Benchmarking farm water-use efficiency in eastern Australian dryland cropping systems

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Abstract

The productivity, profitability and sustainability of dryland cropping systems are closely related to the efficiency with which rainfall is captured and stored in the soil, used in transpiration, and converted to harvestable products. Historically, various water-use efficiency (WUE) indicators have been used to quantify and benchmark the performance of individual crops. However there has been little evaluation of water-use efficiency at higher spatial and temporal scales.

Here we use field (APSIM) and farm (APSFarm) scale simulation models to quantify water-use efficiency at the field and farm scale (WUE_{Farm}, measured as kg grain or $gross margin/ha/mm rainfall) in three contrasting production environments across the eastern Australian rainfed cropping zone. A representative farm business in each of the southern (413 mm annual rainfall), central (634 mm annual rainfall) and northern (633 mm annual rainfall) regions was characterised in terms of the biophysical and financial resources available and the management practices and strategies employed. Current management practices were simulated and results compared with farmer experience and records. WUE_{Farm} ranged from 5.2 to 7.4 kg (cereal equivalents)/ha/mm rainfall and from $0.51 to $0.96/ha/mm rainfall. Both measures of WUE were higher at the low-rainfall site.

Key Words

Water use efficiency, simulation modelling, whole-farm performance

Introduction

In most Australian dryland crop production systems, crop water supply, the sum of in-crop rainfall and plant available soil water at sowing, is generally less than potential crop evapotranspiration, and therefore limits crop yield and profitability. In some locations and seasons however, excess water can result in runoff, drainage and waterlogging with potentially negative effects on natural resources (e.g. soil loss, salinisation) and productivity. The productivity, profitability and sustainability of dryland cropping systems are all closely related to the efficiency with which rainfall is captured and stored in the soil, used in transpiration and converted to harvestable products.

To compare and understand the impact of alternative management practices and strategies, it is useful to have performance indicators that not only relate to the key limiting factors (water in this case) but also apply across a range of spatial and temporal scales. The concept of Crop Water Use Efficiency (CWUE), generally defined as crop yield divided by an estimate of crop water supply or evapotranspiration, has been widely used in the Australian grains industry to benchmark the performance of individual crops, to examine and understand the impact of new management practices and to identify opportunities for improving crop yield (French and Schultz 1984; Angus and van Herwaarden 2001; Sadras and Angus 2006; Hochman et al. 2009).

While useful at the single-crop scale, CWUE is not sensitive to many of the determinants of efficient capture, storage and utilisation of rainfall, either at longer temporal scales (e,g., sequences of crops and fallow periods) or at broader spatial scales (e.g., whole farm). For example, a crop grown after a very long fallow period where extensive cultivation is performed may have a high CWUE while the system as a whole is inefficient due to low fallow efficiencies. Performance indicators and benchmarks are required that are sensitive to the full range of management interventions available to farm business managers.

A number of indicators (e.g., Peterson et al. 1996; Farahani et al. 1998) and frameworks (e.g., Bouman 2005; Routley et al. 2009) have been developed to consider water-use efficiency at these higher-order spatial and temporal scales. However these have not been widely applied in Australian dryland crop production systems, partially because of the difficulties of measuring or estimating some components (e.g., losses of water from the systems through runoff or deep drainage).

In this paper, we use simulation modelling, tested against farmer experience, to benchmark water-use efficiency at a number of spatial and temporal scales for a sample of rainfed grain production businesses in eastern Australia.

Methods

Representative farm businesses from south-west of Toowoomba in southern Qld, south of Parkes in central western NSW and north of Adelaide in SA were selected as case studies. Some characteristics of these farms are listed in Table 1. Through interviews with the farm manager, each farm business was characterized in terms of its soils, climate, machinery, labour and financial resources used in the farm business. The interviews were provided detailed information on farm management strategies (e.g., crop rotations), crop management practices (e.g., conditions and rules for sowing, crop inputs used, etc) and farmer experience with respect to crop yield distributions, grain and input prices and farm overhead costs.

APSFarm, the whole-farm extension of the APSIM cropping system simulation modeling platform (de Voil et al. 2009) was used to simulate the cropping system for each farm business for the 50 year period 1958 – 2007 using daily meteorological records from the nearest BOM weather station. Management options were simulated using rules that reflected actual practice on each farm as determined in the initial interviews. The primary crop rotation used on the farm was simulated in multiple paddocks such that each phase of the rotation occurred each year. Sowing time for each crop was determined by rules that included sowing date windows, sowing rainfall events and, for the Qld farm, an available soil water trigger. Nitrogen fertilizer was applied at sowing in the Qld case study, and in-crop in the other case studies, using either fixed rates or rates to achieve a target soil nitrate N, according to farm practice. All case study farms used zero-till systems and the number and timing of fallow weed control sprays applied during each fallow period was determined by the model using an algorithm that took into account germination rainfall events and subsequent surface soil water conditions. Water use by weed populations between germination and herbicide application was assumed to be minimal and was not simulated.

Table 1 Case study farm characteristics.

Location (Weather station used)	Lat & Long	Area Cropped (Ha)	Usual crop sequence (1)	Predominant soil type & PAWC (mm)	Mean Annual Rainfall (mm) (2)	Mean winter growing season rainfall (mm) (3)
Bongeen, Qld	27?30’S, 151?25’E	890	WffSfSfSff	Black vertosol, 282	633	229
Parkes, NSW	33?14’S, 148?04’E	3400	WfWfBfC	Grey clay loam, 150	634	306
Spalding, SA	33?24’S,	1410	WfBfCf	Red sandy loam,	413	256

138?37’E	89

(1) W= Wheat, S = Sorghum, B = Barley, C = Canola, f = fallow, ff = long fallow. (2) for the 50 years (1958 – 2007), (3) May to October

Simulation model outputs including crop yields, N-fertilizer rates, fallow weed control events and machinery usage were used as input to a spreadsheet-based, whole-farm profitability model. This model included details of non-dynamic crop inputs (e.g., in-crop herbicide and fungicide applications), crop prices and farm overhead costs. Farm machinery fuel, maintenance and depreciation costs were calculated based on machinery usage rates and assumptions about effective life.

A number of indicators of farm biophysical and financial performance were calculated. Some of these indicators (e.g., crop yields, mean annual operating and overhead costs) were validated against farmer experience as expressed in the initial interviews. It is important to note that due to the inherent complexity of farm-level decision making, the spatial heterogeneity present on most extensive farms, and the inability of the simulation models to account for many factors that affect crop yield (e.g., disease, harvest losses, P availability), the results of an analysis such as this can not be expected to ‘replicate reality’. The results can, however, provide a basis to compare alternative management practices at a whole farm level.

Results and discussion

Figure 1 shows the mean simulated water balance for each case study farm for fallow and crop periods, as well as on an annual basis. On average, 91 mm or 23% of fallow rainfall was retained in the soil at the time of sowing of the next crop at Bongeen, compared with 55 mm (17%) at Parkes and 27 mm (19%) at Spalding. There was 28% of fallow rainfall lost as runoff and drainage at Parkes, most of this as drainage, compared with 11% at Bongeen and 8% at Spalding. Crop transpiration accounted for 26% (Parkes) to 35% (Spalding) of annual rainfall. Soil evaporation was the largest component of the water balance at all sites, in particular at Bongeen (62% of annual rainfall). The nature of the non-productive losses of rainfall at the various sites suggests opportunities for improving overall WUE. For example, summer cropping of grain or fodder crops may be appropriate in the Parkes system where currently only winter crops are grown in an environment of relatively uniform seasonal rainfall distribution.

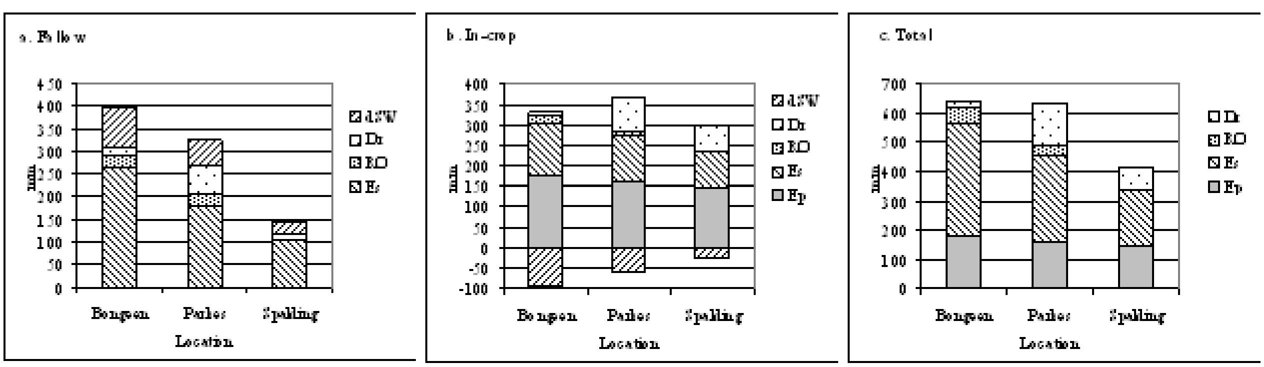

Figure 1. Mean water balance during periods of fallow (a), crop (b) and annually (c) for each location. (Ep = transpiration, Es = soil evaporation, RO = Runoff, Dr = drainage, dSW = change in stored soil water)

Some indicators of whole-farm productive and economic performance over the 50 year simulated period are presented in Table 2. Total productivity was highest in the higher rainfall environments of Bongeen and Parkes while productivity per mm of rainfall (WUE_{Farm}) was substantially higher at Spalding. This high WUE_{Farm} is presumably due to both a higher proportion of rainfall used in crop transpiration at this site (36% vs 26-28%) and the more benign growing conditions during the critical period of yield determination for winter crops (Rodriguez and Sadras 2007).

Table 2. Some biophysical and economic performance indicators (means over the 50 year simulation)

Performance indicator	Unit (2)	Location		
		Bongeen	Parkes	Spalding
Annual Biomass Yield	kg/ha/year	8764	9530	8434
Annual Grain Yield	kg/ha/year	3314	3348	2683
Annual 'cereal equivalent' grain yield (1)	kg/ha/year	3314	3751	3067
WUE_{Farm} –biomass	kg/ha/mm	13.7	15.0	20.4
WUE_{Farm} – grain	kg/ha/mm	5.2	5.3	6.5
WUE_{Farm} – ce grain (1)	kg/ha/mm	5.2	5.9	7.4
Gross Income	$/ha/year	590	801	732
Input Costs	$/ha/year	265	296	335
Gross Margin	$/ha/year	325	505	397
Overhead Costs	$/ha/year	220	178	228
Farm operating profit	$/ha/year	105	327	169
Gross Income	$/ha/mm	0.93	1.26	1.77
Input Costs	$/ha/mm	0.42	0.47	0.81
Gross Margin	$/ha/mm	0.51	0.80	0.96
Overhead Costs	$/ha/mm	0.35	0.28	0.55

Farm operating profit	$/ha/mm	0.17	0.52	0.41

(1) Canola yield adjusted (x 1.66) to account for higher energy requirement (after Loomis & Connor, 1996)

(2) In all cases, mm refers to mm of rainfall

In addition to the biophysical environment, financial performance indicators are clearly influenced by a wide range of market and business structural factors and should be interpreted with caution. The Parkes farm business was almost twice as profitable as the next most profitable farm on a profit per ha basis, due to a combination of higher gross returns and lower input and overhead costs. It was also the most profitable in terms of profit per mm of rainfall due to low overhead costs, while the Spalding farm had the highest gross margin per unit of rainfall.

The Spalding and Bongeen farms had similar distributions of annual profitability over the simulated 50 year period, with the Spalding farm having a greater capacity to capitalise on opportunities in the most favourable years (Figure 2). The Parkes farm was more profitable in almost all years, and had little risk of negative farm operating profit, which was around 20% for the other sites.

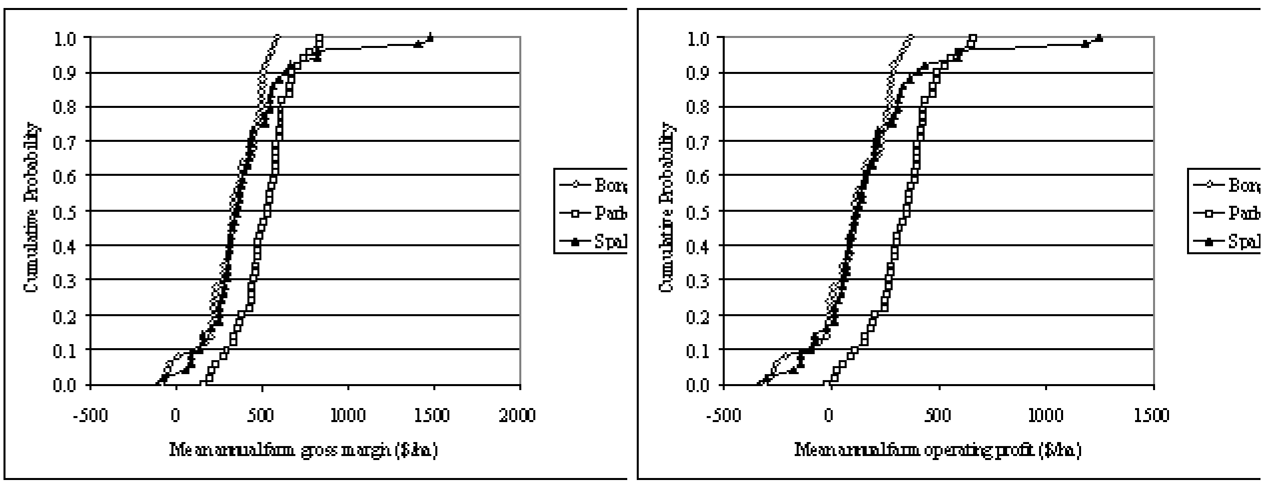

Figure 2. Cumulative distribution functions of mean annual farm gross margin and mean annual farm operating profit for the 3 locations.

Conclusion

We have developed indicators of water-use efficiency that integrate the effects of crop and fallow management practices at a whole-farm level. This approach and these indicators can help identify and assess opportunities to improve whole farm productivity, profitability and economic and environmental risks associated with runoff and deep drainage. In future related work the value of these indicators across a range of alternative management practices and strategies will be assessed.

References

Angus JF and van Herwaarden AF (2001). Increasing water use and water use efficiency in dryland wheat. Agronomy Journal 93, 290-298.

Bouman BAM (2007). A conceptual framework for the improvement of crop water productivity at different spatial scales. Agricultural Systems 93, 43-60.

de Voil P, Rodriguez D, Power B and Rossing W (2009). Simulation of whole farm management decisions. In '18th World IMACS / MODSIM Congress and MODSIM09'. Cairns, Australia. (Eds R Anderssen, R Braddock, L Newham) pp. 642-648.

Farahani H, Peterson G, Westfall D, Sherrod L and Ahuja L (1998). Soil water storage in dryland cropping systems: the significance of cropping intensification. Soil Science Society of America Journal 62, 984-991.

French R and Schultz J (1984). Water Use Efficiency of Wheat in a Mediterranean-type Environment. I The relation between yield, water use and climate. Australian Journal of Agricultural Research 35, 743-764.

Hochman Z, Holzworth D and Hunt JR (2009). Potential to improve on-farm wheat yield and WUE in Australia. Crop and Pasture Science 60, 708-716.

Loomis RS and Connor DJ. (1996). Crop Ecology. Productivity and Management in Agricultural Systems, Cambridge, Cambridge University Press.

Peterson GA, Schlegel A, Tanaka DL and Jones OR (1996). Precipitation use efficiency as affected by cropping and tillage systems. Journal of Production Agriculture 9, 180-186.

Routley RA, Robertson MJ, Bell L, Moore AD and Kirkegaard JA (2009). A framework for evaluating farm water use efficiency in rainfed grain and mixed farming systems. In 'Farming Systems Design 2009 - Methodologies for Integrated Analysis of Farm Production Systems'. Monterey, CA.

Rodriguez, D and Sadras VO (2007). The limit to wheat water use efficiency in eastern Australia. I. Gradients in the radiation environment and atmospheric demand. Australian Journal of Agricultural Research 58, 287-302.

Sadras VO and Angus JF (2006). Benchmarking water-use efficiency of rainfed wheat in dry environments. Australian Journal of Agricultural Research 57, 847-856.