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Quantifying water stress on wheat using remote sensing in the Yaqui Valley, Sonora, Mexico

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ABSTRACT

Remote sensing can allow a more efficient irrigation water management by applying the water when crops require it or when symptoms of water stress appear. In this study, the spatial and temporal distribution of the water deficit index (WDI) and crop evapotranspiration (ET) in wheat were determined through analysis of satellite-based remote sensing images in the Yaqui Valley, Sonora, México. We utilize an empirical model based on the canopy temperature–vegetation cover relationship methodology known as the Moran's trapezoid. We analyze and discuss the spatial and temporal distributions of WDI and ET at the regional and local scales. Results show a linear relationship ($R^2 = 0.96$) between the values of WDI and the number of days elapsed since the last irrigation. The water deficit index could be utilized to estimate the quantity of available water in wheat and to know the degree of stress presented by the crop. Advantages offered by this methodology include obtaining WDI and evapotranspiration values in zones with partial or null vegetation cover and for large irrigation schemes lacking the necessary data for traditional water management.

1. Introduction

In arid and semi-arid regions, irrigated agriculture is threatened by water shortages caused by pronounced droughts or water mismanagements. More efficient use of water in irrigated agriculture, in particular at the field scale where it is related to irrigation scheduling, can be achieved by improved understandings of water stress. The estimation of water stress in plants is of great importance since it can be used to monitor vegetative activity and predict productivity. A detailed knowledge in space and time of the content of water in a crop would improve the management of water resources, contributing water to the crop when and where it is more vital for its development.

The estimation of water content in vegetation can be carried out in four different forms: (1) field sampling, (2) use of meteorological information, (3) application of remote sensing data and (4) use of hydrological models. Field sampling is the most precise and direct method, but is expensive and time consuming. Usually, water content is measured by gravimetric methods, comparing the humid and dry weight of the sample, which implies that estimation requires a certain time (24–48 h) until the sample dries. The employment of evapotranspiration and risk of fire based on basic meteorological information such as air temperature, relative humidity, precipitation and wind speed can allow estimation of the water stress on the physiologic activity of the plants. These estimates, however, rely on theoretical relationships between the atmospheric state and the hydric condition of the plant, which are assumed identical for many species, and may not be representative of regions far away from the measurement location (Chuvieco et al., 2001).

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The most well-known method to detect water stress in a crop, using remote sensing, is through the measurement of the surface temperature of the vegetation cover. The correlation between the surface temperature and water stress relies on the fact that, when a crop transpires, the evaporated water cools the leaves reaching a surface temperature sometimes below the ambient air temperature. Increase in soil moisture also produces a reduction in surface albedo, as well as, an increment in net radiation, a decrease in sensible heat and an increase in latent heat. Furthermore, under wet soil conditions, Bowen ratio (the ratio of sensible heat to latent heat) is reduced and produces a decrease in ground and surface temperature. As the crop becomes stressed, transpiration diminishes and the leaf temperature begins to increase until it equals or surpasses the air temperature (Jackson, 1982). Dry soil conditions also produce an increase in surface albedo and sensible heat, as well as, a decrease in net radiation and latent heat. Moreover, decrease in soil water content produces a decrease in Bowen ratio and an increase in surface temperature (Eltahir, 1998). This method is particularly effective in hot, arid and semi-arid environments where the leaf temperature of a well-irrigated plant can be more than 10 °C cooler than the air, when the relative humidity is low. Conversely, dry bare soil can be 20 °C hotter than air temperature and up to 30 °C higher than non-stressed plant canopy temperature.

Moran et al. (1994) developed the water deficit index (WDI). This index combines the normalized difference vegetation index (NDVI) and the surface temperature of the foliage to determine water deficit conditions in a field with partial vegetation cover. In this method, the relationship of the difference between surface temperature and air temperature ($T_s - T_a$) and vegetation cover is defined in a trapezoidal shape (see Fig. 1). A disadvantage of using the theoretical WDI model is that some of the inputs to estimate the vertices of the trapezoid are difficult to assess, for example, the aerodynamic resistant (highly affected by wind speed and plant architecture), maximum and minimum canopy resistances (both closely related with stomatal closure and highly dependent on leaf condition) and soil heat flux. Despite these difficulties, in our study area, the Yaqui Valley of Sonora, Mexico, the high evaporative demand during the wheat season allows sufficient variety in surface conditions to construct an empirical trapezoid based on wheat foliage temperature and NDVI data. The spatial variation of field conditions includes regions with wet soil surfaces from recent irrigations, fallow fields with completely dry surface, and high foliage fields with recent irrigations or under severe drought.

Due to the difficulties in obtaining the VIIT vertices, we employ an empirical approach which works well in the high evaporative conditions found in Yaqui Valley. In a similar manner, Clarke (1997) worked with an empirical model on melon based on Moran's trapezoid. He carried out measurements in surfaces of dry and humid soils to define the corners labeled 3 and 4 in Fig. 1. In the same manner, vertex 1 was estimated in a well-irrigated melon field with complete foliage cover. Vertex 2 was also measured on a melon crop known for having severe conditions of drought. The empirical trapezoid provided information with enough accuracy to generate maps of water stress on this particular crop.

In this study, we used canopy minus air temperature ($T_s - T_a$) and vegetation cover (NDVI) data measured in several wheat genotypes and under several irrigation managements (including drought conditions) at Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) in the Yaqui Valley. With this data, the corners of the empirical trapezoid were estimated. With the proposed empirical model, four LANDSAT images were processed in order to estimate the spatial and temporal distribution of water deficit index (WDI) in wheat.

The main goal of our study is to demonstrate that the proposed empirical model can be a reliable and useful tool to estimate water requirements for wheat. This methodology can be used to generate more accurate water management practices and facilitate decisions about irrigation applications.

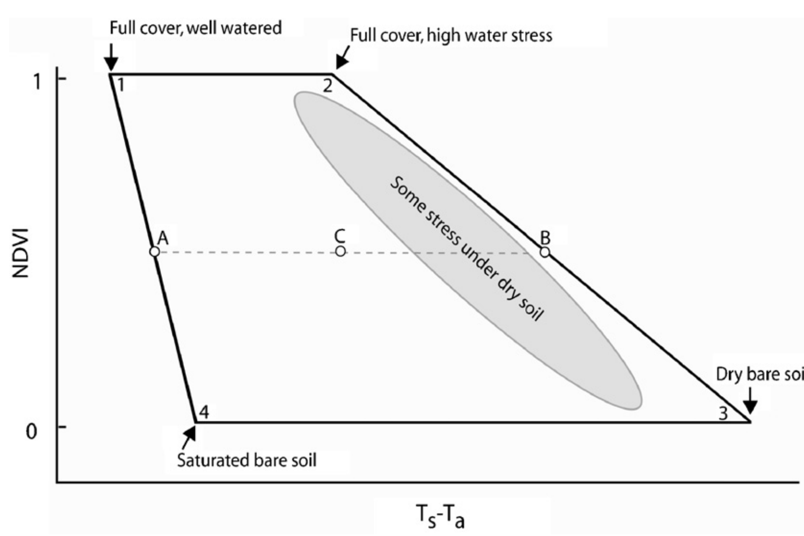

Fig. 1 – Moran's trapezoid. This geometric shape involves the relationship between ($T_s - T_a$) and NDVI. WDI for a point "C" is defined as the ratio of the distances AC and AB. Straight lines connecting vertices 1–4 and 2–3 rely on the assumption that $T_s - T_a$ is linear function of vegetation cover (Moran et al., 1994).