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Establishment and application of spring maize yield to evapotranspiration boundary function in the Loess Plateau of China

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ABSTRACT

The yield to evapotranspiration (Y/ET) boundary function is a simple method for estimating water-limited yield potential and provides a guide for making proper crop management decisions in dryland areas. However, the original approach is arbitrary, and the boundary function is established without following any specific principles. In the present study, based on French & Schultz's boundary function concept and the quantile regression theory, and also linear interpolation to eliminate outliers, we developed an improved method in establishing the Y/ET boundary function. Taking spring maize in the Loess Plateau of China as a case study we selected fundamental data points obtained from 887 records found in 65 papers that were published between 1987 and 2014, and also linear interpolation to eliminate outliers. The results showed that the Y/ET boundary function was $y = 60.5 \times (x - 50)$ with a plateau yield of 15,954 kg ha^{-1} when ET exceeded 314 mm. Without film mulching, the Y/ET boundary function was $y = 47.5 \times (x - 62.3)$ with a plateau yield of 12,840 kg ha^{-1} when ET exceeded 325 mm. We further compared three different crop production methods (plastic film mulching, straw mulching, and no mulching) on maize production in the Loess Plateau. Among these methods, plastic film mulching was the most effective, since it increased the yield potential of spring maize, regardless ET, and hence, improved water use efficiency. Overall, this study provides novel insights into the establishment of the Y/ET boundary functions using specific principles that increase accuracy and help to identify the most profitable crop management systems.

1. Introduction

Dryland agriculture accounts for more than 70% of the total arable land in the world, and produces approximately 60–65% of the total food grains (Biradar et al., 2009). In China, one third of the total cropped area is classified as dryland, of which 40% is located in the Loess Plateau. The yields of dryland crops are lower than those of irrigated crops, and thus, improving productivity is important for maintaining food security and increasing the economic status of local populations (Zhang et al., 2013).

Crop growth simulation models and boundary function analyses have potential to provide insights into the function of crop systems and are important for improving yield potential. Different from simulation models, boundary function analysis is based on actual crop data and provides information about the 'yield potential reality.'

Theoretically, regression analysis can be used to determine the best-fit relationships; however, if the data are spread out, the coefficient of determination is low and the pattern is less distinct. Biscoe and Gallagher (1977) reported that regression analysis does not provide all the needed information to understand the biological mechanisms underlying the complex effects of climate variables on crop growth. In order to overcome these limitations, French and Schultz (1984a,b) plotted crop yield from 61 sites against evapotranspiration (ET) and established a sloping line that enclosed almost all the highest yielding crops at different levels of ET, defining the upper boundary of potential productivity. Yield data below the sloping line were considered to be limited by factors other than ET. The French-Schultz approach is known as the yield to ET (Y/ET) boundary function.

In the boundary function, the intercept on the ET axis is an estimation of the lower limit and related to soil evaporation. The slope of the boundary line is the potential water use efficiency

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(WUE) of a crop. The data points under the boundary line represent the range of data that is limited by factors other than ET such as biotic stress and inadequate nutrition. Despite the drawbacks (Angus and Van Herwaarden, 2001), the Y/ET boundary function is a useful tool that has been successfully applied on different crop systems. Sadras and Angus (2006) used the French-Schultz approach to investigate the relationship between dryland wheat yield and ET in four mega-environments, including the Loess Plateau, the Mediterranean Basin, the Great Plains of USA, and dryland areas in southeastern Australia, the boundary line is used as a benchmark to evaluate the possible improvements in the ratio between marketable produce and evapotranspiration (Molden et al., 2007). The French-Schultz approach was also applied to define the boundary function of the water-limited yield potential of winter wheat and maize in the Loess Plateau (Zhang et al., 2013, 2014) and also the upper boundary of the water-limited yield potential of sunflower in the Western Pampas (Grassini et al., 2009a). Though the water-limited yield potential calculated by the boundary function is just an estimation, the difference between the actual and attainable yield for specific ET provides a guide for making proper crop management decisions (Tow et al., 2011). For example, Trengove and Manson (2003) used the French-Schultz approach to identify the most profitable rotation system among seven crops under the growing conditions of South Australia.

Differences between studies in the establishment of the boundary functions using the French-Schultz approach can be attributed to the lack of specific principles. Grassini et al. (2009b) applied quantile regression (Cade and Noon, 2003) to establish the Y/ET boundary function of dryland maize, using the 95th percentile of yield and the mid-point ET. Compared with the French-Schultz approach, the application of quantile regression is more accurate, since the relationship between the upper boundary of the selected data and the corresponding ET is not always linear. However, in cases that the selected data are sparse or not large enough in a specific ET interval, a representative boundary is difficult to be established.

The present study aimed to improve the French-Schultz approach by applying quantile regression and linear interpolation. With the improved method, we also aimed to establish the Y/ET boundary function of spring maize in the Loess Plateau based on data obtained from previous studies and analyze the yield-water relationships of spring maize under different mulching measures.

2. Data collection

2.1. Research area

The Loess Plateau is located in the northwest of China. It has a semi-arid climate, with extensive monsoonal influence. It is also a vast semi-arid area with annual precipitation from 300 to 600 mm. Additionally, the precipitation is uneven in seasonal and inter-annual distribution while the potential evapotranspiration is high. Hence the limited water resources cannot meet the requirement of crop growth and yields are low compared with those of the humid and sub-humid regions (Parr et al., 1990). The farming in most of the Loess Plateau is a typical dryland farming system. The limited and uneven distribution of the rainfall is a great threat to crop yield.

2.2. Data collection

Data were collected from previous studies found on the China National Knowledge Infrastructure (CNKI) and the Web of Knowledge (WOK) using keywords 'maize,' 'evapotranspiration,' 'yield,' 'water use,' and 'Loess Plateau.' Data reported in tables and graphs were used to construct a dataset for spring maize yield and seasonal ET under dryland farming conditions. To ensure the accuracy of ET calculations; all the soil monitoring depths included in our data set were at least 2 m. In total, we used data from 887 records found in 65 papers published between 1987 and 2014; distributing over 20 different experiment sites in the Loess Plateau (Fig. 1). Due to climate conditions; including temperature and precipitation; spring maize is mainly distributed in areas south of the Great Wall.

3. Results and discussion

3.1. Establishment of the boundary function

In the French-Schultz approach, an arbitrary line is drawn to enclose almost all the highest yields at different levels of ET (French and Schultz, 1984a,b), whereas quantile regression arranges data points into several classes according to ET (Cade and Noon, 2003; Grassini et al., 2009b). Boundary data points are defined as the 95th percentile of yield in each class. In the French-Schultz approach, the boundary data points are selected visually, without following any specific principles. The overall process of selecting data points using

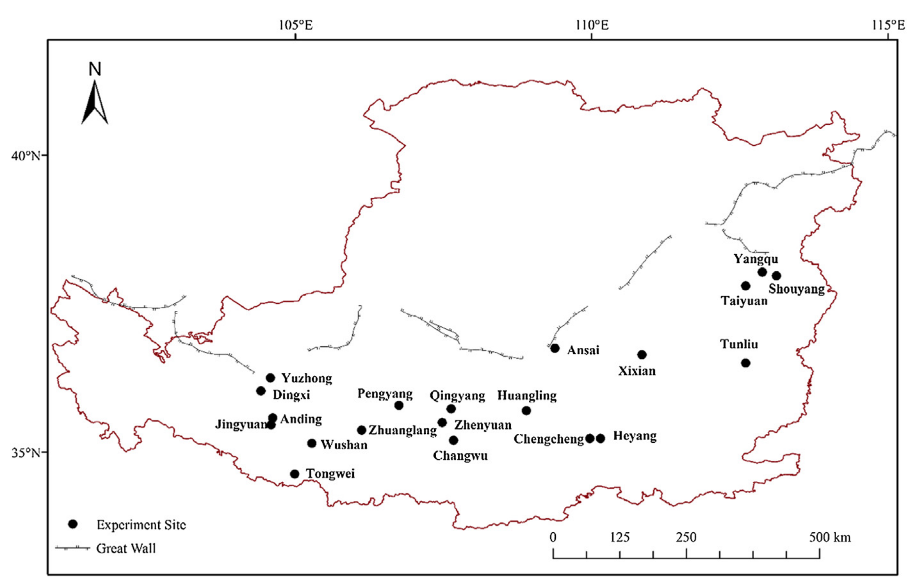

Fig. 1. Distribution of 20 study sites in the Loess Plateau, China.