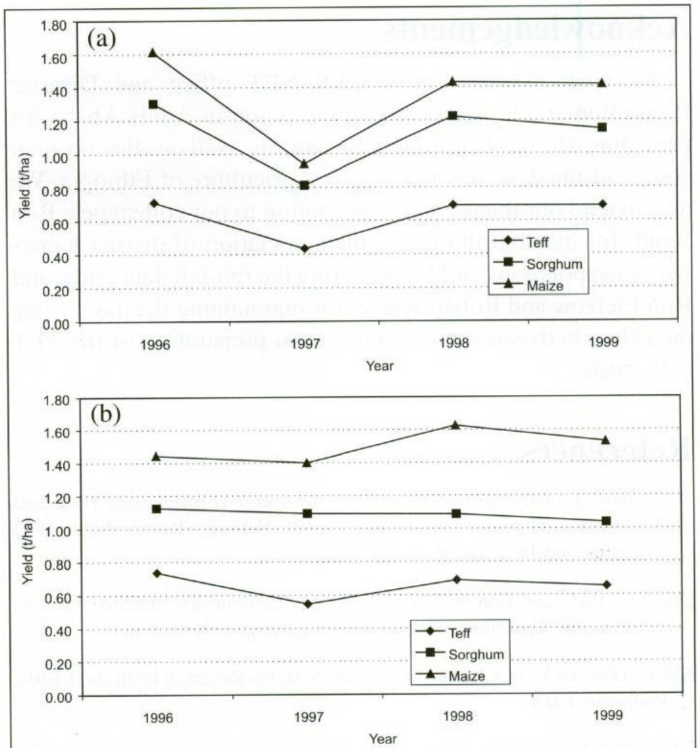

Figure 4. Yield trends of three crops in (a) water-limited and (b) water-unlimited districts in Ethiopia.

Maize WRSI values were observed to track variations in reported yield in water-limited districts. This supports the notion that WRSI-based yield estimates can be developed to estimate a country's production relative to the previous year or a multiyear average. Such estimates can be made immediately upon conclusion of the growing season. Even before the end of the season, WRSI-based yield estimates can be made using long-term average climate data. This is significant for an early warning system. The need to take action to head off food shortages can be identified months earlier than if conventional crop survey figures are awaited.

The yield correlation study among the three cereal crops revealed that there was a positive yield correlation among maize, sorghum, and teff. The relationship between maize and sorghum was stronger than the relationship between maize and teff. The relatively low correlation observed between teff and maize, as compared with that between sorghum and maize, could be due to a difference in the characteristic planting periods. Generally, maize and sorghum are planted early in the meher season, usually completed by the middle of May, whereas teff planting continues throughout July and August (FAO, 1997). We conclude that maize WRSI maps might be used to infer growing conditions for sorghum in the same region and season, but that this should not be done for teff. Further WRSI studies using crop coefficients specific to teff and sorghum should be undertaken to bear this out.

Acknowledgements

We wish to thank the FEWS NET office and Disaster Prevention and Preparedness Commission in Addis Ababa for providing the crop production data, as well as the original source of the data, the Ministry of Agriculture of Ethiopia. We also extend our thanks and appreciation to our colleagues: Ron Smith for his contribution in the association of district names with map polygons and for preparing the rainfall data grids, and Ron Lietzow and Robert Klaver for maintaining the day-to-day data flow between servers and for the preparation of the PET data grids.

References

Doorenbos, J., and Pruitt, W.O. 1977. *Crop water requirements*. Food and Agricultural Organization of the United Nations, Rome, Italy. FAO Irrigation and Drainage Paper 24.

Driessen, P.M., and Konijn, N.T. (Editors) 1992. *Land-use systems analysis*. Wageningen Agricultural University, Wageningen, Netherlands.

ESRI. 2000. *ArcView 3.2a*. Environmental Systems Research Institute (ERSI), Redlands, Calif.

FAO. 1986. *Yield response to water*. Food and Agricultural Organization of the United Nations, Rome, Italy. FAO Irrigation and Drainage Paper 33.

FAO. 1988. *FAO/UNESCO soil map of the World: revised legend*. Food and Agricultural Organization of the United Nations, Rome, Italy. FAO World Resources Report 60.

FAO. 1997. *Irrigation potential in Africa — a basin approach*. Food and Agricultural Organization of the United Nations, Rome, Italy. FAO Land and Water Bulletin. 177 pp.

FAO. 1998. *Crop evapotranspiration: guidelines for computing crop water requirements*. Food and Agricultural Organization of the United Nations, Rome, Italy. FAO Irrigation and Drainage Paper 56.

FEWS NET. 2001. *Ethiopia network on food security*. Famine Early Warning System Network (FEWS NET) Monthly Report 4/01. Available from http://fews.net. Chemonics International, Washington, D.C.

Frere, M., and Popov, G. 1986. *Early agrometeorological crop yield assessment*. Food and Agricultural Organization of the United Nations, Rome, Italy. FAO Plant Production and Protection Paper 73.

Gesch, D.B., Verdin, K.L., and Greenlee, S.K. 1999. New land surface digital elevation model covers the Earth. *EOS, Transactions of the American Geophysical Union*, Vol. 80, No. 6, pp. 69–70.

Kanamitsu, M. 1989. Description of the NMC global data assimilation and forecast system. *Weather and Forecasting*, Vol. 4, pp. 335–342.

Ketema, S. 1987. Research recommendations for production and brief outline of strategy for the improvement of teff [*Eragrotis tef* (Zucc.) Trotter]. In *Proceedings of the 19th National Crop Improvement Conference IAR*, Addis Ababa, Ethiopia.

Los, S.O., Justice, C.O., and Tucker, C.J. 1994. A global 1° × 1° NDVI data set for climate studies derived from the GIMMS continental NDVI data. *International Journal of Remote Sensing*, Vol. 15, No. 17, pp. 3493–3518.

Shuttleworth, J. 1992. Evaporation. In *Handbook of hydrology*. Edited by M. Maidment. McGraw-Hill, New York. pp. 4.1–4.53.

Smith, M. 1992. *Expert consultation on revision of FAO methodologies for crop water requirements*. Food and Agricultural Organization of the United Nations, Rome, Italy. FAO Publication 73.

Stallknecht, G.F., Gilbertson, K.M., and Eckhoff, J.L. 1993. Teff: food crop for humans and animals. In *New crops*. Edited by J. Jancik and J.E. Simon. Wiley, New York. pp. 231–234.

Verdin, J., and Klaver, R. 2002. Grid cell based crop water accounting for the famine early warning system. *Hydrological Processes*, Vol. 16, pp. 1617–1630.

WMO. 1992. *International meteorological vocabulary*. 2nd ed. World Meteorological Organization (WMO), Geneva, Switzerland. WMO Publication 182.

Xie, P., and Arkin, P.A. 1997. A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bulletin of the American Meteorological Society*, Vol. 78, No. 11, pp. 2539–2558.