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Estimating yield of sorghum using root zone water balance model and spectral characteristics of crop in a dryland Alfisol

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ARTICLE INFO

Article history:
Accepted 11 August 2006
Published on line 14 September 2006

Keywords:
Toposequence
Vegetation indices
Water production function
Water stress index

ABSTRACT

This study investigated the relationship between sorghum grain yield for a range of soil depths, with the seasonal crop water stress index based on relative evapotranspiration deficits and spectral vegetation indices. A root zone water balance model was used to evaluate seasonal soil water fluctuations and actual evapotranspiration within a toposequence; soil depth varied between 30 and 75 cm and available water capacity ranged from 6.9 to 12.6% (v/v, %). An empirical model was used to determine root growth. Runoff was estimated from rainfall data using the curve number techniques of the Soil Conservation Services, combined with a soil water-accounting procedure. The high r^2 values between modeled and observed values of soil water in the root zone ($r^2 > 0.70$, significant at $P < 0.001$) and runoff ($r^2 = 0.95$, significant at $P < 0.001$) indicated good agreement between the model output and observed values. Canopy reflectance was measured during the entire crop growth period and the following spectral indices were calculated: simple ratio, normalized difference vegetation index (NDVI), green NDVI, perpendicular vegetation index, soil adjusted vegetation index (SAVI) and modified SAVI (MSAVI). All the vegetation indices, except for the perpendicular vegetation index, measured from booting to anthesis stage, were positively correlated with leaf area index (LAI) and yield. The correlation coefficient for spectral indices with dry biomass was relatively less than for LAI and yield. Modified SAVI recorded from booting to milk-grain stage gave the highest average correlation coefficient with grain yield. Additive and multiplicative forms of water-production functions, as well as water stress index calculated from water budget model, were used to predict crop yield. A multiple regression was carried out with yield, for the years 2001–2003, as the dependent variable and MSAVI, from the booting to the milk-grain stage of crop and relative yield values, calculated using both additive and multiplicative water production functions as well as water stress index, as the independent variables. The multiplicative model and MSAVI, recorded during the heading stage of crop growth, gave the highest coefficient of determination ($r^2 = 0.682$, significant at $P < 0.001$). The multiple regression equation was tested for yield data recorded during 2004; the deviation between observed and estimated yields varied from −6.2 to 9.4%. The water budget model, along with spectral vegetation indices, gave satisfactory estimates of sorghum grain yields and appears to be a useful tool to estimate yield as a function of soil depth and available water.

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0378-3774/$ – see front matter
doi:10.1016/j.agwat.2006.08.002

1. Introduction

The ability to accurately predict the yield of field crops allows producers, economic agencies, and buyers to make decisions with respect to crop management, pricing, and available markets. Other than genetic factor the factors associated with grain yields include soil characteristics (e.g. texture, bulk density, organic matter, nutrient levels), agronomic inputs (fertilizers and soil amendments), field scale management (tillage, drainage and irrigation) and meteorological effects. However, while simulation models can predict yield relatively accurately under ideal conditions, they are much less accurate when the plant suffers stress due to diseases and pests, weed growth, and nutrient and soil water deficiencies.

In dryland/rainfed regions, water has long been considered to be the main limiting resource for crop growth and yield. Although water is limiting, it is often the distribution of water rather than lack of total seasonal amounts that affects crop growth and final yields (Monteith, 1991). Dryland crops frequently suffer crop water stress (i.e. deficit of plant accessible soil water) because of uneven seasonal distribution of rainfall, which may subsequently affect the yield adversely. Actual crop water stress will depend on rainfall partitioning, the water holding capacity of the soil, crop water demands, antecedent soil water content and crop water uptake capacity, and requires at least a simple water balance analysis for calculating all of these components (Barron et al., 2003).

The magnitude of crop water stress/deficit is assessed in terms of the extent by which the actual evapotranspiration (AET) falls short of its potential value (PET) or that the actual soil water content is short of a critical threshold value. A simple water budget model is effective to estimate the availability of water to the crop to meet evapotranspiration. The model only requires knowledge of soil water-holding capacity, rooting depth, crop growth stages, and weather data (Timlin et al., 2001; Victor et al., 1988). The specific indices used to quantify water stress to crop are relative evapotranspiration (AET/PET), relative evapotranspiration deficit (1 − (AET/PET)), or soil moisture deficit (SMD). The effects of stress, as defined by these indices, interact in a complex manner during different periods of the growing season. The combined effect of stress effects in several periods is evaluated by postulating that these effects are additive or multiplicative. Both additive and multiplicative forms of the water production function can predict crop yields within reasonable limits (Rao et al., 1988). While plant available water is a major determinant for crop yields, yield prediction-using crop available water might not give a better picture as other impacts, such as pests and diseases, crop management factors etc., also contribute variability to the yield (Rao and Saxton, 1995).

Remote sensing techniques, in particular multispectral reflectance, can provide an instantaneous, nondestructive, and quantitative assessment of the crop's ability to intercept radiation and estimate for stress and crop yield (Ma et al., 1996; Clevers et al., 1994; Clevers, 1997). Numerous spectral vegetation indices have been developed to characterize vegetation canopies. The most common of these indices, which utilize red and near infrared (NIR) wavelengths, are the simple ratio of infrared to red, or normalized difference vegetation index (NDVI) (Tucker, 1979), or its linear combination i.e., the perpendicular vegetation index (Richardson and Wiegand, 1977). These indices have been found to be well correlated with various vegetation parameters including green leaf area, biomass percent green cover, productivity, and photosynthetic activity (Colwell, 1974; Hatfield et al., 1984; Asrar et al., 1984; Sellers, 1985). Gitelson et al. (1996) proposed a green normalized difference vegetation index (GNDVI), where the green band is used in the equation for NDVI instead of the red band, and showed that the green band, in combination with the NIR band, is more closely associated with the variability in leaf chlorophyll, nitrogen content, and grain yield than the red band.

A number of physical and plant anatomical factors can affect reflectance measurements. When the crop does not cover the entire soil surface, reflectance measured from a certain height above ground level will represent the reflectance of the canopy and the soil surface rather than just the crop itself (Ma et al., 2001). Soil brightness influences have been noted in numerous studies where, for a given amount of vegetation, darker soil substrates resulted in higher vegetation index values when the ratio vegetation index or the NDVI were used as vegetation measures (Colwell, 1974; Elvidge and Lyon, 1985; Huete et al., 1985). A soil adjusted vegetation index (SAVI) was developed to minimize soil influences on canopy spectra by incorporating a soil adjustment factor, L, in the denominator of the NDVI equation. For optimal adjustment of the soil effect, however, the L factor should vary inversely with the amount of vegetation present. A modified SAVI that replaces the constant L in the SAVI equation with a variable L function is presented by Qi et al. (1994). These vegetation indices, calculated from canopy reflectance showing spatial and temporal variation resulting from soil and crop characteristics, are important sources of data for making yield maps (Chang et al., 2005).

Grain sorghum (*Sorghum bicolor* (L.) Moench), a well-adapted crop for southern India, is grown extensively under dryland conditions in Alfisol. Yields of the dryland sorghum are strongly influenced by plant-available soil water content at planting and by growing season rainfall.

The presented analysis in this paper deals with sorghum yield estimation within an Alfisol toposequence using two different approaches: (i) a simple water balance model where additive and multiplicative forms of water production functions are used to predict yield, and (ii) using the spectral characteristics of the crop. Efforts have been made to obtain a better estimation of yield by combining both the water balance approach and use of the spectral characteristics of the crop.

2. Materials and methods

2.1. *Development of a root zone soil water balance model*

A simple root zone soil water balance model is used for estimating the actual evapotranspiration (AET). Here the soil reservoir is divided into two layers: (i) an active layer of depth in which roots are present at any given time and from which both water extraction and drainage would occur, and (ii) a