Evaluation Of Options For Increasing Water Productivity Of Wheat Using CSM-Wheat V4.0

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EXTENDED ABSTRACT

Farmers need to increase irrigation water productivity to remain viable in the face of the increasing costs and decreasing availability of water. Wheat is the predominant winter cereal in the irrigated areas of the southern Murray-Darling Basin (SMDB). We used the model CSM-Wheat V4.0 to evaluate management options for increasing the water productivity of wheat. CSM-wheat is derived from CERES-Wheat and CROPSIM-Wheat and embedded within the Decision Support System for Agro-technology Transfer (DSSAT V4.0).

Genetic coefficients for a current wheat variety (Chara) grown under irrigation were derived using field observations of crop development and yield on a Wilbriggie clay loam. The model was used to evaluate the effect of sowing date and irrigation management for Chara on irrigation water productivity (IWP, g grain/kg irrigation water), crop water productivity (CWP, g grain/kg ET), irrigation water use, yield, and drainage losses. Cumulative probability functions were generated using 41 years of historical weather data at Griffith, NSW.

IWP and CWP varied greatly depending on seasonal conditions. Yield and CWP of rainfed Chara were similar for April and May sowings (means ~3 t/ha and 0.9 g/kg ET, respectively), declined as sowing was delayed to June and July, and increased greatly by starting with a wet soil profile. Irrigation to avoid soil water deficit (SWD) greatly increased CWP by 42 to 141% depending on sowing date. For irrigated Chara, CWP varied from 0.4 to 1.6 g/kg, and was highest when sown on 10 May. The variation in IWP due to seasonal variation in rainfall was much greater than the variation in CWP, and ranged from 0.9 to 2.3 g/kg with July sown Chara to 0.9 to 4.7 g/kg with April sowing. In most years, IWP of Chara was highest with May 10 sowing, exceeding 2 g/kg in about 55% of years.

Under rainfed conditions, starting with a wet profile, earlier sowing (April, May) maximised yield and CWP of Chara, while with irrigation, May was the optimum sowing time with soil water deficit (SWD) driven irrigation. However, most growers do not currently schedule irrigations based solely on SWD or crop water use, due to limited availability of irrigation water. They are more likely to plan for one or two irrigations at key stages, seeking to maximise yield and IWP. There is currently no facility in DSSAT V4.0 to enable automatic growth stage dependent irrigation, which limits the development of meaningful simulations for growers. Furthermore, there is no facility for interaction with groundwater in the model, whereas deep drainage (and upflow) are affected by shallow watertables, which are common in parts of the irrigation areas of the SMDB.

While CWP was similar with flood and sprinkler irrigation, IWP was consistently about 23% higher for sprinkler regardless of seasonal conditions, due to slightly higher yields and lower irrigation amounts. Deep drainage losses were substantially higher with flood irrigation (mean 79 mm/y) than sprinkler irrigation (mean 16 mm/y) and rainfed wheat (mean 11 mm/y). The flood irrigated wheat left more plant available water (PAW) in the profile at harvest (by up to 29 mm) for future crop use or loss depending on subsequent land use. This highlights the importance of analysing the impacts of irrigation management strategies on irrigation requirement and water productivity for crop sequences rather than single crops.

Simulations using CSM-Wheat V4.0 and 41 years of weather data suggest that:

- yield and water productivity of both irrigated and rainfed wheat vary greatly with seasonal conditions
- there is scope for maximising yield and water productivity by timely sowing: for rainfed Chara earlier sowing (Apr/May) was best, while May/Jun sowing was best for Chara irrigated to avoid SWD
- irrigation always greatly increased yield and crop water productivity
- sprinkler irrigated wheat had higher irrigation water productivity than flood irrigated wheat due to slightly higher yield, lower irrigation amount, and lower deep drainage losses.

1. INTRODUCTION

Irrigation farmers in the Southern Murray-Darling Basin (SMDB) are under considerable pressure to increase water productivity in the face of increasing cost and reducing availability of water for irrigation, due to national competition policy and the need to return water to the environment (Humphreys and Robinson 2003). Wheat is the predominant winter cereal in the irrigated areas of the SMDB. The water content of the soil profile at the time of preparation for wheat varies greatly depending on previous land use and rainfall, ranging from wet after rice to very dry after wheat/summer fallow. A range of available wheat varieties with different rates of development in response to temperature and photoperiod allows a wide sowing window from late March to early July. Knowledge of the impact of sowing and irrigation management on crop yield, irrigation water requirement, irrigation water productivity (IWP), and crop water productivity (CWP) can help identify management to maximise returns to land or water. IWP can be defined as grain production per unit of irrigation water applied (g grain/kg irrigation water) and CWP as grain production per unit of evapotranspiration (g grain/kg ET).

Crop simulation models can be used to evaluate management options to increase yield and water productivity, taking into account seasonal variability. The crop model CSM-Wheat, derived from CERES-Wheat and CROPSIM-Wheat, can simulate the growth and development of dryland and irrigated wheat across a range of latitudes in both the northern and southern hemispheres. The model processes in CSM-Wheat V4.0, embedded within the DSSAT V4.0 (Decision Support System for Agro-technology Transfer) cropping system framework, remain very similar to those in recent versions of CERES-Wheat (Hoogenboom et al., 2004). Briefly stated, CSM-Wheat is a process-oriented model that simulates carbon, water and nitrogen balances for the wheat plant/soil/atmosphere system. Model algorithms express relationships between plant processes, including phenological development, photosynthesis, respiration, water uptake, biomass growth and partitioning in response to environmental variables such as temperature, photoperiod, radiation and soil water availability. The model also incorporates knowledge of cultivar- and ecotype-specific traits (known as genetic coefficients) to predict daily growth and development as the crop responds to weather, soil characteristics, and management practices. The model processes in CERES-Wheat have been documented in a fragmented way in various publications (see review by Timsina and Humphreys 2003).

CERES-Wheat has been evaluated and applied in a range of temperate and tropical environments across the world (OtterNacke et al., 1986; Timsina and Humphreys, 2003; Smith et al., 2005). The model performed well in predicting a wide range of parameters (growth, development, yield, ET and soil water content) for irrigated wheat in southern NSW. The objective of this study was to derive genetic coefficients of a current wheat variety (Chara) grown under irrigation in the SMDB, and use CSM-Wheat V4.0 to evaluate management options for increasing CWP and IWP of wheat.

2. METHODS

Data for derivation of genetic coefficients were obtained from a cropping system experiment on a Wilbriggie clay loam at the Murrumbidgee Shire Community Experimental Demonstration Farm at Coleambally, southern NSW. Wheat (var. Chara) was sown on 13 May 2004 into burnt wheat stubble at a row spacing of 15 cm, and diammonium phosphate (185 kg/ha; 35 kg N/ha) was sown with the seed (100 kg/ha). The crop was topdressed with 85 kg N/ha as broadcast urea when the crop reached Zadoks growth stage Z32 (two nodes on the main stem). There were five flood irrigations during the season, applied whenever cumulative ETo-rain since the previous irrigation reached 60 mm.

The model was run with water and N non-limiting for the determination of the genetic coefficients, using actual sowing conditions (date, seed rate, depth, and row spacing), and the DSSAT V4.0 default species file for wheat. The genetic coefficients were determined by selecting a standard default cultivar within DSSAT V4.0, and adjusting the development- and growth-related coefficients to achieve the best possible match between simulated and observed phenology, final biomass, and yield.

The model was then used to estimate yield, components of the water balance, CWP and IWP for Chara under both rainfed and irrigated conditions for a range of sowing dates, initial soil water contents (SWC) and irrigation management. The Willbriggie clay loam soil was used for all simulations. Initial conditions were set on 10 April and all simulations commenced on this date, using 41 years (1963-2003) of weather data at Griffith, NSW. The root hospitability factor (SRGF - Hoogenboom et al., 2004) was adjusted so that the majority of the roots grew in the top 30 cm, with a maximum rooting depth of 90 cm, reflecting the likely situation in Wilbriggie clay loam. The root weighting in soil layers was 1 (0-15 cm), 0.8 (15-30 cm), 0.5 (30-45 cm), 0.2 (45-60 cm), and 0.1

(60-90 cm). The irrigation management depth was set to 50 cm for automatic irrigation scheduling based on plant available soil water (PAW) to that depth. In this soil, PAW i.e., water content between drained upper limit (DUL) and the lower limit (LL), was 60 mm in the top 50 cm, while the water holding capacity of the pore space between DUL and saturation was 33 mm. DUL is the soil water content at field capacity, while crops cannot extract water when the soil is drier than LL. The irrigation section of the Simulation Controls block of FileX (a model file for inputting crop management, experimental details, and simulation options) within the DSSAT Shell was modified to enable specification of the date on which automatic irrigations started, as irrigation water is not normally available between late May and early August in the irrigation areas of southern NSW. All simulations were carried out under N non-limiting conditions. Grain yields and water productivities were calculated for dry grain.

2.1 Sowing date and irrigation (wet initial soil profile)

Four sowing dates (10 April, 10 May, 10 June and 10 July) and two irrigation treatments (rainfed and flood-irrigated) were compared. Irrigation (80 mm) was applied whenever PAW in the top 50 cm declined to 50%, with no irrigations prior to 1 August. The above sowing dates represent the sowing window recommended by NSW DPI for Chara, but also include dates earlier or later than ideal, but still used by many farmers (McRae et al., 2004). Initial SWC for all simulations was at the DUL throughout the profile, as for wheat sown shortly after rice harvest, or after pre-irrigation, which is normal practice in the irrigation areas when wheat is not sown after rice.

2.2 Initial SWC (10 May sowing; rainfed)

Three initial soil water contents (SWC) were comapred: (1) WET: SWC at DUL throughout the profile (PAW 103 mm); (2) DRY: SWC just above LL, over 15-90 cm, and mid-way between LL and DUL from 0-15 cm (PAW 16 mm); (3) Intermediate (INT): SWC mid-way between DUL and LL from 0-60 cm, and just below DUL from 60-90 cm (PAW 62 mm).

2.3 Irrigation method (wet initial soil profile)

Three treatments (rainfed, flood irrigated, and sprinkler irrigated) were compared for Chara sown on 10 May with initial SWC at DUL. Flood irrigation was simulated by applying 80 mm when PAW in the top 50 cm of the soil profile decreased to 50%, while sprinkler irrigation was simulated by adding 20 mm of water when PAW in the top 50 cm decreased to 80%. In both treatments, the irrigation season started on 1 August.

3. RESULTS AND DISCUSSION

3.1 Genetic coefficients

The genetic coefficients determined for Chara were: vernalization (P1V) 15, photoperiodism (P1D) 82, grain filling duration (P5) 770, kernel number (G1) 23, kernel weight (G2) 50, spike number (G3) 1.75 and phyllochron interval (PHINT) 95.

3.2 Sowing date and irrigation (wet initial soil profile)

Crop duration decreased as sowing was delayed after 10 April. The crop took on average 148 days to reach flowering and 210 days to maturity (grain filling 62 days) for earlier sowings, but only around 109 days to flowering and 156 days to maturity (47 days grain filling) for the July sowing, under both rainfed and irrigated conditions.

Yield varied greatly with seasonal conditions, for both rainfed and irrigated wheat (Figure 1). Yield of rainfed wheat sown in May was consistently higher than or similar to yield with April sowing, and declined with delay in sowing after May, probably due to the shorter grain filling period with later sowings. Later sown crops also had a shorter vegetative period and so captured less radiation. With the optimum (May) sowing, rainfed wheat yield ranged from 0.4 t/ha in 1982 (54 mm rain between sowing and maturity) to 7.5 t/ha in 1974 (439 mm rain during the season) (Table 1). Yields with May sowing exceeded 3 t/ha in about 45% of years, declining to about 30% of years with June sowing, and 10% of years with July sowing.

Flood irrigation greatly increased yields for all sowing dates, by averages of 1.9 to 4.3 t/ha depending on sowing date (Figure 1, Table 1). Unlike the rainfed situation, yields were lower for irrigated Chara with April sowing than July sowing. The results suggest that early sowing (April/May) is better for rainfed Chara, while if irrigating, delaying sowing to May/June gives better yields.

Irrigation amounts increased with delay in sowing, due to the crop growing under higher evaporative demand in the latter part of the season (Table 1). In 50% of years, irrigation amounts exceeded 240 mm for April sowing, compared with 320, 400 and 400 mm for May, June and July sowings, respectively.

Table 1. Summary of all model runs: grain yield, water balance components and water productivity of wheat as affected by sowing and irrigation management

Treatments/ Scenarios	Grain yield (t/ha)		ET (mm)		Irrigation (mm)		Deep drainage beyond 0.9 m (mm)		Runoff (mm)		CWP ** (g grain/kg ET)		IWP** (g grain/kg irrig.)	
	mean	range	mean	range	mean	range	mean	range	mean	range	mean	range	mean	range
Sowing date - rainfed***														
April 10	2.91	0.63-5.60	304	117-427	0	0	8.6	0-55	10.2	0-31	0.91	0.29-1.50		
May 10	3.18	0.44-7.46	327	111-449	0	0	10.9	2-58	10.8	0-29	0.91	0.31-1.68		
June 10	2.53	0.24-6.62	330	103-477	0	0	12.6	3-57	11.2	0-31	0.71	0.23-1.51		
July 10	1.92	0.15-4.60	329	100-507	0	0	13.8	5-61	11.8	0-32	0.54	0.10-1.04		
Sowing date - flood irrigated***														
April 10	4.80	2.13-7.08	442	364-493	269	80-480	66.4	29-114	17.4	0-63	1.08	0.58-1.44	1.95	0.86-4.69
May 10	6.85	3.65-8.71	524	382-583	340	160-560	78.7	9-154	19.1	0-77	1.30	0.80-1.55	2.13	1.28-3.94
June 10	6.81	1.51-8.69	556	338-632	371	160-560	84.0	23-152	17.1	0-44	1.21	0.45-1.56	1.93	0.93-3.24
July 10	5.87	2.40-7.51	566	353-662	367	160-480	84.2	31-165	17.1	0-69	1.03	0.68-1.27	1.65	0.91-2.27
Initial soil water content - May 10 sowing- rainfed														
DUL*	3.20	0.44-7.46	327	111-449	0	0	10.9	0-58	10.8	0-29	0.91	0.34-1.68		
INT	2.06	0.03-7.45	294	70-444	0	0	2.0	0-27	9.4	0-27	0.61	0.03-1.68		
DRY	1.52	0.02-6.64	274	64-419	0	0	0	0	9.1	0-27	0.47	0.04-1.58		
Irrigation method - May 10 sowing***														
Flood-irrigated	6.85	3.65-8.71	524	382-583	340	106-472	78.7	9-154	19.1	0-77	1.26	0.80-1.55	2.13	1.28-3.94
Sprinkler	7.30	3.73-9.94	557	471-620	294	160-540	15.5	0-73	20.0	1-41	1.31	0.79-1.63	2.63	1.66-4.36

* DUL, INT and DRY refer to initial SWC as drained upper limit, intermediate and dry (see Methods) set on April 10
** CWP= crop water productivity; IWP= Irrigation water productivity; *** initial SWC at DUL set on 10 April

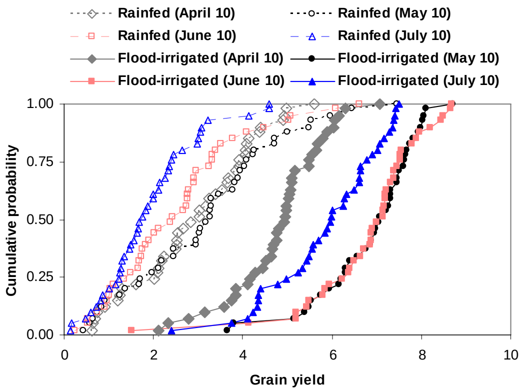

Figure 1. Wheat yield (1963-2003) as affected by sowing date and irrigation

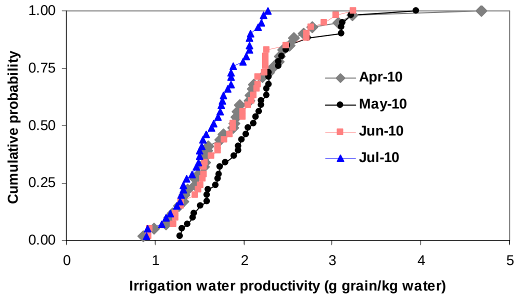

Figure 2. Irrigation water productivity of wheat as affected by sowing date

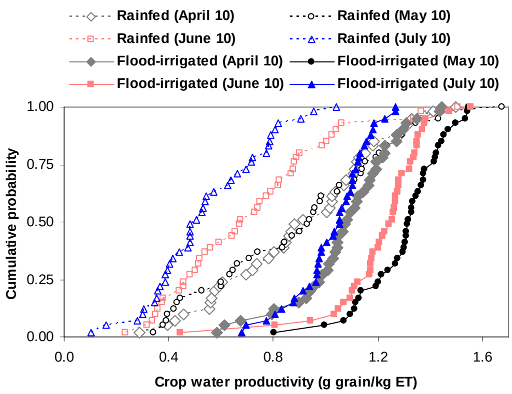

Figure 3. Crop water productivity of wheat as affected by sowing date and irrigation

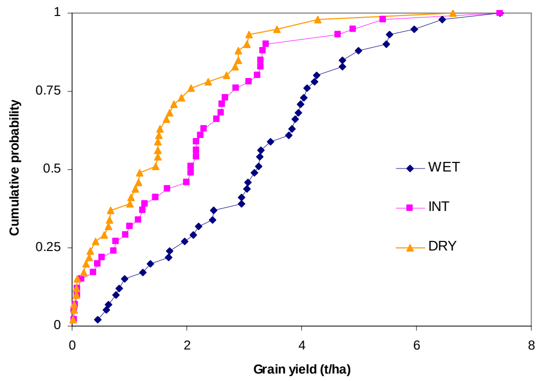

Figure 4. Yield of rainfed wheat as affected by initial soil water content (May 10 sowing)

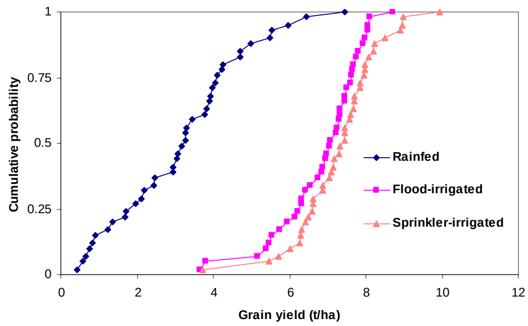

Figure 5. Wheat yield as affected by irrigation management (May 10 sowing)

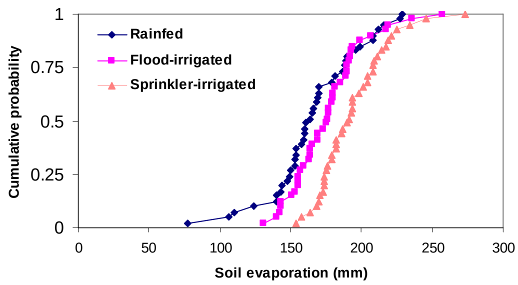

Figure 6. Soil evaporation as affected by irrigation management (May 10 sowing)

Irrigation water productivity was usually highest with May sowing, and declined as sowing was delayed after May, due to lower yield and/or higher irrigation requirement (Figure 2). IWP exceeded 2 g grain/kg water in 55% of years with May sowing, compared with 40-44% of years for April and June sowings, and only about 22% of years for July sowing.

Crop water productivity of irrigated wheat was highest for May 10 sowing and declined as sowing was delayed after May (Figure 3). CWP of the May 10 sowing exceeded 1.3 g grain/kg ET in about 60% of years, compared with ~30% of years for June 10 sowing, and never for July 10 sowing. Irrigation greatly increased CWP except for wheat sown in April. CWP of irrigated wheat for May 10 sowing was 42 to 141% higher than for rainfed wheat at any sowing.

For all sowing dates, mean deep drainage below 0.9 m was much higher (by a factor of 7) for irrigated than for rainfed wheat (Table 1). Deep drainage also increased as sowing was delayed from April to July in both rainfed and irrigated wheat, but the effect was much higher with irrigation (by an average of ~20 mm). Mean surface runoff from rainfed wheat was low (10-12 mm) and was almost doubled with irrigation. Runoff from irrigated wheat was always less then 50 mm, except for one year as a result of heavy rainfall shortly after irrigation. There was little effect of sowing date on runoff for either rainfed or irrigated wheat. The amount of PAW (0-0.9 m) at maturity was higher by up to 29 mm for the flood-irrigated crops than the rainfed crops, but there was little effect of sowing date on PAW for rainfed or irrigated crops.

3.3 Initial SWC (May 10 sowing; rainfed)

In the absence of irrigation, yield for May 10 sowing was always much higher when starting with a full profile prior to sowing (mean 3.2 t/ha), and least with an initially dry profile (mean 1.5 t/ha) (Figure 4, Table 1). Mean CWP was 0.91 g/kg ET when starting with a wet profile, declining to 0.47 g/kg ET for the dry profile. In high rainfall years, there was some runoff from dry profile also. The data demonstrate the importance of starting with a wet profile in raising yields (more than doubled on average) and water productivity of rainfed wheat.

3.4 Irrigation method (wet initial soil profile)

Grain yield of Chara sown on May 10 was consistently higher with sprinkler irrigation than flood irrigation (Figure 5). The number of flood irrigations ranged from 2 to 7, compared with 8 to 27 sprinkler applications, however the total amount was higher with flood irrigation by 46 mm on average. Soil evaporation was consistently higher with sprinkler irrigation than flood irrigation, but only by around 15 mm, and least with rainfed wheat (Figure 6), probably because the soil was wetter more often with frequent sprinkler irrigation. Consistent with this, runoff tended to be slightly (only a few mm) higher with sprinkler irrigation, but was always less than 50 mm in all systems. However, deep drainage (mean 79 mm) was much higher (by a factor of about 5) for flood irrigation than sprinkler irrigation (mean 16 mm), which had similar and generally low levels of deep drainage as compared to rainfed wheat (mean 11 mm).

IWP was consistently higher with sprinkler irrigation due to both higher yield and lower irrigation amount. However, CWP of the two irrigation methods was almost identical, and much higher than for rainfed wheat except in the highest yielding rainfed years (the wettest years).

4. GENERAL DISCUSSION

Irrigation and crop water productivity varied greatly depending on seasonal conditions, through their influence on both yield and crop water use requirement. Starting with a wet soil profile, yield and CWP of rainfed Chara were higher for April and May sowings (means ~ 3 t/ha and 0.9 g/kg ET, respectively), declined as sowing was delayed to June and July, and increased greatly by starting with a wet soil profile. Irrigation greatly increased CWP by 42 to 141% depending on sowing date.

For irrigated Chara, CWP varied from 0.4 to 1.6 g/kg, and was highest when sown on 10 May, averaging 1.3 g/kg. This is similar to the values for irrigated wheat from 13 countries across 5 continents (range 0.6 to 1.7, mean 1.09 g grain/kg ET) (Zwart and Bastiaanssen 2004).

The variation in IWP due to seasonal variation in rainfall was much greater than the variation in CWP, and ranged from 0.9 to 2.3 g/kg with July sown Chara to 0.9 to 4.7 g/kg with April sowing. In most years, IWP of Chara was highest with May 10 sowing, exceeding 2 g/kg in about 55% of years. The results suggest that there is large scope for maximising CWP and IWP by sowing at the optimum time. However, most growers do not currently schedule irrigations based solely on soil water deficit or crop water use, due to limited availability of irrigation water. Many growers are more likely to plan for one or two irrigations at key stages, seeking to maximise yield and IWP. There is currently no facility in DSSAT V4.0 to enable automatic growth stage dependent irrigations, which limits the development of meaningful simulations for growers. Furthermore, there is no facility for interaction with groundwater in the model, whereas deep drainage (and upflow) are affected by shallow watertables, which are common in parts of the irrigation areas of the SMDB.

While CWP was similar with flood and sprinkler irrigation, IWP was consistently about 23% higher for sprinkler irrigation regardless of seasonal conditions, due to slightly higher yields and lower irrigation amounts. The flood irrigated wheat left more water in the profile at harvest (by up to 29 mm) available for crop use or loss depending on subsequent landuse. This highlights the importance of analysing the impacts of irrigation management strategies on irrigation requirement and water productivity for cropping systems rather than single crops.

5. CONCLUSIONS

Simulations using CSM-Wheat V4.0 and 41 years of weather data suggest that:

- yield and water productivity of both irrigated and rainfed wheat vary greatly with seasonal conditions
- there is scope for maximising yield and water productivity by timely sowing: for rainfed Chara earlier sowing (Apr/May) was best, while May/Jun sowing was best for Chara irrigated to avoid SWD
- irrigation always greatly increased yield and crop water productivity
- sprinkler irrigated wheat had higher irrigation water productivity than flood irrigated wheat due to slightly higher yield, lower irrigation amount, and lower deep drainage losses.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Hoogenboom, G., J.W. Jones, C.H. Porter, P. W. Wilkens, K.J. Boote, W.D. Batchelor, L.A. Hunt, and G.Y. Tsuji (2004). DSSAT 4.0. Vol. 1, Overview. ICASA, University of Hawaii, Honolulu, USA.

Humphreys E, and D. Robinson D (2003). Increasing water productivity in irrigated rice systems in Australia: institutions and policies. In ‘Rice Science: Innovations and Impact for Livelihood’ (Eds Mew TW, Brar DS, Peng S., Dawe D and Hardy B) pp. 885-900. Proceedings of the International Rice Research Conference, 16-19 September 2002, Beijing, China (IRRI, Chinese Academy of Engineering and Chines Academy of Agricultural Sciences, Beijing, China).

Otter-Nacke, S., Godwin, D., Ritchie, J.T. (1986). Testing and validating the CERES-Wheat model in diverse environments. IFDC, Muscle Shoals, Alabama, USA, 147 p.

McRae, F.J., D.W. McCaffery and P.W. Matthews (2005). Winter Crop Variety Sowing Guide 2005. NSW Department of Primary Industries. NSW, Australia, 92 pp.

Smith, D.J., E. Humphreys and D.C. Godwin (2005). Effect of management, site and seasonal conditions on net recharge and yield of wheat sown after rice. CSIRO Land and Water Technical Report (in review).

Timsina, J. and E. Humphreys (2003). Performance and applications of CERES and SWAGMAN Destiny models for rice-wheat systems in Asia and Australia: a review. CSIRO Technical Report #3. CSIRO Land and Water, Griffith, Australia.

Zwart, S.J. and W.G.M. Bastiaanssen (2004). Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management 69, 115-133.