Agricultural Water Management 169 (2016) 61–76

Contents lists available at ScienceDirect

Agricultural Water Management

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

An alternative approach to whole-farm deficit irrigation analysis: Evaluating the risk-efficiency of wheat irrigation strategies in sub-tropical Australia

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ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form 2 February 2016
Accepted 13 February 2016
Available online 27 February 2016

Keywords:
Supplementary irrigation
Water use efficiency
Soil water
Partial irrigation
Supplemental irrigation

ABSTRACT

Uncertainty exists as to the optimum whole-farm irrigation strategy for wheat growing in subtropical Australia under water-limited conditions. While deficit irrigation has been shown to have greater economic water productivity (EWP) in such circumstances in other regions, there are limitations to the cost/revenue function approach traditionally used to evaluate EWP, including inapplicability across environments. These limitations can however be overcome with the use of a validated cropping systems model.

The APSIM farming systems model was therefore used to determine whether growing larger areas of deficit irrigated wheat is more profitable than full irrigation of a smaller area in sub-tropical Australia, under water limited conditions. Optimal irrigation strategies were not only profitable but also those considered risk-efficient, i.e. closest to a 1:2 'line of indifference' that identifies the two unit increase in risk (measured as standard deviation) acceptable to farmers in return for a unit increase in profit. The value of stored soil water was assessed by simulating rainfed crop production on unirrigated land, and/or assigning an economic value to stored soil water remaining at the end of the season.

The results demonstrated that deficit irrigation of larger areas of wheat was generally more profitable and risk-efficient than smaller areas of full irrigation. When precipitation or stored soil water at sowing was increased, the most risk-efficient strategies were those that spread water across a larger area at a reduced frequency of irrigation. However in a low rainfall environment when water was expensive and soil water had the same economic value as irrigation water, fully irrigating a smaller area was the most profitable and risk-efficient option. The importance of evaluating farm-management strategies using EWP (i.e. incorporating gross margins) instead of crop water productivity (grain yield per unit of water use) was evident, as re-ranking of farm-management strategies occurred between these alternative methods of calculating whole-farm WP. Accounting for the intrinsic value of stored soil water and precipitation was fundamental to understanding the benefit of deficit irrigation strategies in water limited situations, as the larger crop area sown in conjunction with deficit irrigation strategies accessed much larger absolute volumes of soil water and precipitation. Future evaluations of deficit irrigation strategies should account for such considerations.

1. Introduction

Maximum crop water productivity (yield per unit of evapotranspiration) for a single production field of spring wheat has generally been achieved in conjunction with high levels of water input at yield levels of 7–8 t/ha (Steiner et al., 1985; Musick et al., 1994; Zhang and Oweis, 1999). This occurs because greater transpiration water use on a given field area decreases the proportion of 'unproductive' water use that is lost through evaporation, as long as the crop responds to increased water input at maximum transpiration efficiency (French and Schultz, 1984; Peake, 2015). Water productivity (WP) is defined herein as suggested by Barker et al. (2003): "the ratio of crop output to water either diverted or consumed, the

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http://dx.doi.org/10.1016/j.agwat.2016.02.013

ratio being expressed in either physical or monetary terms, or some combination of the two".

However the profitability of irrigation enterprises relies on maximising economic water productivity (EWP) for an entire farm rather than an individual field. Maximum farm-scale EWP for irrigated wheat has often been achieved through the use of deficit or supplemental irrigation (Zhang and Oweis, 1999; Tavakkoli and Oweis, 2004; Geerts and Raes, 2009), although in dry seasons the advantages of deficit irrigation strategies are less apparent (Pereira et al., 2002). Deficit irrigation is defined herein as the deliberate under-irrigation of the crop such that it receives less water than the amount required to achieve maximum evapotranspiration (English, 1990; Fereres and Soriano, 2007).

In practice, deficit irrigation under water-limited conditions enables irrigation and cropping over a larger area than could otherwise be achieved if the crop water requirement was fully met. Deficit irrigation may be highly relevant to irrigated wheat growers in the northern grains region of eastern Australia (also known as the northern grains region), who consider that the typical water availability prior to sowing an irrigated wheat crop would be enough for only a single furrow-irrigation event during the season per unit of irrigable farm area, or approximately 1.3–1.5 ML ha^{-1} (Hamish Bligh, Rob Holmes, Phil Lockwood (pers. comm.)). However, uncertainty exists as to the optimum whole-farm irrigation strategy for wheat growing in the region as irrigated wheat cropping has been historically uncommon.

Alternative irrigation strategies have frequently been compared using crop production functions (sometimes combined with additional economic or cost/revenue functions) that examine the relationship between yield or economic return, and water consumed. The prevalence of production functions in WP evaluation studies (Capra et al., 2008) is no doubt due to their simplicity, however they ignore the important economic factors involved in deciding whether irrigating a larger area is indeed more profitable, such as the additional cost of preparing, sowing and managing a larger cropping area, and the price of irrigation water. Therefore other studies have used the framework of English (1990) to combine production functions with cost/revenue functions. Unfortunately, there are additional disadvantages that apply to both cost/revenue and production functions.

Firstly, the functions vary between environments (Zhang, 2003), do not account for variable crop response to water deficit at different growth stages (Geerts and Raes, 2009), and may not be applicable in a specific cropping season if climatic conditions (especially rainfall) are markedly different from the median (Pereira et al., 2002). They also do not account for the losses of irrigation water during storage, distribution or application which vary between alternative irrigation strategies that hold water in 'on-farm' storage for varying durations, and make up a large proportion of irrigation water losses (Dalton et al., 2001). Additionally, they assume that irrigation water is applied uniformly across the entire study area and do not account for the alternative whole-farm management strategies available to irrigated farmers. Such alternatives include growing part of the farm as a rainfed crop, or leaving some of the arable area fallow to increase stored soil water reserves for a subsequent crop.

Furthermore, evaluations of WP in wheat that have used crop production and cost-revenue functions have generally not accounted for the volume of water stored in the soil at the end of the cropping season (Zhang and Oweis, 1999; Tavakkoli and Oweis, 2004; Ali et al., 2007). Such analyses typically calculate water consumption as the sum of in-season precipitation and applied irrigation water, or by estimating evapotranspiration. However, if end-of-season stored soil water were assigned an intrinsic value in economic analyses, full irrigation strategies could be relatively more profitable because they are more likely to leave water in the soil at physiological maturity (Zhang et al., 2004). Such considerations are relevant to irrigation areas of sub-tropical eastern Australia, where late sown summer crops (e.g. sorghum, maize, mungbeans) can be sown immediately following a wheat crop.

The deficiencies outlined above can each be addressed with the use of a validated cropping systems model. For example, Lobell and Ortiz-Monasterio (2006) optimised on-farm WP for farmers in the Yaqui Valley, Mexico. Their results showed that the most profitable irrigation strategy for spring wheat varied depending on the amount of stored soil water at sowing, with deficit irrigation more profitable when stored soil water at sowing was plentiful, although they did not account for soil water remaining at the end of the season.

In a review of irrigation management techniques in water scarce environments, Pereira et al. (2002) stated: *"More research approaches are required to relate yield responses with gross margin or revenue responses to water deficits. The development of decision support tools integrating irrigation simulation models, namely for extrapolating field trials data, economic evaluation and decision tools should be useful to base the appropriate irrigation management decisions for water scarcity conditions"*. Additionally, a crop modelling approach can be used to demonstrate the level of risk associated with different agronomic strategies, by using many decades of historical weather data to assess how well a strategy works in wet, average or dry cropping seasons, the frequency at which the different types of season are likely to occur, and thus how often the agronomic strategy of choice is likely to be advantageous (Hammer et al., 1996; Hochman et al., 2009).

In response to the limited scope of previous WP analyses along with their inapplicability across multiple locations, the objective of this study was to determine whether optimum whole-farm economic water productivity (EWP) under water-limited conditions is achieved through deficit irrigation of a larger cropping area, as opposed to fully irrigating a smaller area, in the northern grains production region of eastern Australia. The study was conducted in the context of broad-scale furrow-irrigated farms where irrigation water rather than land is the limiting factor to production, using the APSIM farming systems model. A significant emphasis of the methodology was validation of the APSIM model for use in simulating water use of wheat in furrow-irrigated fields.

2. Materials and methods

2.1. Overview

A key component of simulation model experiments is that the model must first be 'validated'—that is, the model needs to accurately simulate the system being investigated. The APSIM farming systems model used in this study (Keating et al., 2003; Carberry et al., 2009; Holzworth et al., 2014) is the most widely used crop model in Australia, and has been demonstrated to accurately predict grain yield of high-yielding rainfed and irrigated wheat plot trials in sub-tropical and temperate regions of Australia (Asseng et al., 1998; Chenu et al., 2011; Peake et al., 2011) as well as in Europe and India (Asseng et al., 2000; Balwinder-Singh et al., 2011). APSIM has also been successfully utilised by commercial cropping enterprises to identify optimum rainfed and irrigated cropping strategies (e.g. Carberry et al., 2009; Power et al., 2011; Gaydon et al., 2012).

APSIM was previously evaluated 'on-farm' in irrigated spring-wheat production systems of the northern grains region (Peake et al., 2014), and satisfactorily simulated yield and soil water content in the absence of lodging and severe vegetative N stress. However their evaluation of APSIMs ability to predict water use was conducted on three separate commercial fields, so additional