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Review

Meta-analysis of crop yields of full, deficit, and partial root-zone drying irrigation

Michael O. Adu [a,*], David O. Yawson [b], Frederick A. Armah [b], Paul A. Asare [a], Kwame A. Frimpong [c]

[a] Department of Crop Science, School of Agriculture, College of Agriculture and Natural Sciences, University of Cape Coast, Cape Coast, Ghana
[b] Department of Environmental Science, School of Biological Science, College of Agriculture and Natural Sciences, University of Cape Coast, Cape Coast, Ghana
[c] Department of Soil Science, School of Agriculture, College of Agriculture and Natural Sciences, University of Cape Coast, Cape Coast, Ghana

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ABSTRACT

Techniques that reduce the volume of water applied in irrigation are desirable in the face of dwindling water resources and increasing demand for food. Various water-saving irrigation strategies, involving, the application of water below full crop-water requirements, have been advanced. This study employed meta-analysis to examine the relative crop yield performance of full irrigation (FI), deficit irrigation (DI) and partial root-zone drying irrigation (PRDI). The review included 35 studies, representing 14 study countries, and reporting 43 crop yields of (i) DI against that of PRDI; (ii) FI against that of DI; and (iii) FI against that of PRDI. Overall, crops under DI produces similar yields as PRDI but yields under both are typically lower than yields of FI. There were variations in yield response of different crops to DI and PRDI, suggesting crop and/or context-specificity. The main factors contributing to the yield response were crop species and soil texture. Crop yields between FI, DI and PRDI vary significantly if crops are more frequently irrigated. It is concluded that DI and PRDI result in yields lower than those of FI but yields of DI and PRDI are comparable. Economically justifying and weighing the cost of water-saving irrigation strategies against the expected yield penalties is therefore crucial.

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* Corresponding author.
E-mail address: michael.adu@ucc.edu.gh (M.O. Adu).

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1. Introduction

Water is a major determinant of biomass production and yields of crops due to its critical role in photosynthesis, nutrient dissolution and uptake, transport and other physiological processes in crop plants. Sufficient availability of water in the root zone is therefore crucial throughout the growing season of a crop. As a result, crop production is the most water-intensive human activity, accounting for about 70% of water abstracted worldwide (Yang et al., 2006; Yawson et al., 2014). Of this, irrigation accounts for 60–80% (Huffaker and Hamilton, 2007). However, in the face of growing water scarcity and demand for food, there is a need to increase water use efficiency (WUE) in crop production without incurring large yield and environmental penalties (Carrijo et al., 2017). Given that the increasing WUE in crops is a major challenge to breeding due to the intricate relationship between transpiration and photosynthesis, agronomic approaches are crucial and inevitable.

Globally, only 17% of croplands are under irrigation but this accounts for 40% of total food production (Molden et al., 2010). While irrigation can increase crop yields four-fold compared to rain-fed production (Sepaskhah and Ahmadi, 2010), water use efficiencies (WUEs) are not particularly high in irrigation production systems. Some agronomic water-saving options promoted include better irrigation scheduling, up-to-date irrigation systems and reuse of wastewater. These options can potentially decrease the use of fresh water for irrigation by 30% (Dworak et al., 2007; Psarras et al., 2014). Water-saving approaches that directly target reductions in water input include deficit irrigation (DI; applies to conventional or sustained or regulated deficit irrigation in this study) and partial root-zone drying irrigation (PRDI). Compared to full irrigation (FI) in which crops receive their full evapotranspiration requirements, DI involves the application of water below the crop's full water requirement, in a closely controlled manner over a prescribed part or parts of the seasonal cycle of plant development (Kriedemann and Goodwin, 2003). In contrast, PRDI involves alternating irrigation in space and time to generate wet-dry cycles in different sections of the root system to simultaneously maintain plant water status at maximum water potential and control vegetative growth for prescribed parts of the seasonal cycle of plant development (Sadras, 2009; Kriedemann and Goodwin, 2003).

Although the mode of operation of DI and PRDI differs significantly, both are designed to improve WUE and limit excessive vegetative growth (Kriedemann and Goodwin, 2003). With DI (especially regulated DI), water application is manipulated over time, where water deficit is imposed in a controlled way over a critical period during the crop's growth. In contrast, with PRDI, water is manipulated over space, where water deficit is applied by separating alternating dry and moist roots using dual irrigation lines that can be operated separately (Kriedemann and Goodwin, 2003). It has been reported that PRDI improves irrigation water productivity (IWP, yield per unit applied irrigation water) with respect to controls receiving markedly more water, but similar gains are often attained with DI (Sadras, 2009). In a meta-analysis, Sadras (2009) concluded that the water productivity gains from DI and PRDI were statistically comparable and that it is important to identify conditions under which one method would be economically preferable to the other. However, in terms of crop yield, it is not clear which of these methods is superior and how well they compare with full irrigation. At least, between DI and PRDI, the results are inconsistent (e.g. see Savic et al., 2009; Kirda et al., 2007; Ismail and Phizackerley, 2009).

Therefore, there is a need to establish the effect and superiority of DI and PRDI on crop yields, vis-à-vis FI, to justify recommendation of one approach over another. The present study therefore used meta-analysis to examine the performance of FI, DI and PRDI in terms of crop yields. We distinctly conducted meta-analysis of crop yield between DI (control) and PRDI, FI (control) and DI, and FI (control) and PRDI. Some of the related crop and soil properties which could contribute to the differences in crop yields, including crop species, agronomic purpose of crops (cereals or vegetables or fruits or arable crops, etc.), location of the experiment (field or greenhouse), the frequency of water supply to the crops and soil texture were also analysed. To enable comparison under similar scale and conditions, the review was limited to studies reporting on all three irrigation practices.

2. Methods

2.1. Literature search and selection of relevant primary studies

We searched for primary studies published between January 1990 and December 2016 that reported yield comparisons between full irrigation (FI), regulated deficit or conventional deficit irrigation (DI) and partial root-zone drying irrigation (PRDI). The search was done in Scopus, AGORA and in Google Scholar. Combinations of the following search terms were used in all databases: "Full* Irrigation" OR Deficit* Irrigation" OR "Partial root-zone*" OR "Partial root zone*"AND Yield.

We applied several selection criteria to ensure that minimum scientific standards were met. Studies were only included if (i) they reported yield data on individual crop species in a DI, PRDI treatment and there was a control treatment of full irrigation (FI); (ii) they reported primary data; (iii) the scale of the yield observations for the FI, DI and PRDI were comparable; (iv) reported the mean (X), sample size (n) and a measure of dispersion (SE, SD, 95% CI; not necessarily mandatory) as numerical or graphical data, or if SD of yields could be estimated from the reported data for all three irrigation regimes; and (v) the data were not already included from another paper, in order to avoid multiple counting. Standard deviations (SD)