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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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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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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 field evaluation was conducted in the present study to assess the ability of APSIM to predict wheat water use under multiple furrow irrigation regimes in the same field.

After validation of the APSIM model, simulation experiments were conducted to determine the optimum irrigation strategies for maximising whole-farm economic water productivity (EWP). This initially involved the simulation of six alternative land uses (fallow land, rainfed cropping, and four levels of irrigation input), followed by the calculation of EWP for combinations of these land-uses that used the maximum farm area and irrigation water allocation. Whole-farm EWP was then determined for alternative economic analyses where different values (inexpensive vs. expensive) were assumed for both irrigation water and stored soil water.

2.2. Validation of the APSIM model

2.2.1. Field experiments

A field experiment was conducted at the Australian Cotton Research Institute farm (S 30°12′ 22.24″, E 149°35′ 55.34″) near Wee Waa, NSW in 2011. Three furrow irrigation treatments were applied in a completely randomised block design across three replicates, such that the nine plots of the cultivar Spitfire (sown on 6th–7th June) were aligned in a single row, and furrow irrigation treatments could be applied to individual plots. Ten metre wide sections of wheat were sown as buffer between irrigation treatments to prevent sub-surface flow of irrigation water between plots. Plots were eight metres long and two metres wide, sown on raised beds with 7 rows of wheat spaced 25 cm apart, and separated by 50 cm wide ‘furrow gaps’.

The three treatments consisted of a (1) a single irrigation at sowing, (2) an irrigation at sowing followed by a single in-crop irrigation, and (3) sown without an irrigation, then fully irrigated after GS32 (Tottman, 1987). The experiment was conducted on soil with low levels of residual soil N, as the experiment was sown soon after the harvest of a cotton crop (Table 1). This meant that N fertiliser could be applied during the season for the fully irrigated treatment in order to reduce lodging risk through the use of the canopy management technique of in-crop N application (Sylvester-Bradley et al., 1997; Sylvester-Bradley et al., 2000; Peake et al., 2014). N fertiliser was applied at sowing for the partially irrigated treatments. Soil and fertiliser N and irrigation volumes for the three irrigation treatments are listed in Table 1.

The soil was a brown vertosol, with plant available water capacity (PAWC) of 248 mm measured to 180 cm, and bulk density ranging from $1.31\,\text{g}\,\text{cm}^{-3}$ in the surface (0–15 cm) layer to $1.47\,\text{g}\,\text{cm}^{-3}$ in the deepest layer measured (150–180 cm). Meteorological data were collected at the site using an automated weather station. Grain yields are reported at 12% moisture.

Soil water content was measured as described in the field monitoring of Peake et al. (2014) for soil layers deeper than 15 cm. This required neutron moisture meter (NMM) readings with a CPN 503 DR Hydroprobe (CPN International, Martinez, CA, USA) to be taken with a 16-s count at regular intervals during the season. NMM data were calibrated to gravimetric soil water content using soil cores taken at sowing and periodically during the season to sample a range of moisture contents. For calibration, access tubes were installed in the holes from which the samples for gravimetric analysis were collected, and NMM readings immediately taken. The surface layer (0–15 cm) was monitored using a ML2x Theta probe (Delta-T Devices, Cambridge, UK) calibrated on the same cores used to calibrate the NMM. Soil characterisation data for Drained Upper Limit (DUL) and Crop Lower Limit (CLL) were obtained as described by Dalgliesh and Foale (1998) for DUL, and by using the lowest NMM moisture readings in the rainfed treatments to determine CLL (similar to Ritchie (1981), and Ratliff et al. (1983)).

2.2.2. APSIM validation simulations

Results from the field trials were compared with APSIM simulations of each experimental treatment. The field data described previously (Section 2.2.1) was used to parameterise each simulation as appropriate. The APSIM “skip_row_factor” parameter (set at 0.2) was used to simulate the decreased light interception due to 50 cm ‘furrow gaps’ between the irrigation beds as discussed by Peake et al. (2014) and Peake (2015). The cultivar Spitfire has not previously been parameterised for use in APSIM, so the cultivar H45 was used within the simulations for the 2011 experiments on the basis of its appropriate representation of Spitfire’s flowering date.

2.3. Investigation of whole-farm economic water productivity using long-term APSIM simulation experiments

2.3.1. Land-use simulations

The investigation of whole-farm EWP first required simulation of six land-uses with varying levels of irrigation input; fallow land, rainfed cropping, three deficit irrigation land-uses, and a fully irrigated land-use. Long-term APSIM simulations were conducted for each land-use at three locations and using two levels of stored soil water at sowing (100 mm or zero), in order to assess the applicability of alternative irrigation strategies at a range of locations and sowing conditions.

The four irrigated land-uses were simulated in conjunction with 100 mm of stored soil water as follows: (1) ‘One irrigation’ (LU1), a deficit irrigation land-use involving a single irrigation where the entire irrigation supply was applied evenly across the entire farm, (2) ‘Two irrigations’ (LU2), a partially irrigated land-use that applied the irrigation water across half of the farm, split into two applications, (3) ‘Three irrigations’ (LU3), a land-use that involved up to three irrigation events on one third of the farm area, and (4) ‘Fully irrigated’ (LU4), a land-use that used up to four irrigations on one quarter of the farm area. In a small number of seasons which experienced high levels of growing season rainfall, the second, third or fourth irrigation were not always applied due to high levels of soil moisture. In such cases the simulation was still included as part of the analyses, hence the number of irrigations represent a potential

Table 1
Soil mineral N status, fertiliser N and irrigation water volumes for the validation experiment at Narrabri in 2011.

Irrigation treatment	Soil residual N prior to sowing (kg N ha^{-1})	Fertiliser N applied prior to sowing (kg N ha^{-1})	In-crop fertiliser N (kg N ha^{-1}, date)	Irrigation (mm, date)
Sowing irrigation	36	150	–	[a], 9-Jun
Sowing + 1 in-crop irrigation	36	150	50, 5th Sep	[a], 9-Jun 100, 6th Sep
Sown on rain moisture, full ‘in-crop’ irrigation	36	10	150, 5th Aug 50, 5th Sep	50, 9th Aug 40, 6th Sep 40, 27th Sep 75, 20th Oct

[a] The sowing irrigation was not measured, as it was applied before the initial measurement of soil water.

Table 2
Proportion of land-use areas used for the seven farm-management strategies when 100 mm of stored soil water was available at sowing prior to irrigation, and 140 mm of irrigation was applied on average for both sowing and in-crop irrigations.

Farm-management strategy	Irrigation land-use	Alternative land-use	Irrigated area (ha)	Maximum no. of irrigations	Associated area of fallow or rainfed land-use (ha)
S	LU1—sowing irrigation only	NA	1000	1	None
S + 1/F and S + 1/R	LU2—sowing + 1 in-crop irrigation	Fallow or rainfed	500	2	500
S + 2/F and S + 2/R	LU3—sowing + 2 in-crop irrigations	Fallow or rainfed	333	3	667
S + 3/F and S + 3/R	LU4—sowing + 3 in-crop irrigations	Fallow or rainfed	250	4	750

Key to farm-management strategy abbreviation: 'S' denotes sowing irrigation; '+1,2 or 3′ denotes number of additional irrigations applied; '/F or/R' denotes alternative land use = fallow (F) or rainfed cropping (R).

maximum rather than the actual number of irrigations applied in all simulations. The two remaining land-uses were abbreviated as LUR (rainfed cropping) and LUF (fallow land).

Similar land-use simulations were then conducted with zero soil water available at sowing prior to irrigation. However for these land-use simulations the crop area was adjusted to account for the larger sowing irrigation of 230 mm that was required to fill a completely dry soil profile, compared with the irrigation of 140 mm that was required to fill the soil profile when 100 mm of soil water was already stored at sowing.

2.3.2. *Farm-management strategies*

Farm management strategies were comprised of combinations of the six-land uses that fulfilled each of two criteria: (1) use of the maximum farm area, and (2) planned use of the maximum irrigation allocation. For the purposes of this study the farm was assumed to be 1000 ha in size, with 1400 ML of irrigation water stored 'on-farm' at the beginning of June (the time of sowing), representing the typical limited water availability status for broad-scale furrow irrigators of the northern grains region as discussed previously. Furrow irrigation was the focus of this study as it is the predominant form of irrigation infrastructure deployed across the region.

Seven farm-management strategies were developed for investigation in conjunction with 100 mm of stored water at sowing. One of these involved deficit irrigation of the entire farm area, and the remaining six were derived from a factorial combination of the four irrigated land-uses in conjunction with the two remaining land-uses; rainfed cropping or fallow land (Table 2). Only four farm-management strategies were developed for the zero soil water simulations (Table 3), all of which included fallow land as the sole alternative land-use because rainfed cropping in the region is known to be substantially unviable in the absence of stored soil water at sowing (Moeller et al., 2009).

2.3.3. *General methods for land-use simulations*

All long-term simulations were conducted using a 110 year historical weather data set obtained from the SILO database (Jeffrey et al., 2001) for three locations; Emerald, Goondiwindi and Gunnedah, representing the north, middle and southern end of the northern grains region. Representative APSIM soil types (Peake et al., 2010) were used for each location, with Typical Vertosol #3 (PAWC = 255 mm) used at Gunnedah, and Typical Vertosol #7 (PAWC = 204 mm) used at Emerald and Goondiwindi. Water accumulation in fallow fields was simulated according to the specific curve number characteristics associated with each of the 'Typical Vertosol' soil types as per the APSOIL database (Dalgliesh et al., 2006). The cultivar Kennedy was used for all long term simulations, with maximum kernel weight increased to 45 mg following the field observations of Peake et al. (2014). The APSIM "skip_row_factor" parameter (set at 0.2) was used to simulate decreased light interception due to 'furrow gaps' as discussed in Section 2.2.2.

Peake et al. (2014) observed under-prediction of grain yield in fields managed using low levels of soil N at sowing (approximately 50 kg ha^{-1} N or less) for the reduction of lodging risk. Therefore all long-term simulations conducted in this study were carried out assuming moderate levels of soil + fertiliser N at sowing for fully irrigated treatments (100 kg ha^{-1} N), and higher levels in rainfed and partially irrigated treatments (120 and 150 kg ha^{-1} N). The N application schedule (Table 4) aimed to replicate farmer best-practice and thus varied between rainfed and irrigated land-uses depending on yield expectation and the need to reduce lodging risk.

Additional 'tactical' N applications were applied within each simulation if residual soil N decreased below 50 kg N ha^{-1} prior to anthesis, to simulate in-crop N application in response to increased yield expectations in high rainfall years (Table 4). N application strategies did not vary between the zero and 100 mm sowing soil

Table 3
Proportion of land-use areas used for farm-management strategies when zero stored soil water was available prior to sowing, an irrigation of 230 mm was applied at sowing, and average in-crop irrigation was 140 mm.

Farm management strategy	Irrigation land-use	Alternative land-use	Irrigated area (ha)	Maximum no. of irrigations	Associated area of fallow (ha)
S/F	LU1—sowing irrigation only	Fallow	600	1	400
S + 1/F	LU2—sowing + 1 in-crop irrigation	Fallow	375	2	625
S + 2/F	LU3—sowing + 2 in-crop irrigations	Fallow	273	3	727
S + 3/F	LU4—sowing + 3 in-crop irrigations	Fallow	214	4	786

Key to farm-management strategy abbreviation: 'S' denotes sowing irrigation; '+1,2 or 3′ denotes number of additional irrigations applied; '/F denotes alternative land use = fallow (F).

Table 4
Fertiliser N application regime for the different land-use simulations.

Land-use	Soil + fertiliser N available at sowing (kg ha^{-1})	Scheduled in-crop N application (kg ha^{-1})	Tactical in-crop N application[a]
LUR—rainfed	120	–	30 kg N ha^{-1} per application
LU1—sowing irrigation only	150	–	30 kg N ha^{-1} per application
LU2—sowing + 1 in-crop irrigation	150	50 (with in-crop irrigation, variable growth stage)	30 kg N ha^{-1} per application
LU3—sowing + 2 in-crop irrigations	100	100 (GS31)	30 kg N ha^{-1} per application
LU4—sowing + 3 in-crop irrigations	100	100 (GS31)	30 kg N ha^{-1} per application

[a] Tactical in-crop N was only applied if total soil N was below 50 kg N ha^{-1} between the end of tillering and the beginning of flowering, and either 10 mm of rain or an irrigation event occurred.

water simulations as the sowing irrigation event negated the variation in stored soil water.

Irrigation storage was assumed to be a single dam 33 ha in area with maximum storage capacity of 2800 ML, slightly above-average capacity for broad-scale irrigated farms in the region (CCCCRC, 2011). APSIM manager-logic was used to alter the volume of stored water each day in response to rainfall, evaporation (calculated using the FAO56 method of Allen et al. (1998)), and seepage of 2 mm per day (the median seepage for farm storages in the region (CCCCRC, 2011)). Differences in mean long-term runoff between the farm-management strategies were negligible and not accounted for in the modelling of irrigation water storage volumes. The length of the simulated wheat growing season was determined as the time between sowing and physiological maturity, and used to calculate crop evapotranspiration as well as the net usage of soil water.

The sowing irrigation events were applied one day after sowing, partly to simulate the practice of 'watering up' after dry sowing, a common practice in the region due to the short time-frame (6–8 weeks) between cotton harvest and wheat sowing. The default APSIM irrigation efficiency was set at 0.75 for all simulations; hence for irrigation events of 120 mm, 90 mm was added to the crop root zone, and 30 mm was assumed lost to the cropping system as evaporation, deep drainage, and tail drain losses. The APSIM term 'irrigation efficiency' therefore encompasses both distribution efficiency and application efficiency (Dalton et al., 2001). In-season irrigation applications occurred when the soil water deficit to a depth of 120 cm was greater than 100 mm or 1 ML ha^{-1}, the typical irrigation 'refill point' used by furrow irrigators throughout the region.

Irrigated land-uses with multiple irrigation events had a smaller proportion of the stored irrigation water applied during the first irrigation of the season, compensating for the greater storage losses they incurred over time and ensuring that irrigation-event volumes were approximately equal for each irrigation event. For example, the 'LU1' land-use had 100% of the available irrigation water applied to the entire 1000 ha farm on the date of irrigation. However the 'LU2' irrigation treatment had approximately 45% of the available irrigation water applied on the first irrigation date to the cropped area, and 100% of the remaining water applied on the second irrigation date.

It should be noted that furrow irrigators have only a limited ability to adjust irrigation timing, as the size of the soil water deficit is closely related to the amount of irrigation water that can be applied in practice. Growers who delay irrigation applications in an attempt to conserve water for later growth periods typically end up applying more water per unit area than intended, and then have insufficient water remaining to irrigate the entire cropped area. Hence this study did not attempt to optimise the timing of these in-crop irrigations during the growing season.

Irrigation scheduling was modified slightly for the LU3 and LU4 land-uses. This allowed application of irrigation at a smaller soil water deficit than normal in years when insufficient rain fell to allow incorporation of scheduled N applications at the beginning of stem elongation (GS31). If the soil water deficit was less than 50 mm, an 80 mm irrigation was applied to incorporate N, at an irrigation efficiency of 0.6. If the soil water deficit was greater than 50 mm, the full irrigation amount for the first scheduled irrigation was applied, also at an irrigation efficiency of 0.6. This simulated the larger distribution and application losses that occur when applying irrigation to moist soil early in the growing season, solely for the purpose of incorporating the in-crop N application.

2.3.4. *Determination of partial gross margins*

Partial gross margins (GMs) were used to evaluate the economic return of different farm-management strategies by subtracting the costs involved in preparing land and managing the wheat crops from the income generated by the wheat production. They are described as 'partial' gross margins because long-term costs associated with infrastructure (e.g. depreciation) and other farm overheads were not included in the analysis. The pricing of each operation was based on gross margins prepared for irrigated wheat in northern New South Wales (Scott et al., 2012) but modified slightly to reflect grower practices across all irrigation areas of the northern grains region. Ultimately, the fixed cost per unit area of irrigated and rainfed production was determined to be similar at \$236.24 ha^{-1} for rainfed crops, and an additional \$11 ha^{-1} applicable to irrigated crops (the cost of an additional fungicide and insecticide application). The cost of fertiliser and water (and their application) were the main costs that varied between simulations. Nitrogen (priced at \$1.32 per kilogram of N) was assumed to be applied as urea, with no cost of application when it was applied 'water-run' (i.e. dissolved in irrigation water), and a cost of \$8 ha^{-1} for applying 65 kg ha^{-1} of urea with a spreader before a rain event. Other macro and micronutrients were assumed to be replaced at a rate identical to the amount of these nutrients removed per tonne of grain, calculated at \$21 t^{-1} ha^{-1}. The cost of insurance and levies were applied at 3.07% of the price of grain (which was \$250 per tonne), while the variable cost of harvesting was applied at \$10 per tonne of yield above 2.5 t ha^{-1} (the minimum yield level to which fixed harvesting costs were applied). The grain price was applied consistently across land-uses and seasons, reflecting the lack of importance placed on grain protein concentration by local growers during the period encompassed by this study. This was due to the small price differences available for higher quality grades that gave little incentive to achieve specific grain protein and end-user quality requirements.

2.3.5. *EWP analyses*

Four alternative EWP analyses were developed using a factorial combination of high vs. low water price, and including/excluding the application of this price to the net usage of stored soil water through the wheat growing season. The irrigation water price was applied to the net usage of soil water in order to reflect that stored soil water has an economic value, because it decreases the amount

Table 5
The four alternative analyses used for calculating whole-farm EWP.

EWP analysis	Calculation method
GM_{40}	Irrigation water price of \$40 ML^{-1}, △SW not priced
GM_{40} + △SW	Irrigation water price of \$40 ML^{-1} with △SW also priced at \$40 ML^{-1}
GM_{120}	Irrigation water price of \$120 ML^{-1}, △SW not priced
GM_{120} + △SW	Irrigation water price of \$120 ML^{-1} with △SW also priced at \$120 ML^{-1}

△SW: the net change in stored soil water between sowing and harvest.

of water required to sow the subsequent crop planned for the production field. Low-priced water was assumed to cost \$40 per megalitre, a price that incorporated the cost of pumping water in and out of the farm storage without applying a price directly to the water because it was assumed to be harvested from a flood event. High-priced water was assumed to cost \$120 ML^{-1}, incorporating pumping costs as well as an \$80 ML^{-1} price directly applied to the water, as sometimes occurs when river flow volumes are low and irrigated producers purchase water from a limited pool available to growers within a district. Abbreviations used for these analyses are listed in Table 5.

2.3.6. Evaluation terminology

For simplicity of communication, the following abbreviations are used to describe different forms of crop (CWP) and economic (EWP) water productivity throughout the results and discussion:

1. CWP_{ET}—measured as yield divided by evapotranspiration (kg^{-1} mm^{-1} ha^{-1}); used only to evaluate individual land-uses.
2. CWP_{ET+IE}—measured as yield divided by the sum of evapotranspiration, irrigation storage/distribution losses, and infield drainage losses (kg^{-1} mm^{-1} ha^{-1}); used to evaluate either individual land-uses or the whole-farm management strategies.
3. EWP—'economic' water productivity calculated using one of the partial gross margin (GM) analyses. Effectively the unit measure for EWP is partial GM (\$) per 1400 ML of irrigation water, for the entire 1000 ha farm. However for simplicity of discussion, the measure of partial GM will be stated simply as a dollar value.

3. Results

3.1. APSIM validation

3.1.1. Field observations and agronomic management

The 2011 validation experiment received higher than average rainfall, although the month of July was dry. While cold temperatures were experienced just prior to anthesis, no visible frost damage symptoms were observed. Substantial rainfall in late November after physiological maturity delayed harvest, but was not observed to cause any grain sprouting that could have affected measured grain yield.

The fully irrigated treatment was grown using the canopy management technique of in-crop N application (Sylvester-Bradley et al., 2000) for the reduction of lodging risk. Plots in this treatment were visibly N stressed by the end of tillering and remained so until the application of in-crop N in early August, after which they recovered rapidly. The 'sowing' and 'sowing + 1 in-crop' irrigation treatments had the majority of their N requirement applied at sowing, and showed no signs of visible N stress at any crop stage. No significant lodging was observed in any of the treatments prior to harvest.

3.1.2. Comparison of simulated and observed yield and water use

APSIM accurately simulated water use in the 'sowing irrigation' and 'sowing + 1 in-crop irrigation' treatments (Fig. 1a and b). Water use for the fully irrigated treatment was predicted accurately during early-season growth while N stress was beginning to develop (Fig. 1c, solid line), however predicted and observed water use diverged in late August as APSIM was unable to simulate the recovery in crop biomass that was observed in the field, a trend previously observed by Peake et al. (2014). Simulated grain yield of the partially irrigated simulations were similar to the observed grain yields of 3.7 and 5.1 t ha^{-1} (at or within a standard error of approximately 0.5 t ha^{-1}). However the simulated yield of the fully irrigated simulation was 2.2 t ha^{-1}, nearly 4 t ha^{-1} below the observed grain yield.

An alternative simulation of the full irrigation treatment was conducted to determine whether APSIM was able to simulate late-season water use in this treatment. This was achieved by (1) altering the simulated date of N application to the day of sowing to eliminate vegetative N stress, and (2) resetting soil water after each of the first two irrigation events, to compensate for the subsequent over-simulation of early-season water-use (due to improved N availability). The simulation of late season water use for the fully irrigated treatment was satisfactory once these compensations were made (Fig. 1c, dotted line) as was the prediction of grain yield which increased to 5.6 t ha^{-1}, close to the observed yield of 6.1 t ha^{-1}.

As discussed in Section 2.3.3, long-term simulations of the alternative land-uses were carried out using moderate levels of sowing N to ensure that severe N stress would not be experienced, thus the land-use simulations were conducted within the known operating capabilities of the model.

3.2. Land-use simulations

3.2.1. Environmental characterisation

The three environments used for the long-term land-use simulations differed in terms of temperature, radiation and rainfall through the wheat growing season. Average daily temperature and radiation decreased from north to south, with Emerald having higher average daily temperature and radiation (18.4 °C and 18.9 MJ m^{-2}) on average from June to October than Goondiwindi (14.8 °C and 17.2 MJ m^{-2}) and Gunnedah (13.3 °C and 15.9 MJ m^{-2}). Average rainfall from June to October was similar at Goondiwindi and Gunnedah (212 and 237 mm) but lower at Emerald (156 mm). The higher temperatures at Emerald led to decreased duration of the simulated wheat growing season, with the average number of days from sowing to harvest being 128 days, compared with 142 and 153 at Goondiwindi and Gunnedah. As a result, growing season rainfall (calculated as cumulative rainfall between the date of sowing and physiological maturity in each simulation) showed greater differences between environments than June to October rainfall, at 101, 174 and 212 mm, respectively for Emerald, Goondiwindi and Gunnedah.

3.2.2. Comparison of land-use simulations

Irrigation storage losses were greater in the more frequently irrigated land-uses, which required water to be held in storage to allow irrigation later in the growing season (Table 6). Up to 11% of the irrigation water stored at sowing was lost to seepage and evaporation in the 'LU4' land-use, compared with between 5% and

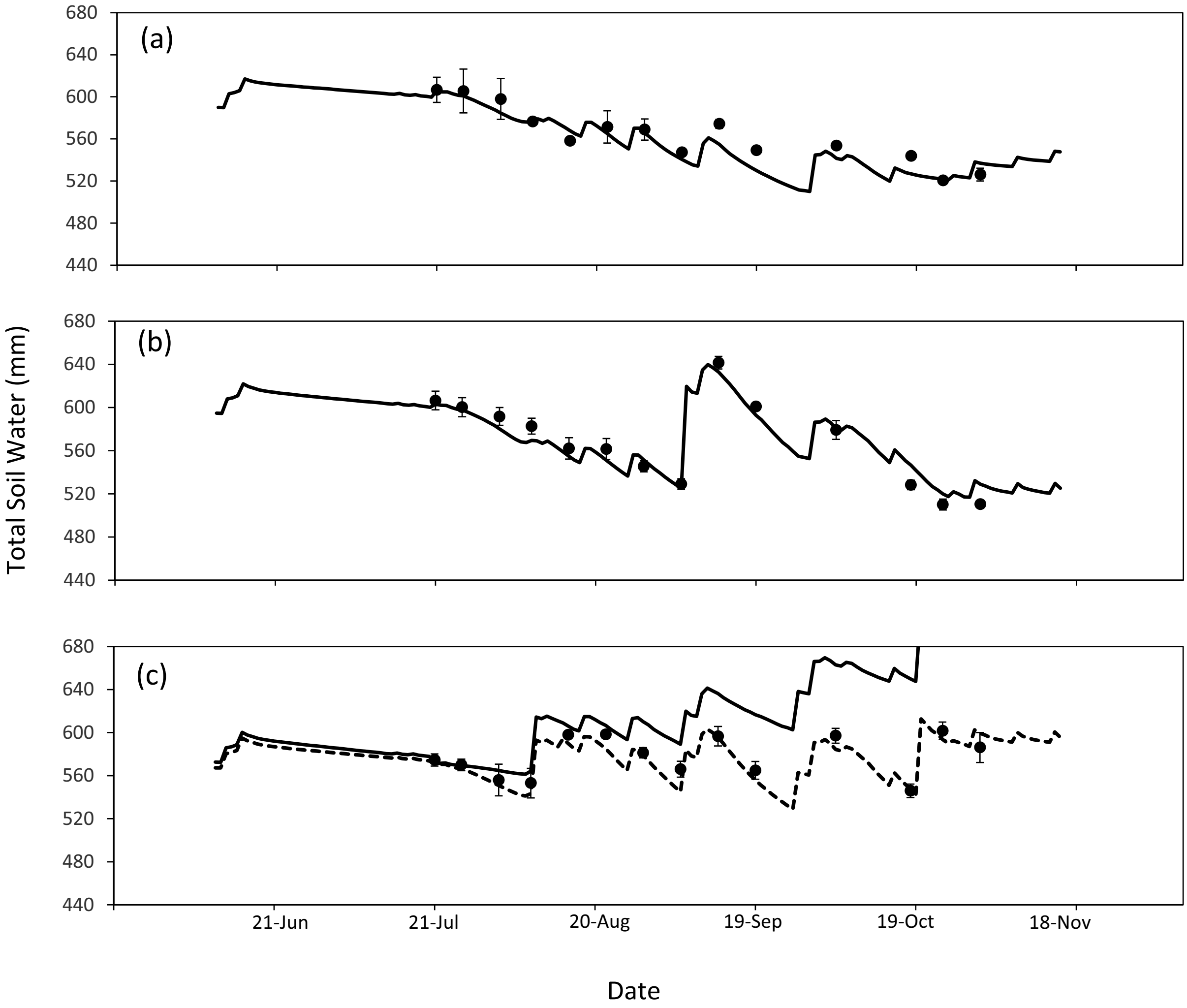

Fig. 1. APSIM simulated total soil water (solid line) and measured total soil water (black circles) for a range of management regimes at Narrabri in 2011: (a) irrigated at sowing with all N applied at sowing (b) irrigated at sowing with one in-crop irrigation and all N applied at sowing, and (c) sown into stored moisture at sowing with low residual soil N levels, with four in-crop irrigations and two in-crop N applications. The dotted line in (c) shows simulated water use from an additional APSIM simulation that was amended to prevent the underestimation of biomass in response to severe early N stress.

7% being lost when the irrigation was applied earlier in the season across a larger land area in the 'LU2' land-use.

Unsurprisingly, grain yield and evapotranspiration increased in land-uses with greater irrigation input at each location (Fig. 2a–f), for the simulations that had 100 mm of stored soil water at sowing. CWP_{ET} (grain yield per unit of evapotranspiration) was also greater in the land-uses that involved higher levels of irrigation (Fig. 2g–i). However CWP_{ET+IE} (which included seepage and storage losses of irrigation water in the denominator term) peaked in the second most heavily irrigated treatment (LU3) (Fig. 2j–l). This was due to the increased seepage and storage losses incurred by the most frequently irrigated treatment (LU4), which had similar grain yield to LU3. These trends were almost identical to those found in the simulations where zero stored soil water was available at sowing (data not shown).

3.3. EWP analysis of farm-management strategies

3.3.1. Assessing the risk efficiency of farm management strategies

A disadvantage of using mean partial GM as a measure of EWP is that the mean value does not demonstrate the season to season variability associated with alternative management options. This variability is demonstrated in the relationship between gross margin and growing season rainfall for the 'GM_{40}' analysis of the 'zero soil water at sowing' simulations for Goondiwindi (Fig. 3). While the difference between mean partial GM for farm-management strategies in this analysis was small ($5000, or $5 per hectare), the optimum farm-management strategy varied substantially between seasons. In high rainfall years, applying a single irrigation to the entire farm at sowing was most profitable, however the same strategy was least profitable in low rainfall years. In median years (decile 0.5 in Fig. 3b), all farm-management strategies exhibited similar partial GM.

In order to encapsulate this risk/return trade-off, a commonly used modified mean-variance approach (e.g. Barah et al., 1981; McCown et al., 1991; Carberry et al., 1993; Hammer et al., 1996) was used to identify optimum or 'risk-efficient' farm management strategies. The approach (demonstrated in Fig. 4 re-using the data from Fig. 3) first involves plotting mean gross margin vs. standard deviation of the mean for each farm-management strategy. A line (termed the risk/return frontier) is then drawn, beginning at the origin, after which it is then joined to the farm-management strategy with the smallest coefficient of variation (CV, i.e. standard deviation/mean), labelled point 1 in Fig. 4. The frontier then proceeds to the farm-management strategy with the next lowest CV that has a

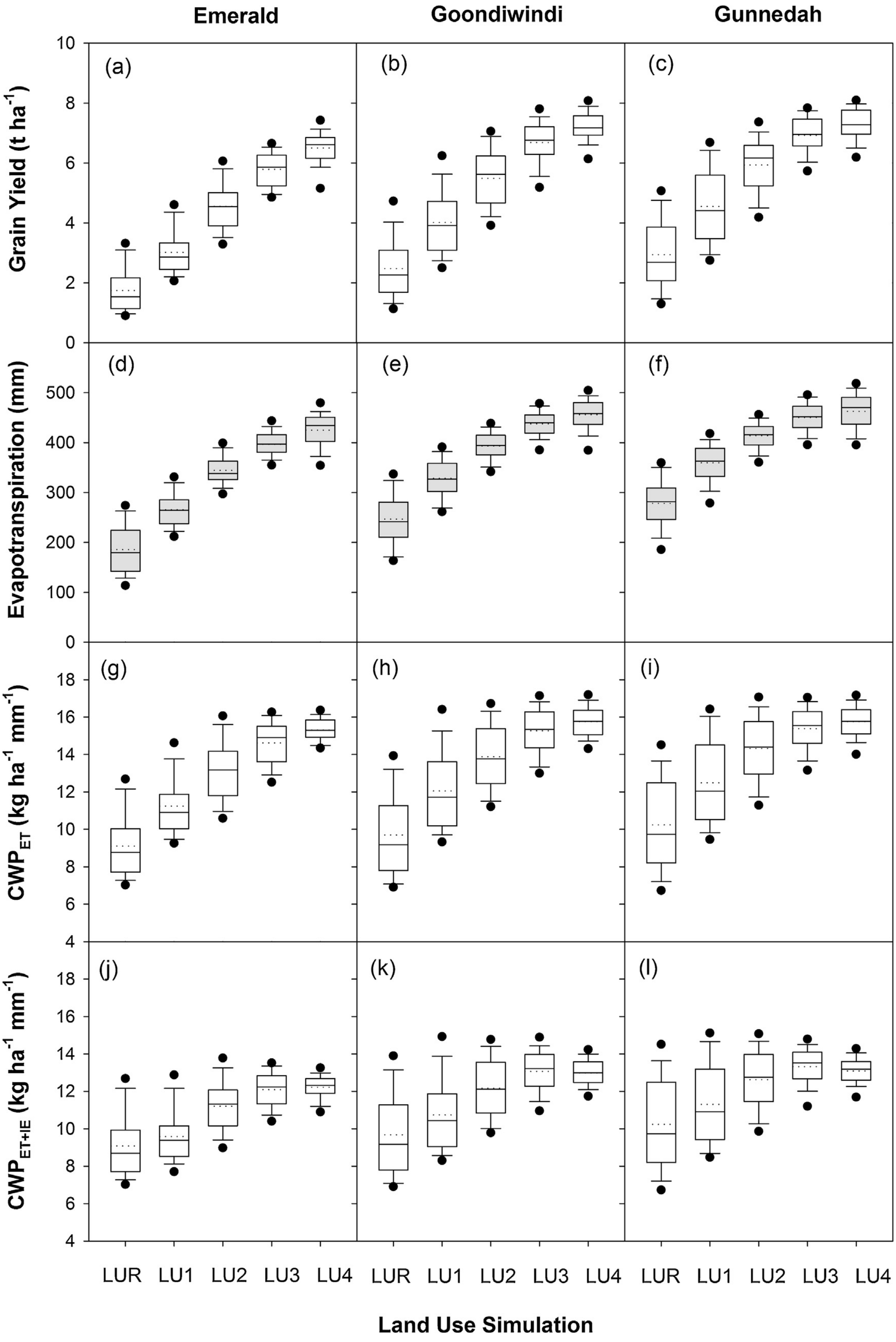

Fig. 2. Boxplots for grain yield, evapotranspiration, CWP_{ET} (grain yield/ET) and CWP_{ET+IE}(grain yield/(ET + drainage + irrigation storage losses)) for the five cropped land-use options and three locations, for long term simulations using 100 mm of stored soil water at sowing. Land use simulations are abbreviated as follows: LUR = Rainfed, LU1 = sowing irrigation only, LU2 = sowing + 1 in-crop irrigation, LU3 = sowing + 2 in-crop irrigations, LU4 = sowing + 3 in-crop irrigations. Boxed areas indicate the upper and lower quartiles, whiskers represent the upper and lower deciles, and the area bounded by circles represents 90% of all years. Median year is represented by the solid line within the interquartile range box, while the mean value is represented by the dotted line.

Table 6
Simulated water lost (as % of the 1400 ML of irrigation water stored at sowing) from storage as evaporation or seepage for the simulated irrigated land-uses at Emerald, Goondiwindi and Gunnedah.

Location, and stored soil water at sowing (mm)		Land use simulation			
		LU1	LU2	LU3	LU4
Emerald	(100)	0.0	6.0	8.3	11.4
	(Zero)	0.0	6.5	7.9	11.0
Goondiwindi	(100)	0.0	6.5	8.1	11.1
	(Zero)	0.0	6.0	7.5	10.3
Gunnedah	(100)	0.0	7.2	8.2	11.1
	(Zero)	0.0	5.0	7.7	10.6

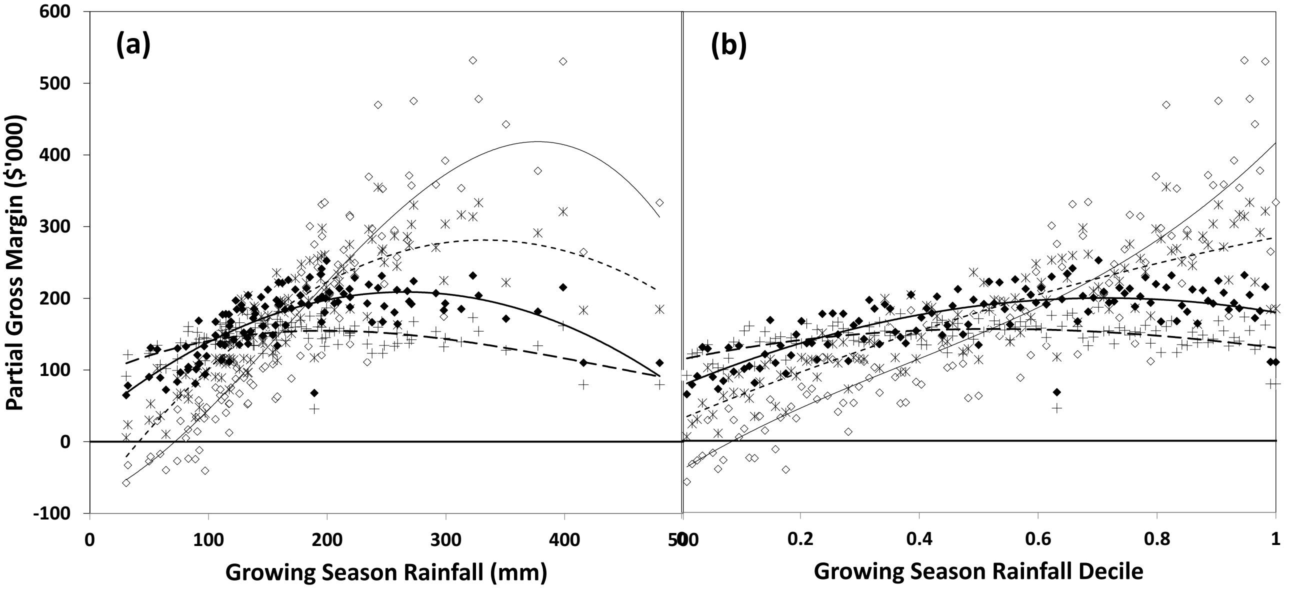

Fig. 3. Partial GM ('GM$_{40}$') vs. (a) growing season rainfall, and (b) growing season rainfall decile, for the farm-management strategies compared at Goondiwindi when zero soil water was available at sowing. (◊—) = 'S/F', i.e. all irrigation at sowing; (*- - -) = S + 1/F; (⧫—) = S + 2/F; (+– – –) = S + 3/F.

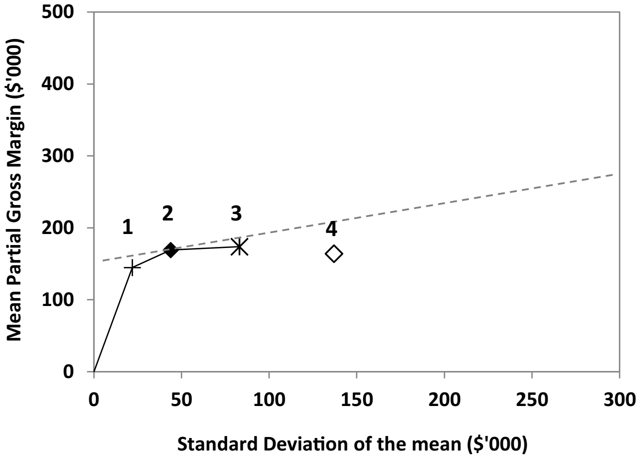

Fig. 4. Mean partial GM ('GM$_{40}$') vs. standard deviation of the mean for farm-management strategy comparison at Goondiwindi when zero soil water was available at sowing. (——) Risk/return frontier; (- - - -) 1:2 line of indifference; + = all irrigation at sowing ('S/F'); ⧫ = S + 1/F, * = S + 2/F, ◊ = S + 3/F. Points 1–3 lie on the risk/return frontier, while point 4 lies slightly below and is not joined to the risk/return frontier.

higher GM and standard deviation than the previous point on the frontier (labelled point 2).

This rule is applied until no further farm-management strategies have both a greater partial GM and standard deviation. Strategies situated on this frontier are potentially logical choices for a grower depending on their level of risk aversion, whereas strategies lying beneath the frontier (e.g. point 4) would be illogical in terms of either maximising mean partial GM or reducing risk, as alternative strategies exist that fulfil either criteria.

An additional frontier used in the analysis is termed the 'line of indifference' (the dashed line in Fig. 4). This line represents the 1:2 ratio between gross margin and standard deviation that has been found to represent the intermediate level of risk/return trade-off preferred by the majority of growers in multiple cultures (Barah et al., 1981; Ryan, 1984; McCown et al., 1991) and has previously been used in conjunction with the risk frontier (McCown et al., 1991; Carberry et al., 2000). For simplicity of presentation, only the 1:2 line of indifference will be presented on remaining risk/return graphs.

In the particular example in question (Fig. 4) it can be seen that point 2 (S + 1/F) is the farm-management strategy with the most favourable position on the risk/return frontier, as its mean partial GM is close to the highest, possessing the second lowest standard deviation and a noticeably larger mean partial GM than the strategy with the lowest standard deviation. For the remainder of this study these 'optimum' strategies are referred to as the most 'risk-efficient' strategies. The most risk-efficient strategies are likely to be preferred by farmers when there is no seasonal forecast available that might cause them to amend their strategy to take advantage of a wetter or drier than average season. The absence of such forecasts is assumed for the analyses conducted herein.

3.3.2. *Risk/return analyses—Emerald*

When evaluating CWP_{ET+IE} at Emerald, the 'irrigation + rainfed' strategies were more risk efficient (Fig. 5a) than the 'irrigation + fallow' strategies, each having CWP_{ET+IE} of approximately 10 kg mm^{-1} when 100 mm of soil water was available at sowing. The strategy with the highest mean CWP_{ET+IE} (S + 2/R) also had the second lowest variance, and was considered the most risk efficient strategy as it was closest to the 1:2 line of indifference.

However when calculating EWP, different irrigation strategies were closest to the 1:2 line of indifference depending on the particular EWP analysis used (Fig. 5b–e). Most farm-management strategies lay close to the 1:2 line of indifference when $\triangle$SW was not priced in the calculation of partial GM (Fig. 5b and d). However when $\triangle$SW was included in the calculation of partial GM, the single sowing irrigation and partially rainfed strategies were less risk efficient than the strategies that incorporated an area of fallow land (Fig. 5c and e). While it did not always have the greatest EWP, the S + 2/F strategy was the most consistently risk-efficient as it was located on or near the line of indifference for each of the EWP analyses.

When zero soil water was available, all strategies except S + 3/F were situated on the line of indifference in the CWP_{ET+IE} analysis (Fig. 5f). In contrast two strategies (S + 2/F and S + 3/F) had similarly high EWP and were closest to the line of indifference in each of the EWP analyses (Fig. 5g–j). While the S/F and S + 1/F strategies were considered risk efficient in the CWP_{ET+IE} analysis, they were substantially below the line of indifference in the EWP analyses.

3.3.3. *Risk/return analyses—Goondiwindi and Gunnedah*

The results of the risk-return analyses at Goondiwindi and Gunnedah are discussed simultaneously as they were similar at these locations, but in contrast to those observed at Emerald. When 100 mm of water was available at sowing, four strategies ('S', S + 1/R, S + 2/R, S + 3/R) were markedly closer to the line of indifference in the CWP_{ET+IE} analysis than the remaining farm-management strategies (Figs. 6a and 7a). The S + 1/R and S + 2/R strategies were also at or near the line of indifference for all of the EWP analyses (Figs. 6b–e and 7b–e). The three strategies involving areas of fallow land were only close to the line of indifference in the $GM_{120} + \triangle SW$ analysis (Figs. 6e and 7e). The valuation of $\triangle$SW within the EWP analyses improved the relative profitability of the three strategies involving fallow land, but not to the same extent observed at Emerald.

When zero soil water was available at sowing, farm-management strategies that spread water across a wider area became more risk-efficient as the price of water increased, and as growing season rainfall changed with location. In the CWP_{ET+IE} analysis at both locations the S/F strategy was the most risk efficient (Figs. 6f and 7f). However in the EWP analyses, the S/F strategy receded from the line of indifference when $\triangle$SW was priced, and when the price of water increased (Figs. 6g–j and 7g–j). Ultimately the S + 2/F strategy was the most consistent at Goondiwindi, being situated on the line of indifference for all the EWP analyses, while the S + 1/F and S + 2/F strategies were equally consistent at Gunnedah where average rainfall was slightly higher.

4. Discussion

4.1. *APSIM validation*

One of the key aspects of the methodology of this study was to confirm the ability of APSIM to simulate water use of furrow-irrigated wheat when comparing multiple irrigation treatments at the same location. As demonstrated in the results, APSIM closely simulated grain yield and water use of the irrigated experiment in Narrabri for the rainfed and single in-crop irrigation treatments, which were grown with high levels of sowing N. Although the model was initially unable to simulate the grain yield and water use of the fully irrigated treatment (grown using the canopy management strategy of in-crop N application), satisfactory simulation of grain yield and water use for this treatment was ultimately achieved when N was applied at sowing in the simulation. This finding adds further evidence to the observations made by Peake et al. (2014) that the APSIM wheat module under-estimates the ability of spring wheat cultivars to recover from severe N stress during tillering, when fertiliser N is subsequently applied during the cropping season and incorporated under ideal (irrigated) conditions for rapid N uptake.

Long-term simulations were therefore carried out using moderate levels of sowing N to ensure they were conducted within the known operating capabilities of the model. It should also be remembered that the analyses herein assume that lodging is avoided through the use of agronomic methods such as cultivar choice, in-crop N application and reduced plant populations. These strategies must therefore be successfully applied in production fields in order to maximise the relevance of the simulation experiment results.

4.2. *Water productivity analyses*

The results of the CWP analyses conducted on alternative land-uses at an individual field scale showed that the more heavily irrigated land-uses had the highest water productivity when measured as CWP_{ET} (grain yield/evapotranspiration). When irrigation inefficiencies were incorporated into the denominator term (as CWP_{ET+IE}), water productivity decreased in the most frequently irrigated treatment, compared with the next most irrigated treatment. These results agreed with trends previously demonstrated in multiple field studies (e.g. Steiner et al., 1985; Musick et al., 1994; Zhang and Oweis, 1999) that increasing irrigation increases water productivity of spring wheat when calculated on a single field basis, until yields approach yield potential.

However, the profitability of irrigation enterprises is dependent on maximising EWP for an entire farm rather than CWP for an individual field, the importance of which can be demonstrated from the results of the current study. At each location, farm-management strategies considered risk-efficient in the CWP_{ET+IE} analysis were not always risk-efficient in the EWP analyses, particularly when non-irrigation water availability was low (i.e. at the low rainfall environment or when stored soil water at sowing was low). Similar results were obtained in maize by Rodrigues et al. (2013) and Paredes et al. (2014) who found re-ranking of optimal strategies depending on whether CWP or EWP analyses were used.

The results of the whole-farm EWP analyses demonstrated that deficit irrigation strategies involving larger areas of wheat were more profitable on average than smaller areas of full irrigation in the two environments with higher in-season rainfall (Goondiwindi and Gunnedah), and were also more risk-efficient. At these environments, one of the deficit irrigation strategies was more profitable and risk-efficient than full irrigation for all permutations of sowing soil water and method of calculating EWP, regardless of whether rainfed wheat or fallow land was used as the alternative land-use to the fully irrigated area. At the environment with lower in-season rainfall (Emerald), deficit irrigation strategies were superior in most EWP analyses except when irrigation water was expensive and the stored soil water remaining at the end of the season was assigned the same value, in which case growing a smaller area of fully irrigated wheat was the most risk-efficient and profitable strategy.

These results broadly agree with the field-based studies of Zhang and Oweis, (1999) and Ali et al. (2007) who also found that EWP for wheat was generally maximised under deficit irrigation. However, it is important to note that the present study demonstrated

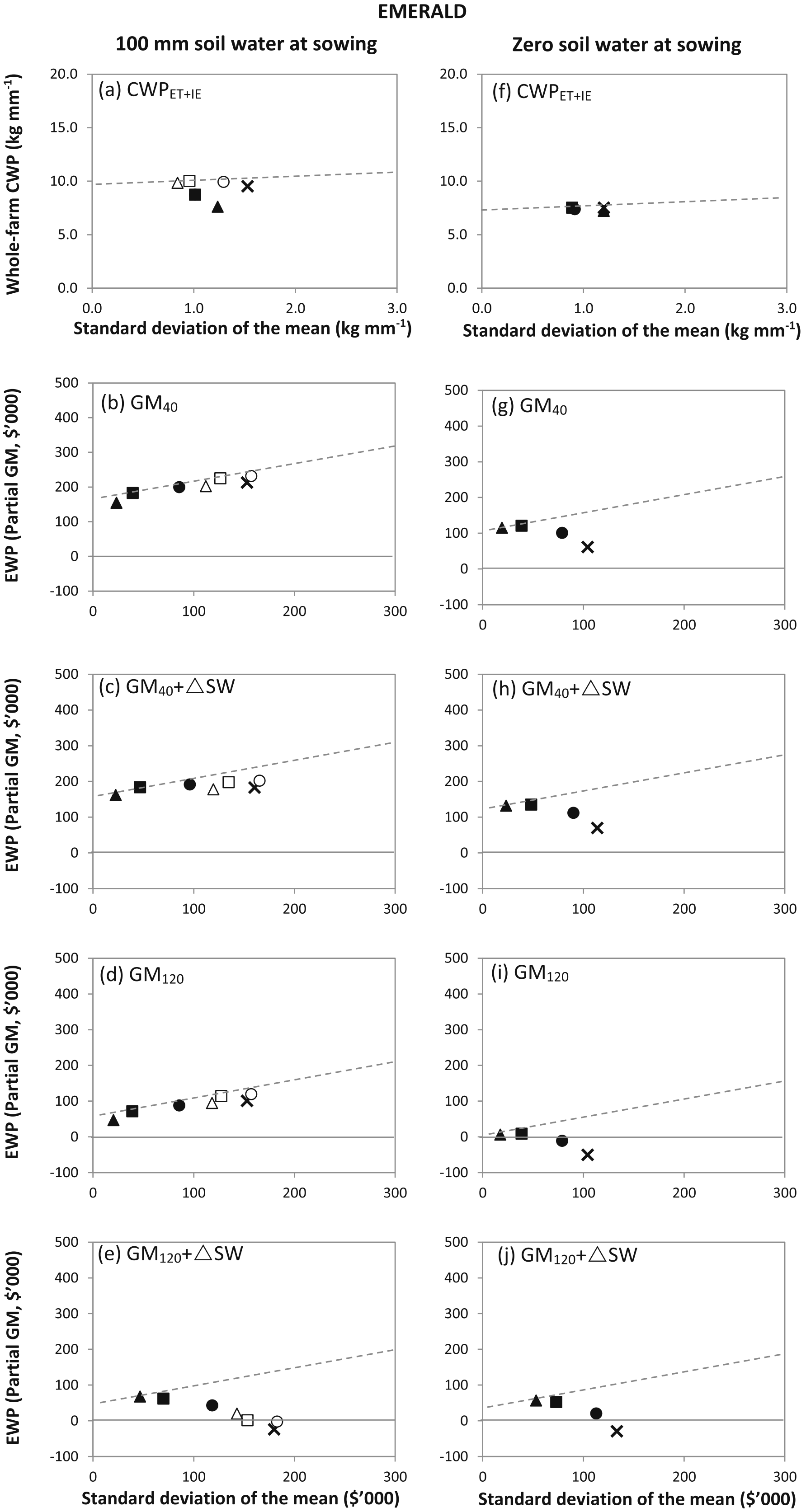

Fig. 5. (a and f) Farm scale CWP_{ET+IE} vs. standard deviation of the mean, and (remaining graphs) EWP vs. standard deviation of the mean, from the comparison of farm-management strategies at Emerald with (a–e) 100 mm or (f–j) zero soil water at sowing. The alternative methods of calculating EWP were (b and g) GM_{40}; (c and h) $GM_{40} + \Delta SW$; (d and i) GM_{120}; (e and j) $GM_{120} + \Delta SW$. Farm-management strategies are denoted as follows: × = S (a–e) or S/F (f–j), ● = S + 1/F; ■ = S + 2/F, ▲ = S+3/F; ○ = S + 1/R; □ = S + 2/R, △ = S + 3/R.

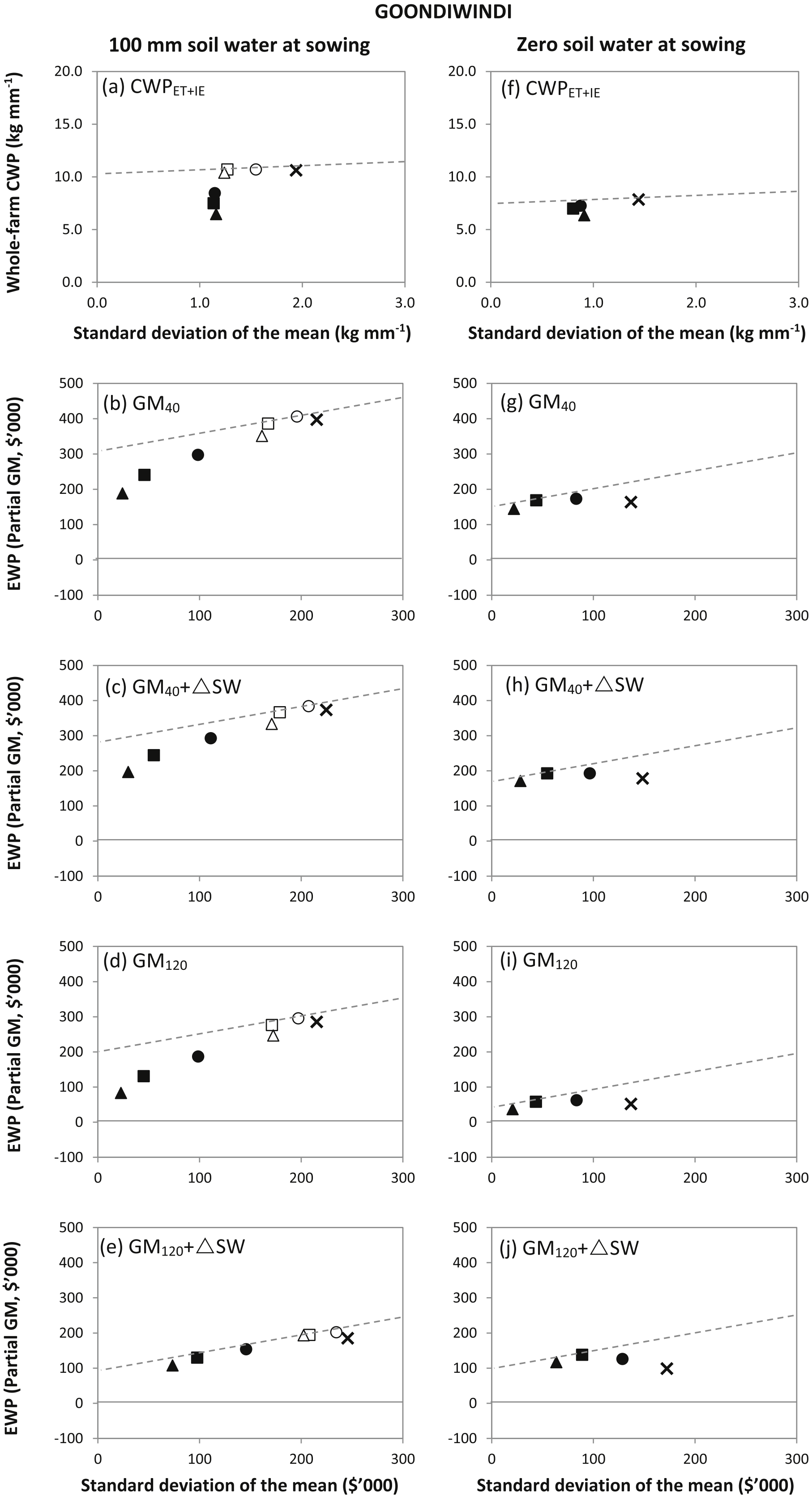

Fig. 6. (a and f) Farm scale CWP_{ET+IE} vs. standard deviation of the mean, and (remaining graphs) EWP vs. standard deviation of the mean, from the comparison of farm-management strategies at Goondiwindi with (a–e) 100 mm or (f–j) zero soil water at sowing. The alternative methods of calculating EWP were (b and g) GM_{40}; (c and h) $GM_{40} + \Delta SW$; (d and i) GM_{120}; (e and j) $GM_{120} + \Delta SW$. Farm-management strategies are denoted as follows: × = S (a–e) or S/F (f–j), ● = S + 1/F; ■ = S + 2/F, ▲ = S + 3/F; ○ = S + 1/R; □ = S + 2/R, △ = S + 3/R.

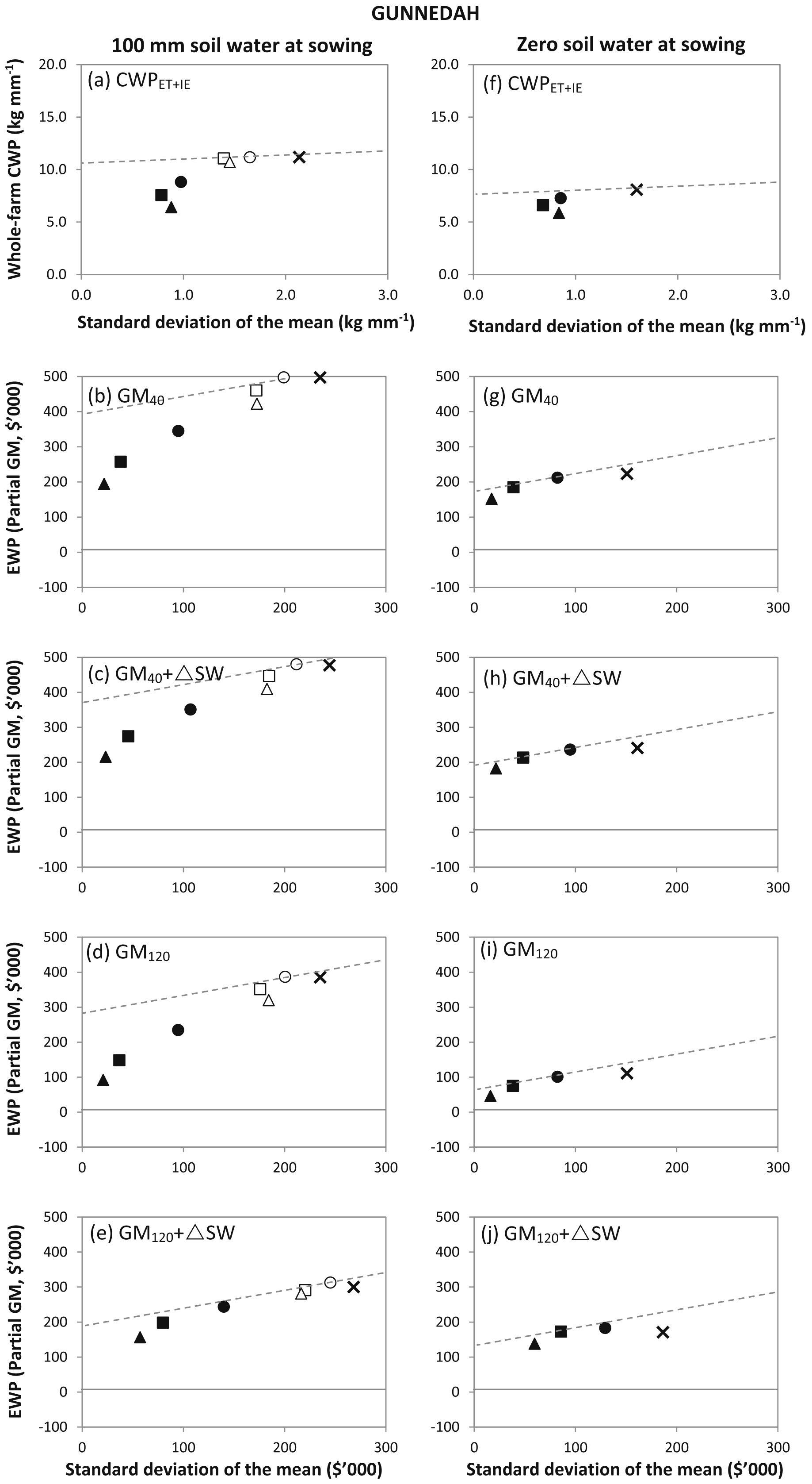

Fig. 7. (a and f) Farm scale CWP_{ET+IE} vs. standard deviation of the mean, and (remaining graphs) EWP vs. standard deviation of the mean, from the comparison of farm-management strategies at Gunnedah with (a–e) 100 mm or (f–j) zero soil water at sowing. The alternative methods of calculating EWP were (b and g) GM_{40}; (c and h) $GM_{40} + \Delta SW$; (d and i) GM_{120}; (e and j) $GM_{120} + \Delta SW$. Farm-management strategies are denoted as follows: × = S (a–e) or S/F (f–j), ● = S + 1/F; ■ = S + 2/F, ▲ = S + 3/F; ○ = S + 1/R; □ = S + 2/R, △ = S + 3/R.

the importance of several aspects of deficit irrigation analysis that have rarely been considered by other studies on deficit irrigation in wheat, and the inclusion of these factors frequently altered the choice of optimum deficit irrigation strategy. In particular, the strategies considered the most risk-efficient in the current study were those that incorporated rainfed crops sown on the unirrigated area.

4.2.1. Assessing the intrinsic value of soil water and its impact on the choice of irrigation strategy

While Lobell and Ortiz-Monasterio (2006) examined the interaction between varying levels of soil water at sowing on the success of different irrigation strategies, they did not specifically investigate the amount of soil water remaining at the end of the season or account for the value of this water. In the current study the intrinsic value of stored soil water was investigated through (1) the inclusion of rainfed cropping on unirrigated land, allowing an assessment of the value of stored soil water across the entire farm by evaluating its crop production potential, and (2) by assigning an economic value to soil water, such that the net change in stored soil water through the season was given the same monetary value as irrigation water.

The use of deficit irrigation across a larger area accesses a greater absolute volume of stored soil water and precipitation (and potentially in some farming systems, water from a subterranean water table). This can be illustrated by considering the results from the four farm-management strategies that consisted of irrigated land in conjunction with fallow land. When 100 mm of stored soil water was available at sowing, the optimum irrigation + fallow strategy was generally one that spread the water over a wider area (i.e. S/F, or S + 1/F). These strategies accessed additional water equivalent to the difference in the cropping area multiplied by the volume of stored soil water and precipitation, per unit area. As the 1000 ha farm in this study had 100 mm (or 1 ML ha^{-1}) of stored soil water per hectare, this meant an additional 50 ML of stored soil water was available for crop use in the sowing irrigation (S/F) strategy that irrigated 1000 ha, compared with the S + 1/F strategy that applied two irrigations to 500 ha of land. Additionally, at Gunnedah for instance, a further 212 mm of rainfall fell on average during the growing season equating to a further 1060 ML available to crop production in the sowing irrigation strategy. The difference in partial GM between the S/F and S + 1/F strategies was large in some EWP analyses (e.g. $150,000 at Gunnedah in the GM$_{40}$ analysis), but heavily biased due to the additional soil water and precipitation used to grow crops over the wider area of the S/F strategy that was unavailable to the S + 1/F strategy. The equivalent strategy that included rainfed cropping (S + 1/R) had an almost identical gross margin to the 'S' strategy at Gunnedah because it was able to use the additional precipitation and stored soil water in producing the rainfed crop, and was more risk-efficient due to its lower year-to-year variability.

Ultimately the analyses showed (unsurprisingly) that rainfed cropping was either similar to or more profitable than fallow land when used in conjunction with deficit irrigation strategies in most of the EWP analyses, and was also more risk-efficient. It is important to note however that the ability to choose rainfed cropping alongside an irrigated area will fluctuate between seasons due to variability in soil moisture at sowing (required both for seed germination and as a stored soil moisture 'buffer' for reliable crop production). Irrigated growers may therefore prefer to irrigate the entire cropping area in certain seasons in response to these practical limitations.

Assigning an economic value to stored soil water impacted on the choice of the most risk-efficient farm-management strategy by reducing the relative profitability of strategies that cropped larger farm areas in comparison to the strategies that included fallow land. In the higher rainfall environments this did not cause significant changes to the relative risk efficiency of the alternative farm-management strategies, but did increase the number of strategies at or near the line of indifference when the price of water was high. However in the low rainfall environment (Emerald) it significantly re-ranked the farm-management strategies such that irrigation + fallow strategies became more profitable and risk-efficient than the irrigation + rainfed strategies.

4.2.2. The effect of stored soil water, environment and year-to-year variability on the choice of risk-efficient irrigation strategies

The importance of stored soil water at sowing in determining the optimum farm-management strategy was first apparent when developing simulation scenarios for the study, as strategies that included rainfed cropping were not considered viable (and hence, not simulated) when there was zero stored soil water at sowing, a well understood principle in the region (e.g. Moeller et al., 2009). However in order to assess the effect of additional soil water at sowing, it was necessary to compare farm-management strategies that were simulated for both levels of sowing soil water, i.e. only the strategies that incorporated irrigation in conjunction with fallow land. Comparison of these strategies showed that increasing soil water at sowing altered the most risk-efficient strategy to one that had a larger deficit irrigated area with reduced frequency of irrigation, for each of the environments studied. These results agree with those of Lobell and Ortiz-Monasterio (2006), who also showed that deficit irrigation of spring wheat was more profitable in conjunction with high levels of stored soil water at sowing.

The most profitable and risk-efficient farm-management strategies varied between environments according to the relative difference in average rainfall between the environments. When 100 mm of soil water was available at sowing and rainfed cropping was considered as a potential land-use, optimal strategies in the higher rainfall environments (Gunnedah and Goondiwindi) were generally irrigation + rainfed strategies that utilised irrigation water across a wider area. These results were similar to those observed in an area of southern Australia with similar growing season rainfall to Gunnedah by Gaydon et al. (2012), who found that maximum farm profitability under limited water situations was obtained by spreading irrigation water over a wider area in winter cereal crops. The same trend was not observed at the lowest rainfall environment where all strategies were either ranked similarly, or strategies including fallow land were considered the most risk-efficient. The identification of different optimal strategies between environments was unsurprising, given the relationship already identified between soil water and risk-efficient deficit irrigation strategies that is logically extended to variable precipitation between environments. Oweis and Hachum (2006) also identified alternative optimum deficit irrigation strategies for different wheat growing environments in Syria with varying rainfall.

It should be remembered that the risk-efficiency of the different irrigation strategies is a long term average generated from multi-year simulations. In individual seasons with markedly higher rainfall than the mean, strategies spreading irrigation water across a wider area will be more profitable than the strategy that is most risk efficient across all years. Conversely in low rainfall years, strategies that have increased irrigation frequency on a smaller crop area are likely to have increased profitability compared with the most risk-efficient strategies from the long term analyses. While it is possible that the use of seasonal climate forecasts could improve the probability of selecting a better strategy for the particular season (e.g. Hammer et al., 1996), evaluation of the value of seasonal forecasting in improving the selection of deficit irrigation strategies is beyond the scope of the present study.

5. Conclusions

The results of the simulation study into whole-farm water productivity in a limited water situation demonstrated that applying deficit irrigation strategies across larger areas of wheat was generally more profitable and risk-efficient (on average across seasons) than full irrigation of smaller areas. The optimal deficit irrigation strategies typically involved using one-third to one-half of the farm area to grow partially irrigated wheat, while the remaining area was sown to rainfed wheat.

Increased access to non-irrigation water (i.e. in higher rainfall environments or through greater stored soil water at sowing) altered the relative risk-efficiency of irrigation strategies and meant that larger areas of deficit irrigated cropping (with decreased frequency of irrigation across the area) became more risk-efficient. However in a low rainfall environment where water was expensive and soil water was given the same economic value as irrigation water, fully irrigated wheat in conjunction with fallow land was the most risk-efficient strategy. The importance of evaluating farm-management strategies using EWP instead of CWP was also evident in this study, as re-ranking of the risk/return profile occurred between these alternative methods of calculating whole-farm WP.

Accounting for the intrinsic value of stored soil water and precipitation was identified as fundamental when assessing the benefits of deficit irrigation strategies in water limited situations, given that the larger land area utilised by deficit irrigation strategies accessed much larger absolute volumes of soil water and precipitation. The use of rainfed crops in the whole-farm simulation analyses demonstrated the intrinsic value of this additional water, and altered the choice of optimum farm-management strategy. Re-ranking of farm-management strategies was also observed when applying an economic value to soil water remaining at the end of the cropping season. Future evaluations of deficit irrigation strategies must begin to account for such considerations.

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