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Review

Determining water use efficiency of wheat and cotton: A meta-regression analysis

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ABSTRACT

A great challenge for agricultural production is to produce more food with less water, which can be possibly achieved by increasing crop water use efficiency (WUE). This study systematically reviewed 52 cases from 49 empirical studies with field experimental results on wheat and cotton. This research investigated yield-water use relations under both furrow and micro irrigation systems, compared optimal water use to achieve maximum WUE and maximum yield, calculated water saving potentials under various scenarios, and evaluated the effects of influential factors using meta-regression analysis. The results suggest that to achieve maximum WUE rather than maximum yield, water use for wheat can be reduced by 30.4% with a grain yield decrease of 14.8%, and water use for cotton can decrease by 51.4% with a yield reduction of 51.7%. Compared with furrow irrigation, micro irrigation reduces wheat water use by 22.7% and increases yield by 36.7%. While for cotton, micro irrigation reduces water use by 36.8% and decrease yield by 21.4%. Under the scenario of a 10% yield reduction, water use decreases by 25% for wheat and by 20–22% for cotton. Compared with maximum yield, other yield levels reduce water use by 2–15% on average for wheat, and by 15–17% for cotton. Achieving maximum WUE reduces water use by 14–31% compared with other sub-optimal WUE levels. The meta-regression analysis showed adoption of micro irrigation systems, and farm management practices on soil and water significantly improved wheat and cotton WUE. Assessments of the publication selection bias and genuine effects illustrate the application of weighted least squares in conducting meta-regression analysis.

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1. Introduction

With the rapid growth of the world population, fresh water becomes increasingly scarce across the globe. Agriculture is the largest water-consuming sector and water shortage is a principal limiting factor for crop production. The problem is most acute in regions where rainfall is limited or highly variable. For example, the annul precipitation is less than 200 mm in arid areas of Hexi Corridor, Gansu Province, northwestern China (Huang et al., 2012; Fan et al., 2014); it's only about 105 mm in Xinjiang Province, China, and a majority occurs from June to August (Kang et al., 2012); in North China Plains, although the mean precipitation is 500–600 mm, the annual crop evapotranspiration (ET) of 800–900 mm considerably exceeds the precipitation (Jin et al., 1999; Liu et al., 2002). Therefore, to offset water deficit and maintain a high crop grain yield in those areas, agricultural production relies heavily on irrigation. In addition, water scarcity is due to lack of surface water in some areas of the world, such as northwestern China and North China Plains, Southern Texas High Plains of U.S., and parts of Uzbekistan, Syria, Turkey and India (Fan et al., 2014; Murray et al., 2012). In such regions, groundwater becomes a primary source for agricultural irrigation, resulting in persistent declining of groundwater levels and considerably large zones of groundwater depression (Bordovsky et al., 1999; Du et al., 2006; Ibragimov et al., 2007; Liu et al., 2011; Oweis et al., 2011; Singh et al., 2010; Yazar et al.,2002).

Limited availability of irrigation water requires fundamental changes in irrigation management and promotes application of water saving techniques. Traditionally, furrow, flood and basin irrigations are the common methods. These irrigation systems tend to over-irrigate croplands, resulting in a waste of water and low water use efficiency (WUE) (Yazar et al., 2002b). Micro irrigation systems (e.g., drip emitters, drip tape, spray, and sprinklers), either spraying water to plants or dripping near their root zone, save 30–70% of the irrigation water and has gained increasing popularity in irrigated agricultural production (Ibragimov et al., 2007; Kang et al., 2012; Yazar et al., 2002b). With unique agronomic and economic advantages, micro irrigation also shows a potential of precisely applying water and chemicals across croplands which reduces labor and energy inputs (Gärdenäs et al., 2005; Levidow et al., 2014). Much research regarding the irrigation effects on cotton demonstrated that micro irrigation systems led to improved yields and more efficient water use than traditional methods (Bucks et al., 1988; Hodgson et al., 1990; Mateos et al., 1991). Comparative studies between micro and traditional irrigation systems have revealed a significant increase of grain yields, harvest index and crop water use efficiency (Cetin and Bilgel, 2002; Ibragimov et al., 2007; Schneider and Howell, 2001; Yazar et al., 2002a), provided that the irrigation systems are properly designed, managed, operated and maintained.

Meta-regression analysis (MRA) is a statistical model used to analyze data points obtained from separate empirical studies (Phillips, 1994; Stanley and Jarrell, 1989). MRA has the advantage of being able to systematically account for a complex set of potential factors that may influence some dependent variable under concern, and to draw conclusions from the analysis of literature (Loomis and White, 1996; Smith and Kaoru, 1990; Stanley, 2001). To the best of authors' knowledge, however, a comprehensive meta-regression analysis of the relations between WUE and irrigation systems as well as other farm management practices has not yet been conducted, and the purpose here is to fill this gap.

Based on a pooled database obtained from empirical studies, this paper compares WUE with estimation of production functions under both furrow and micro irrigation systems, and evaluates WUE of wheat and cotton using meta-analytical techniques. Specifically, the objectives are: (1) to investigate minimum and maximum values of WUE for wheat and cotton, explore potential water saving under various scenarios, and provide a comparable benchmark for future studies, (2) to explore the potential relationship between WUE and various influential factors, especially effects of micro irrigation and farm management practices on crop, soil, water and fertilizer[1] in improving WUE of wheat and cotton, and (3) to evaluate the application of MRA in synthesizing studies of agricultural water management, and examine publication selection bias and applicability of multiple econometric models.

2. Literature review

2.1. Crop water use efficiency and farm management practices

Higher WUE and/or higher yield can be achieved by applying various farm best management practices (BMPs) (Levidow et al., 2014), for instance, no/minimum/rotational tillage, straw/film mulching, etc. The research by Hou et al. (2012) showed that compared to the conventional tillage, the rotational tillage significantly improved soil moisture status, increased the amount of soil

[5] The coding of the selected studies originally included several other variables, including precipitation, more categories of climates, and fertilizer application rate. Given the primary goal of this study and multicollinearity concerns, these variables were finally excluded from the analysis to ease the analysis and interpretation of the results.

[1] Crop management practices include crop rotations, annual double cropping, planting catch crops, better crop varieties, etc. (Ingram et al., 2012). Soil management practices refer to alternative/rotational tillage, no/minimum tillage, terracing maintenance, sowing (Ingram et al., 2012; Jalota et al., 2008). Water management practices include investigation of crop water requirements and crop evapotranspiration during various growing stages, scientific irrigation scheduling, amount of effective rainfall, and supplementary irrigation (Cayci et al., 2009; Kang et al., 2012). Fertilizer management practices include investigating optimal combination of N, K, and P fertilizer, and varying frequencies and amount of fertilizer application during multiple growing stages (Komilov et al., 2003; Qin et al., 2016).