Agricultural Water Management 210 (2018) 158–164

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Crop yield and water use efficiency under aerated irrigation: A meta-analysis

Ya-Dan Du[a,b], Wen-Quan Niu[a,b,c,*], Xiao-Bo Gu[a,b], Qian Zhang[a,b], Bing-Jing Cui[a,b], Ying Zhao[d]

[a] Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas of Ministry of Education, Northwest A&F University, Yangling, Shaanxi, 712100, China

[b] College of Water Resources and Architectural Engineering, Northwest A & F University, Yangling, Shaanxi, 712100, China

[c] Institute of Soil and Water Conservation, Northwest A & F University, Yangling, Shaanxi, 712100, China

[d] College of Resources and Environmental Engineering, Ludong University, Yantai 264025, China

ARTICLE INFO

Keywords:
Aerated irrigation
Yield
Water use efficiency
Meta-Analysis

ABSTRACT

Aerated irrigation (AI) is well recognized to improve yield and water use efficiency (WUE) by improving the soil root zone environment and increasing crop water and fertilizer absorption. However, the effects of AI on crop yield and WUE are variable. We conducted a meta-analysis to: 1) quantify the effect of AI on crop yield and WUE; and 2) identify soil factors and management practices that favor increased yield and WUE under AI relative to control. Results showed that AI is benefit to increase crop yields and WUE (grand mean increases of 19.3% and 17.9%, respectively). However, its effectiveness depends on the environmental and managerial factors of the studies evaluated. Larger responses were found in medium-textured soils, acidic soils (pH $<$ 7), and/or crops receiving high levels of irrigation. At a drip tape placement depth of 10–20 cm and AI frequency of more than once every three days, Venturi aerated equipment produced the largest effect size. Our findings highlight the potential of AI to increase yield and WUE, and identify the conditions under which these results can be achieved. AI techniques can be used successfully around the world, and have the advantages of low cost and easy operation.

1. Introduction

By 2050, the global population is expected to reach 9 billion, an increase of 3 billion people from 2000 (Bagatur, 2014). This rapidly increasing population creates a huge challenge for feeding the population on decreasing arable land area and scarce water resources. Water is an essential substance for ensuring agricultural productivity (Sauer et al., 2010). A report by Mekonnen and Hoekstra (2016) suggested that water scarcity affects 4 billion people globally. Furthermore, competition for water resources among agricultural, industrial, and urban consumers has become increasingly serious. In order to ensure water availability and feed the growing human population, it is necessary to develop novel strategies for growing crops that reduce the amount of water used, while also increasing, or at least maintaining yield.

One practice that has been proposed to increase water use efficiency (WUE) is an irrigation strategy called aerated irrigation (AI) (Bhattarai et al., 2006; Abuarab et al., 2013). The rhizosphere during irrigation and several hours after irrigation remains near-saturated, which significantly decreases air permeability and oxygen level in the root zone (Niu et al., 2012a). Oxygen deficiency in the root zone has been shown to inhibit root growth, reducing the ability of the root system to absorb water, and resulting in drainage and leakage of higher water volumes with concomitant decreases in WUE (Bhattarai et al., 2006; Niu et al., 2012b). However, AI can transport aerated water to the root zone, which has the potential to ameliorate hypoxic or anoxic conditions and promote plant water and nutrient uptake.

Many researchers have studied the effects of AI on crops, but the results are not consistent. Some studies indicated that AI greatly increases crop yield, ranging from 20 to 150%, which is very important for saving scarce water resources and maintaining higher crop yield (Busscher, 1982; Melsted et al., 1949; Bryce et al., 1982). Opposite results, however, have indicated that AI not only has no effect on crop yield, but even delayed flowering and fruit formation (Bonachela et al., 2010; Ben-Noah, 2012; Vyrlas et al., 2014). This raises the question: is it necessary to conduct AI when to irrigation? Previous studies have reported that different AI methods have different effects on crops, which may be due to factors such as crop type, soil characteristics, and burial depth of subsurface tubing (Chen et al., 2011; Niu et al.,2013; Li et al., 2016a). How do we then conduct AI based on experimental conditions? Answer this question is difficult when experiments at only one location.

Meta-analysis, however, is a statistical model used to analyze

* Corresponding author at: No. 26 Xinong Road, Yangling, Shaanxi Province, 712100, China.
E-mail addresses: dyd123027@163.com (Y.-D. Du), nwq@nwafu.edu.cn (W.-Q. Niu).

https://doi.org/10.1016/j.agwat.2018.07.038
Received 8 February 2018; Received in revised form 19 July 2018; Accepted 29 July 2018

datapoints from separate empirical studies (Stanley and Jarrell, 1989). Meta-analyses have the advantage of being able to systematically account for a complex set of potential factors that may influence some dependent variable of concern and to draw conclusions from the literature (Smith and Kaoru, 1990; Stanley, 2001). We applied a meta-analysis to systematically analyze the available information on the effect of AI on yield and WUE. Such a comprehensive analysis may increase the quantitative understanding of AI on yield and WUE, and may help to improve recommendations for AI application. Therefore, our objectives were to: 1) quantify the effects of AI systems on WUE and crop yield relative to the control; 2) and identify management strategies and soil characteristics that increase yield and WUE under AI systems.

2. Materials and methods

2.1. Data collection

A meta-analysis was conducted to characterize the responses of crop yield and WUE to the application of AI. Data were extracted from studies where irrigation without AI (control) could be compared to an equivalent treatment with AI, with all other factors unchanged. Conducting systematic and exhaustive literature searches and screening are critical for comparing and evaluating crop yield and WUE using AI. Extensive literature searches using several search engines, including Elsevier (Science Direct), Web of Science, Springer Link, Google Scholar, Baidu Search were conducted up to December 2017 using the following key words: aerated irrigation, aeration, oxygation, and oxygen, air injection, yield, venturi, hydrogen peroxide and WUE. Some additional studies were located by scanning the reference lists of identified publications. Our objective was to determine the potential effect of AI on crop yield and WUE. We did not have any restrictions on publication time and language. Approximately 520 articles relating to any combinations of relevant keywords were reviewed initially. Two rounds of article screening were subsequently carried out. The first screening excluded articles unrelated to AI of crops, e.g. dynamic changes in bubble profile under AI, water and air flow under AI, only AI application without information on crop yield and water use. The second screening excluded articles for which the authors were unable to obtain or calculate WUE values, and relating soilless cultivation experiment. After the two rounds of article screening, 62 empirical studies focusing on crop yield and WUE under AI remained.

Papers during the final screening were then scrutinized and included if they met the following criteria: 1) the experimental design had to be detailed enough to determine all the critical aspects of the treatment, including aerated volume, aerated equipment, and irrigation levels; 2) included an experiment and control and ensured that the treatment was the same as the control in all aspects except for the inclusion of aerated irrigation; 3) used replicated samples for each treatment. Of all the studies, 27 studies with 71 pairwise comparisons were used for crop yield, and 19 studies with 57 pairwise comparisons were used for WUE (expressed as the ratio of crop yield and water consumption).

Data were extracted from tables presented in the manuscripts or from the figures by GetData Graph Digitizer 2.26 (http://www.getdata-graph-digitizer.com/index.php). If replicate numbers (n) and standard errors (SE) were given, the standard deviation (SD) were calculated according to $SD = SE \times \sqrt{n}$. When no measures of variance were available, we contacted the corresponding authors to obtain such data. The following additional, moderating variables were recorded and categorized (if they were reported) to maximize in-group homogenization: soil texture (clay and non-clay) according to USDA soil texture classes (USDA, 1993); soil pH (< 7 or ≥7), bulk density (< 1.35 or ≥1.35) using by USDA soil texture classes (USDA, 1993); crop type (vegetables/industrial crops or cereals); experimental type (field or pot) due to the aeration was carried out in the field and during lab incubation; burial depth of subsurface tubing (≤10, 10–20 and ≥20); irrigation volume (< 100% field capacity (FC) or ≥100FC); AI frequency (< 3d or ≥3d); AI machine (compressor, chemical method, or Venturi); and AI volume.

AI volume was presented in different ways in these studies, including aerated duration (i.e. h/d aeration), gravimetric air content of water (i.e. mg/L) (Bagatur, 2014), aerated quantity per unit area (i.e. L/Ha), percentage of soil porosity (SP) (Niu et al., 2013), and injected air by volume of water (AV). Since SP and AV were the most common and quantifiable, we grouped them into two categories for AI volume according to the references: 1) High AI, when the air volume in the root zone was not allowed to drop below 50% of the soil porosity (SP ≥ 50%), or if the AV was expressed, it was not allowed to be lower than 12% air in the irrigation water (AV) (AV ≥ 12%), 12% is the conventional AV (Bhattarai et al., 2005); and 2) Low AI, when the air volume in the root zone was below 50% of the soil porosity (SP < 50%), or if the AV was below 12% air in the irrigation water (AV) (AV < 12%).

2.2. Data analysis

For crop yield and WUE, the natural log of the response ratio (R) was used as the measure of effect size, and was calculated using the ratio between a given variable in the treatment group (x_t) to that in the control group (x_c) (Hedges et al., 1999):

$$R = \ln(\frac{x_t}{x_c}) \tag{1}$$

The variance of effect size (Var_R) was calculated as below:

$$Var_R = \frac{s_t^2}{n_t x_t^2} + \frac{s_c^2}{n_c x_c^2} \tag{2}$$

Where s_t, s_c, n_t and n_c were the standard deviation of the treatment group and control group, and replicate numbers in the treatment group and control group, respectively. In order to acquire the overall effect size of the treatment group relative to control group, the weighed response ratio (R_{pool}) was calculated as in Jian et al (2016) and Lu et al (2013):

$$R_{pool} = \frac{\sum_{i=1}^{m}\sum_{i=1}^{k} w_{ij} R_{ij}}{\sum_{i=1}^{m}\sum_{i=1}^{k} w_{ij}} \tag{3}$$

Where, m is the number of compared groups, k is the number of comparisons in the corresponding group, and w_{ij} is the weighting factor.

$$w_{ij} = \frac{1}{Var_R} \tag{4}$$

The variance of R_{pool} was calculated as follows:

$$Var(R_{pool}) = \frac{1}{\sum_{i=1}^{m}\sum_{j=1}^{k} wij} \tag{5}$$

The 95% confidence interval (95% CI) for the R_{pool} was calculated with the following equation:

$$95\%\, CI = R_{pool} \pm 1.96 \times \sqrt{Var(R_{pool})} \tag{6}$$

If the 95% CI did not overlap with zero, the effect size of the treatment was considered significantly different from the control. When the 95% CI between categories did not overlap, we considered the effect sizes to be significantly different from each other. In order to facilitate interpretation, all results of the analyses herein were reported as the percentage change with AI application relative to the control treatment ([R-1] × 100%).

To examine the heterogeneity between studies, Higgins' I^2 statistic was used to describe the percentage of the total variation among studies. Three categorizations of 25% (low), 50% (moderate), and 75% (high) heterogeneity were adopted (Higgins et al., 2003). Publication bias was assessed visually using a funnel plot. If evidence of publication