Cotton Catchment Communities CRC

FINAL REPORT

(due on completion of project)

Part 1 - Summary Details

Cotton CRC Project Number: 1.02.09

Project Title: Maximising profitability with limited water in cotton farming systems

Project Commencement Date: 01/04/2007 **Project Completion Date:** 31/03/2010

Cotton CRC Program: The Farm

Part 2 – Contact Details

Administrator: Helen Kamel, R&D Coordinator Plant Science
Organisation: Agri-Science Queensland, DEEDI, Toowoomba
Postal Address: PO Box 241, Darling Heights, Toowoomba, QLD 4350
Ph: 07-4631-5380 **Fax:** 07-4631-5378 **E-mail:** helen.kamel@deedi.qld.gov.au

Principal Researcher: Jose Payero
Organisation: Agri-Science Queensland, DEEDI
Postal Address: 203 Tor Street, Toowoomba, QLD 4350
Ph: 07-4688-1513 **Fax:** 07-4688-1197 **E-mail:** jose.payero@deedi.qld.gov.au

Supervisor: Graham Harris
Organisation: Agri-Science Queensland, DEEDI
Postal Address: 203 Tor Street, Toowoomba, QLD 4350
Ph: 07-4688-1559 **Fax:** 07-4688-1197 **E-mail:** graham.harris@deedi.qld.gov.au

Signature of Research Provider Representative: ____________________________

Part 3 – Final Report Guide (due within 3 months on completion of project)

(The points below are to be used as a guideline when completing your final report.)

Background

1. *Outline the background to the project.*

With diminishing water supply, changing weather patterns and pressure to enhance environmental flows it is imperative to optimise water use efficiency (WUE) on cotton/grain farming systems. Growers are looking for strategies that make best use of limited water. It is still not clear how to best use the available water at farm and field scale. At farm scale, the issue concerns trade-offs between area planted, irrigation intensity and crop rotations. At field scale, there are novel ways to grow crops with limited water and include supplementary irrigated skip- row configurations, deficit irrigation, crop rotations, etc. This research project investigated the impact of management strategies to deal with limited water supplies on the yield and quality of irrigated cotton and wheat. The data collected from this research could be incorporated into existing crop models. These models can be used to develop information products and training packages that will aid irrigators and their consultants in making management decisions in response to limited water supplies that maximise crop profitability.

Objectives

2. *List the project objectives and the extent to which these have been achieved.*

The objectives of this project were:

- Objective (1): to develop irrigation management guidelines for the main irrigated crops on the Darling Downs for full- and deficit-irrigation scenarios, taking into account the critical factors that affect irrigation decisions at the local level.
- Objective (2): to quantify the evapotranspiration (ET) of Bollgard II cotton and wheat and its relationship to yield and quality under full- and deficit-irrigation scenarios.
- Objective (3): to increase industry awareness and education of farming systems practises for optimised economic water use efficiency.

Methods

3. *Detail the methodology and justify the methodology used. Include any discoveries in methods that may benefit other related research.*

The methodology used to address each objective was as follows:

Objective (1) was addressed by:

- Collaborating with ASPRU to develop the APSFarm model within APSIM to be able to perform multi-paddock simulations. APSFarm was then tested by conducting a case study at a farm near Dalby.
- Conducting semi-structured interviews with individual farmers and crop consultants on the Darling Downs to document the strategies they are using to deal with limited water.

Objective (2) was addressed by:

- Building and installing 12 large (1 m x 1m x 1.5 m) weighing lysimeters to measure crop evapotranspiration. The lysimeters were installed at the Agri-Science Queensland research station at Kingsthorpe in November 2008.
- Conducting field experiments to measure crop evapotranspiration and crop development under four irrigation treatments, including dryland, deficit-irrigation, and full irrigation. Field experiments were conducted with cotton in 2007-08 and 2008-09, and with wheat in 2008 and 2009.
- Collaborating with USQ on a PhD thesis to quantify the impact of crop stress on crop evapotranspiration and canopy temperature. Glasshouse experiments were conducted with wheat in 2008 and with cotton in 2008-09.

Objective (3) was addressed by:

- Conducting a field day at Kingsthorpe: A field day was conducted at Kingsthorpe on 26/11/09. The field day included a farm shed meeting with four speakers and a field walk to show the lysimeter site. The field day was successful and attracted about 80 participants.
- Presenting information in conferences: The results of this project have been presented at conferences in Australia and overseas (see publication list below). For example, one poster was presented at the 2008 Australian cotton conference, and four posters were presented at the 2010 Australian cotton conference. Two posters from this project were presented at the 2010 Australian irrigation conference (in Sydney). In 2009, one paper was presented at a conference in California, and another at a conference in India. Two papers will be presented at the Australian Agronomy Conference in New Zealand (November 2010). Another paper was presented at the Australian Agronomy conference in 2008 in Adelaide.
- Presenting information at farmers meeting: Two presentations were made at the 2008 Grains Research Update at Dalby dealing with how to manage irrigation under limited water situations (see publication list below).

- Presentations to crop consultants: Presentations on irrigation management was made as part of training to crop consultants from Pacific Seeds (in 2007) and from Pioneer Seeds (in 2008). Presentations were also made at the University of Southern Queensland, as part of NCEA "WaterTap" meetings in 2006 and 2009.
- Extension publications: In 2007, one article was published in "Spotlight on Cotton R&D" in 2007 and another one in the "Downs Water Chat" newsletter (see publication list below).

Results

4. Detail and discuss the results for each objective including the statistical analysis of results.

Objective (1): to develop irrigation management guidelines for the main irrigated crops on the Darling Downs for full- and deficit-irrigation scenarios, taking into account the critical factors that affect irrigation decisions at the local level.

To accomplish this objective, we collaborated with ASPRU to help them develop the APSFarm model within APSIM to be able to perform multi-paddock simulations. We then applied APSFarm to conduct a case study at a farm near Dalby. This case study served to validate and fine-tune the model. Details of APSFarm and its application in the context of this project are presented in **Appendix I, Appendix II,** and **Appendix III.**

We also conducting semi-structured interviews with individual farmers and crop consultants (5 farmers and 5 consultants) on the Darling Downs to document the strategies they are currently using to deal with limited water issues. The results of these interviews are documented in **Appendix IV**. A desktop review was also conducted to develop irrigation guidelines for the darling Downs. This is still a work in progress, but the current version of the guidelines is shown in **Appendix V**.

Objective (2): to quantify the evapotranspiration (ET) of Bollgard II cotton and wheat and its relationship to yield and quality under full- and deficit-irrigation scenarios.

- Twelve large (1 m x 1m x 1.5 m) weighing lysimeters to measure crop evapotranspiration were designed, constructed and installed. Two different designs were constructed and tested from which a final design was used to build the 12 lysimeters. The 12 lysimeters were installed at the Agri-Science Queensland research station at Kingsthorpe in November 2008. Details of the design, installation and performance are described in **Appendix IX**. As part of another project internally funded by Agri-Science Queensland, we also built and installed a total of 23 lysimeters (including the 12 lysimeters from this project). In addition to the 12 lysimeters installed at Kingsthorpe, we installed 9 lysimeters at Gatton and 2 at Kingaroy. Therefore, we now have the capacity to measure crop evapotranspiration under three different environments, which also gives us the capacity to work with different crops, including vegetables and peanuts. The Kingsthorpe field experiments had presented opportunities for us to collaborate with other researchers. For example, since 2009, we have been collaborating with Dr. Peter

Grace from QUT to evaluate the impact of irrigation practices on the emission of Nitrous Oxide. We have also collaborated with researchers from USQ (see details below).

- We have conducted field experiments to measure crop evapotranspiration and crop development under four irrigation treatments, including dryland, deficit-irrigation, and full irrigation at Kingsthorpe. The lysimeter data for the cotton 2008-09 season is included in **Appendix XI**. Field experiments were conducted with cotton in 2007-08 and 2008-09, and with wheat in 2008 and 2009. Lysimeter data were collected from cotton in 2008-09, but the crop was severely affected by herbicide drift damage. Data was also collected during the 2009 wheat crop, but the crop was also severely affected by crown rot and hail damage late in the season. Good data was collected from cotton in 2007-08 and from wheat in 2008. Some of the results from cotton are presented in **Appendix VI** and **Appendix VII**. **Appendix VI** describes the crop water use, water extraction distribution, crop development, lint yield and quality of cotton grown under four irrigation regimes. **Appendix VII** describes the comparison of water extraction of cotton planted on single-skip and solid row configurations. Data for wheat is presented in **Appendix VIII**, which describes a comparison of irrigation and nitrogen management strategies for wheat.
- We also collaborating with Dr. Rabi Misra and Dr. Jyotiprakash Padhi from the University of Southern Queensland –USQ- on a PhD thesis to quantify the impact of crop stress on crop evapotranspiration and canopy temperature (Funded by CRC-IF). For this dissertation, data was collected from the field experiments at Kingsthorpe and from glasshouse experiments that were conducted with wheat in 2008 and with cotton in 2008-09. Some of the results from the glasshouse experiment conducted with wheat in 2008 are presented in **Appendix X**. The cotton experiment had similar results. The following dissertation resulted from this work:

  > "*Padhi, J. 2009. Incorporating spatial variability in soil and crop properties for effective irrigation. Ph.D. Dissertation, University of Southern Queensland.*"

Outcomes

5. *Describe how the project's outputs will contribute to the planned outcomes identified in the project application. Describe the planned outcomes achieved to date.*

Outcomes for objective (1): to develop irrigation management guidelines for the main irrigated crops on the Darling Downs for full- and deficit-irrigation scenarios, taking into account the critical factors that affect irrigation decisions at the local level.

The interviews of consultants and growers have indicated a range of strategies are currently being used to deal with limited water. The strategies could be broadly divided into: cropping system strategies, specific crop strategies, irrigation system management and business strategies. There are some obvious communalities across growers and consultants, but there were some differences in approaches identified. Some economic analysis and validation comparing the different strategies, however, seem to be needed, since some strategies are based on anecdotal evidence alone. There is also a need to further research the advantages of the different irrigated skip-row configurations, especially in terms of quantifying the real potential for saving water and real improvement in water use efficiency (WUE) that each configuration offers.

Contributing to the development of APSfarm was an interesting exercise, resulting in a tool that could be used to evaluate strategies at the whole-farm scale. It is, however, intended as a research tool rather than an easy tool for growers to use. The development process provided a good opportunity to interact with modellers and growers.

Progress has been made in producing the *"Limited Water Guidelines for the Darling Downs."* A rough draft has been produced (**Appendix V**), but the final product is yet to be finalized and published. **We request an extension for another year with existing unspent funds to complete this task and enable additional research information to be included.**

Outcomes for Objective (2): to quantify the evapotranspiration (ET) of Bollgard II cotton and wheat and its relationship to yield and quality under full- and deficit-irrigation scenarios.

We have collected a lot of field data from cotton and wheat. Some of this information is reported in detail in the attached **Appendixes**, and there is still a lot of information to be analysed, written and published. We are currently using some of the knowledge gained from this project in the design of new web-based tools to help growers make irrigation decisions. However, for the 2007-08 cotton crop we did not have the lysimeters yet, and in 2008-09, the crop was damaged by herbicide drift. Also, the late-planting of cotton has resulted in low yield due to delay in maturity, since we have been trying to grow cotton after wheat. We still would like to collect some lysimeter data with an earlier-planted cotton crop that would allow proper crop maturity and yield development. **Therefore, we are requesting an extension of the project for another year with existing unspent funds to be able to collect good lysimeter data for cotton.**

Objective (3): to increase industry awareness and education of farming systems practises for optimised economic water use efficiency.

A series of extension activities were undertaken during this project (see Methods for objective 3 above). Also, a series of publications have come out of this project (see Publications, below). There are also some additional publications that will be written from the data collected during this project. Also, the irrigation guidelines, once completed, can be incorporated into the proposed updated "WATERpak."

6. *Please describe any:-*
   a) *technical advances achieved (eg commercially significant developments, patents applied for or granted licenses, etc.);*

   None to report at this time.

   b) *other information developed from research (eg discoveries in methodology, equipment design, etc.); and*

For this project, two different lysimeters systems were designed and constructed to measured crop evapotranspiration in the field (**Figure 1 and 2**). One prototype of each design was built and tested. Both designs worked well, but design 2 was used to build the rest of the lysimeters due to lower cost. The prototype for design 1 was installed at the Agri-Science Queensland research station at Kingaroy and is currently in operation. We have been using this lysimeter to measure ETc from other crops, including barley, peanuts, and maize over the last two years.

We also collaborated with USQ in the design of an electronic scale system to measure crop evapotranspiration of crop grown in pots in a glasshouse (**Figure 3**). We used this system to determine the effect of water stress in the daily evapotranspiration of wheat and cotton.

Figure 1. Lysimeter design 1, Constructed of normal steel and the inner lysimeter box rests on two springs, which serve as a counterbalance for the dead mass. The load cells only need to measure the mass changes due to water loss rather than having to measure the total mass of the inner lysimeter box.

Figure 2. Lysimeter design 2, constructed of stainless steel and the total mass of the inner lysimeter box rests directly on the load cells.

Figure 3. Electronic scale system used to measure evapotranspiration from crops in the glasshouse at the University of Southern Queensland (USQ), Toowoomba.

c) *required changes to the Intellectual Property register.*

None to report at this time.

Conclusion

7. *Provide an assessment of the likely impact of the results and conclusions of the research project for the cotton industry. What are the take home messages?*

- APSfarm has been developed and has been successfully applied to evaluate the feasibility of practices at the whole-farm scale. It has proven useful to evaluate the economic feasibility of options under limited-water scenarios for a case study near Dalby. There is still a need for new research around some of the limited-water practices, which need to be incorporated into the model (ie. How to estimate water use under skip-row configuration).

- From growers and crop consultants interviews we learned that there is a great variety of strategies, at different scales, that they are using to deal with limited water situation. The strategies will be summarised in the *"Limited Water Guidelines for the Darling Downs"* that we are currently preparing. However, further research around some of these strategies is needed to evaluate their usefulness.

- As a result of this project, we design, built, installed and tested two innovative lysimeter systems. As a result we now have a state-of-the-art lysimeter facility to be able to conduct replicated experiments to investigate daily water use of a variety of crops under Australian conditions, using different irrigation treatments. With this facility we can investigate the impact of stress on crop water use. Extending the initiative of this project, we have been able to build additional lysimeters with Agri-Science Queensland internal funding. Now we have 12 lysimeters at Kingsthorpe, 9 lysimeters at Gatton, and 2 lysimeters at Kingaroy. This allows us to investigate crop water use of a variety of crops under different environments.

- From a cotton field experiment with four irrigation treatments and three replications conducted at Kingsthope during the 2007-08 season, we found that:
    - The seasonal potential evapotranspiration (ETp) at Kingsthorpe was about 750 mm. Cumulative daily ETp increased linearly from sowing to 60 days after sowing (DAS) at 2.4 mm d^{-1} and at 5.29 mm d^{-1} after that. All treatments received some stress, which affected actual crop evapotranspiration (ETc), resulting in seasonal ETc of 417 to 628 mm (56 to 84% of ETp).
    - A computer model based on the FAO-56 procedure estimated the seasonal ETc of all treatments to within 3% compared with a seasonal water balance estimate (based on neutron probe measurements).

  - From 30-min EnvironScan soil water measurements at 10 cm depth intervals we found that the cotton extracted soil water from as deep as 150 cm. However, about 80% of the seasonal soil water extraction was from the top 60 cm and 90% was from the top 80 cm. Also, from about 32 days after sowing (DAS) to 100 DAS, the depth of soil water extraction increased almost linearly at a rate of 1.89 cm d^{-1} or 2.36 times the crop canopy height. Therefore, irrigation management for cotton should focus on keeping good soil water content in the top 80 cm of soil rather than relying on deep soil water extraction.
  - Irrigation affected crop development. For example, daily accumulation in above-ground dry biomass was linearly related to daily cumulative ETc (at a rate of 11.28 g m^{-2} mm^{-1}) and to cumulative transpiration (at a rate of 12.08 g m^{-2} mm^{-1}).
  - Crop stress affected reproductive development and lint quality, but did not affect lint yield under the conditions of this experiment. Severe stress caused the crop to stop producing bolls, while the mildly stressed plants kept producing bolls until the end of the season. Bolls produced late in the season did not develop and mature properly. Crop stress and delay in crop maturity significantly affected lint quality. Several indicators of lint quality, including micronaire, were linearly related to seasonal ETc.
- Measurements of soil water between skip and solid planted cotton were made at three positions (P1, P2, and P3) with respect to the crop row throughout the 2007-08 season. We found that:
  - In general, the skip configuration tended to have more soil water available in the top 105 cm soil profile between 58 and 98 days after sowing, during the vegetative development stage. The time when the additional water was available for the skip configuration varied with measuring position (P1, P2, and P3). The additional water was available earlier in the season at position P3, which was available during 58 and 65 DAS, compared with positions P1 and P2 where the additional water was available later in the season (72 to 98 DAS).
  - For the entire season, however, both configurations extracted about the same amount of soil water, which was about 128 mm, suggesting that both configurations were water-limited and extracted all the water that was available. The 128 mm added to the seasonal rainfall of 271 mm allowed us to estimate the seasonal water use at about 399 mm, which was about half of the seasonal grass-reference evapotranspiration (ETo = 804 mm) for the site.
  - Because of the additional water available between 58 and 98 DAS, the crop under the skip configuration grew about 10 cm taller. The additional water, however, was

    - not enough to produce significant differences in crop yield between the skip and solid configurations.

- A replicated field experiment with wheat using four irrigation treatments (initiating irrigation at 50%, 60%, 70% or 85% depletion of available soil water) and three nitrogen treatments (100, 150 or 200 kg N/ha) was conducted in 2008 at Kingsthorpe. We found that:
    - Increasing irrigation significantly increased crop yield, but decreased grain protein content. Irrigation also increased crop leaf area index and plant height, which resulted in increased crop lodging problems. No response was observed from the nitrogen treatments due to high initial soil nitrogen content.
    - Economic analysis showed that additional irrigation increased gross margins when calculated in terms of $/ha. However, a slightly deficit-irrigated treatment (initiating irrigation at 60% depletion) resulted in similar or higher gross margins compared with a fully-irrigated treatment (initiating irrigation at 50% depletion) when compared in terms of $/ML of water inputs. Severely stressed treatments (initiating irrigation at 70% and 85% depletion) resulted in the lowest gross margins, both in a $/ha and $/ML basis.
- A glasshouse experiment to evaluate the effect of crop stress on wheat evapotranspiration (ETc) was conducted in Toowoomba during the winter of 2008. The experiment was repeated with cotton in the summer of 2008-09. From the wheat experiment we found that:
    - Changed weather conditions for crops grown in a glasshouse, compared with field conditions, can have a significant impact on crop development and maturity. Water stress significantly reduced daily crop evapotranspiration (ETc), and crop coefficients (Kc), and accelerated crop maturity.
    - The relationship between the relative Kc and soil water depletion fraction was found to vary between irrigation cycles, especially for crops exposed to severe water stress. It was suggested that the different relationships result from decreased biomass and leaf area index caused by water stress, which in turn translate into decreased ETc. An unique relationship like that suggested by FAO-56 seems to only be applicable to crops subjected to mild stress or when stress occurs only late in the growing season when the plants are fully grown.
    - Seasonal ETc was found to be linearly related to crop biomass production, grain yield and harvest index. These results are important for modeling crop water use and yield under water stressed conditions.

- A cotton field experiment with four irrigation treatments and three replications was conducted at Kingsthorpe in 2008-09. Twelve weighing lysimeters (one per plot) were used to measure ETc. We found that:
    - The measured ETc showed the expected normal daily variability associated with changes in weather conditions, crop growth, soil moisture, and crop stress. The measured daily ETc and Kc values were very sensitive to rain and irrigation, which affected evaporation, and by crop stress, which affected crop transpiration.
    - Daily basal crop coefficients (K_{cb}) fitted to data for the fully-irrigated treatment were different from values suggested in FAO-56 for cotton, both as related to the Kcb values for each growth stage and also as related to the length of the growth stages. Differences could be due to both variety (Bollgard®II rather than conventional) and environmental conditions.
    - Our data suggests that a curvilinear, rather than linear, decrease in relative Kc as a function of soil water depletion fraction seems to describe the effect of water stress on relative crop Kc better than the linear function suggested in FAO-56 for WDF>0.6 for cotton.

Extension Opportunities

8. *Detail a plan for the activities or other steps that may be taken:*

   (a) to further develop or to exploit the project technology.

We plan to continue using the lysimeter facility developed during this project to investigate crop water use of other crops or to relate crop water use of cotton to other variables, such us to remote sensing inputs, especially under deficit-irrigation. We also plan to continue using this site to collaborate with QUT in evaluating the impact of irrigation in the emission of Nitrous Oxide. We also intend to continue analysing the field data that has already been collected from these project and preparing additional publications.

(b) for the future presentation and dissemination of the project outcomes.

We will continue preparing publications from the data collected, which will be presented in future conferences and in journals. Also, we intend to finalize the limited water guidelines for the Darling Downs and make it available to growers in a variety of formats. Likewise, we plan to continue producing short articles that will be published in our "*More Profit per Drop*" blog. Here is a list of some of the publications that we plan to prepare from the data collected in this project:

1. Design of weighing lysimeter facility (design 1)
2. Design of weighing lysimeter system (design 2)
3. Relative ETc and Kc of wheat in a Glasshouse
4. Relative ETc and Kc of Cotton in a Glasshouse

5. Comparison of water use from Solid and Skip cotton
6. Determining wheat cover from digital images
7. Evaluation of wheat Zadok growth stages for the Darling Downs
8. Evaluating cotton soil water extraction from EnvironScan data
9. Effect of stress on cotton fibre quality
10. Effect of stress on wheat grain quality
11. Effect of irrigation management on wheat yield and development
12. Effect of irrigation on the reproductive development of cotton
13. Effect of irrigation on canopy development of cotton
14. Grower's strategies to deal with limited water on the Darling Downs
15. Effect of soil moisture on canopy water content for wheat and cotton
16. Effect of water stress on cotton ETc and Kc

(c) for future research.

We would like to collect at least an additional year of cotton data using the lysimeters. Also, we would like to use the facility at Kingsthorpe to relate daily ETc and Kc to vegetation indexes (such as NDVI) obtained from remote sensing inputs. Also, there is opportunity to add value to some of the work that is currently being conducted in Narrabri looking at using canopy temperature to evaluate crop stress. Our site is well equipped to do this type of work and we have expertise in this area. Also, we would like to investigate further the daily water use of crops planted in different row configurations. Over the last two years, as part of a different project, we have been investigating a technique (surface renewal) that will be well-suited to this task. We will also like to continue measuring crop water use (and CO2 fluxes) of cotton from commercial farms using the Eddy Covariance technique. This will add value to the ETc measured with the lysimeters at the plot scale. We have submitted 3 PRP's to the CRDC to conduct this work.

Publications

9. A. List the publications arising from the research project and/or a publication plan.

(NB: Where possible, please provide a copy of any publication/s)

Publications related to this project include:

1) **Payero, J.O.**, Harris, G., Robinson, G., 2010. Cotton soil water extraction. Poster presented at the 15th Australian Cotton Conference. 10 - 12 August, 2010. Gold Coast Convention & Exhibition Centre, Broadbeach, Queensland, Australia.
2) **Payero, J.O.**, Harris, G., Robinson, G. Singh, J., 2010. Soil water use from single-skip and solid cotton. Poster presented at the 15th Australian Cotton Conference. 10 - 12 August, 2010. Gold Coast Convention & Exhibition Centre, Broadbeach, Queensland, Australia.
3) **Payero, J.O.**, Harris, G., Robinson, G. Singh, J., 2010. Measuring crop water use of local crops. Poster presented at the 15th Australian Cotton Conference. 10 - 12 August, 2010. Gold Coast Convention & Exhibition Centre, Broadbeach, Queensland, Australia.

4) **Payero, J.O.**, Harris, G., Robinson, G. Singh, J., 2010. Measuring crop water use and CO_2 by Eddy covariance. Poster presented at the 15th Australian Cotton Conference. 10 - 12 August, 2010. Gold Coast Convention & Exhibition Centre, Broadbeach, Queensland, Australia.

5) Power, B., Rodriguez, D., deVoil, P., Harris, G., **Payero, J.O**. 2010. A multi-paddock bio-economic model of irrigated grain-cotton farming systems. Proceedings of the 2010 Australian Irrigation Conference, 8-10 June, Sydney, Australia, pages 252-253.

6) Padhi, J., **Payero, J.O.,** Misra, R. 2010. Measuring the effect of water stress on wheat evapotranspiration. Proceedings of the 2010 Australian Irrigation Conference, 8-10 June, Sydney, Australia, pages 203-204.

7) Padhi, J., Misra, R. J., **Payero, J.O.,** 2010. Prospective of infrared thermography as an irrigation scheduling technique in a wheat crop. Proceedings of the 2010 Australian Irrigation Conference, 8-10 June, Sydney, Australia, pages 258-259.

8) Power, B., DeVoil, P., Rodriguez, D., Harris, G. and **Payero, J.O**., 2009. Integrating sub-models at differing scales to improve the profitability of irrigated farm business, Farming Systems Design 2009, An International Symposium on Methodologies for Integrated Analysis of Farm Production Systems, Monterey, CA, pp. 1-2.

9) Padhi, J., Misra, R.K., **Payero, J.O**. 2009. Use of infrared thermography to detect water deficit response in an irrigated cotton crop. International Conference on Food Security and Environmental Sustainability (FSES 2009), 17-19 December, 2009, Indian Institute of Technology, Kharagpur, India.

10) **Payero, J.O.** and Harris, G.A., 2008. Optimising irrigated grain production with limited water. Proceedings of the 2008 Grains Research Update. Grains Research and Development Corporation, 19-20 August, Dalby, Australia, pp. 75-80.

11) **Payero, J.O.**, 2008. Optimising maize yield under irrigation. Proceedings of the 2008 Summer Crop Grains Research Update. Grains Research and Development Corporation, 19-20 August, Dalby, Australia, pp. 68-74.

12) Power, B., DeVoil, P., **Payero, J.O.**, Rodriguez, D. and Harris, G., 2008. Using the farm- scale system model APSFarm to improve profitability of irrigation cropping enterprises. 14th Australian Society of Agronomy Conference, 21-25 September 2008, Adelaide, South Australia, pp. 4.

13) **Payero, J.**O., Harris, G.A., Power, B., Goyne, P. 2008. Maximizing profits with limited water. Poster presented at the 14th Australian Cotton Conference-New beginnings-cotton in a climate of change, Broadbeach, Queensland, Australia, 12-14 August 2008.

14) **Payero, J.O**., McIntyre, G.T. and Harris, G., 2007. Darling Downs crop competitions show very high water use efficiencies, Spotlight on Cotton R&D, Cotton Research and Development Corporation, Spring 2007, pp. 13-14.

15) **Payero, J.O**., 2007. Do you know your Water Use Efficiency, Downs Water Chat, Irrigation Extension Newsletter, issue #6, Dalby, Australia, pp. 2.

16) **Payero, J.O**. 2007. Soil Water and Irrigation Scheduling. Presentation as part of training to crop consultants from Pacific Seeds, Toowoomba, Australia, 29 July 2007.

17) Misra, R.K., Padhi, J., **Payero, J.O**. 2010. Improved calibration of load cells as a basis to accurate measurement of evapotranspiration with a mini-lysimeter system. Manuscript to be submitted for publication.

18) Padhi, J. 2009. Incorporating spatial variability in soil and crop properties for effective irrigation. Ph.D. Dissertation, University of Southern Queensland.

Other conference papers:

19) **Payero, J.O.**, Harris, T.R. Robinson, G. 2010. Development of a lysimeter research facility for Crop evapotranspiration measurement. To be presented at the 15th Australian Agronomy Conference, Lincoln, New Zealand, 15-18th November 2010.

20) **Payero, J.O.** , Robinson, G., Harris, G. 2010. Evaluation of irrigation and nitrogen management strategies for winter wheat production on the Darling Downs. To be presented at the 15th Australian Agronomy Conference, Lincoln, New Zealand, 15-18th November 2010.

B. Have you developed any online resources and what is the website address?

Developing online resources was not part of this project. However, we have used knowledge gained from this project to develop a new web-based tool to help growers make irrigation planning decisions. The new tool is called "***CropWaterUse***" and can be found at http://cropwateruse.dpi.qld.gov.au/. Also, we are now in the process of developing a new tool for to help growers make day-to-day irrigation scheduling decisions, which should be available online later this year. We have also created a new blog to provide information to growers, including some of the findings from this project. The blog is called "***More Profit per Drop***," and can be found at http://moreprofitperdrop.wordpress.com/.

Part 4 – Final Report Executive Summary

Diminishing water supply, changing weather patterns and pressure to enhance environmental flows are making it imperative to optimise water use efficiency (WUE) on cotton/grain farming systems. Growers are looking for better strategies to make the best use of limited water, but it is still not clear how to best use the available water at farm and field scale. This research project investigated the impact of management strategies to deal with limited water supplies on the yield and quality of irrigated cotton and wheat. The objectives were: (1) to develop irrigation management guidelines for the main irrigated crops on the Darling Downs for full- and deficit-irrigation scenarios, taking into account the critical factors that affect irrigation decisions at the local level, (2) to quantify the evapotranspiration (ET) of Bollgard II cotton and wheat and its relationship to yield and quality under full- and deficit-irrigation scenarios, and (3) to increase industry awareness and education of farming systems practises for optimised economic water use efficiency.

Objective (1) was addressed by (A) collaborating with ASPRU to develop the APSFarm model within APSIM to be able to perform multi-paddock simulations. APSFarm was then tested by conducting a case study at a farm near Dalby, and (B) conducting semi-structured interviews with individual farmers and crop consultants on the Darling Downs to document the strategies they are using to deal with limited water. Objective (2) was addressed by (A) building and installing 12 large (1 m x 1m x 1.5 m) weighing lysimeters to measure crop evapotranspiration. The lysimeters were installed at the Agri-Science Queensland research station at Kingsthorpe in November 2008, (B) conducting field experiments to measure crop evapotranspiration and crop development under four irrigation treatments, including dryland, deficit-irrigation, and full irrigation. Field experiments were conducted with cotton in 2007-08 and 2008-09, and with wheat in 2008 and 2009, and (C) collaborating with USQ on a PhD thesis to quantify the impact of crop stress on crop evapotranspiration and canopy temperature. Glasshouse experiments were conducted with wheat in 2008 and with cotton in 2008-09. Objective (3) was addressed by (A) conducting a field day at Kingsthorpe in 2009, which was attended by 80 participants, (B) presenting information in conferences in Australia and overseas, (D) presenting information at farmers meeting, (E) making presentations to crop consultants, and (F) preparing extension publications.

As part of this project we contributed to the development of APSfarm, which has been successfully applied to evaluate the feasibility of practices at the whole-farm scale. From growers and crop consultants interviews we learned that there is a great variety of strategies, at different scales, that they are using to deal with limited water situation. These strategies will be summarised in the *"Limited Water Guidelines for the Darling Downs"* that we are currently preparing.

As a result of this project, we now have a state-of-the-art lysimeter research facility (23 large weighing lysimeters) to be able to conduct replicated experiments to investigate daily water use of a variety of crops under different irrigation regimes and under different environments. Under this project, a series of field and glasshouse experiments were conducted with cotton and wheat, investigating aspects like: (A) quantification of daily and seasonal crop water use under non-stressed and stressed conditions, (B) impact of row configuration on crop water use, (C) impact of water stress on yield, evapotranspiration, crop vegetative and reproductive development, soil water extraction pattern, yield and yield quality. The information obtained from this project is now being used to develop web-based tools to help growers make planning and day-to-day irrigation decisions.

Appendix I

A multi-field bio-economic model of irrigated grain-cotton farming systems (DRAFT)

B Power, D Rodriguez, P deVoil, G Harris, J Payero.

Agri-Science Queensland, and Agricultural Production Systems Research Unit (APSRU), PO Box 102 Toowoomba Queensland 4350, Australia
Email of corresponding author: brendan.power@deedi.qld.gov.au

Abstract

Static-equilibrium models are used to model and explore the optimal allocation of limiting resources in complicated farming systems. This approach however is limited in its applicability due to a reliance on assumptions about likely yields, prices, water allocations, etc.; and an inability to accommodate tactical and strategic responses to changes in climate and markets.

Here we present an alternative functional and dynamic modelling framework that integrates multiple bio-physical models that operate at differing scales i.e. the management unit, the farm and the sub-catchment. Interviews with farmers provide farm specific data, such as water sources and their annual allocations, water storage capacities, cropping areas, agronomy, irrigation management and field layout relative to storages. Farm business constraints are included such as limits to the availability of resources, e.g. land, irrigation water, finance, labour, machinery and time. Then plant, soil and agronomy interactions are simulated within homogeneous irrigation management units (described here as fields) using the point scale Agricultural Production System sIMulator (APSIM). Multiple fields within the farm are then represented in silico by various instances of APSIM using the farm scale model APSFarm that allows for machinery and labour constraints, and whole farm economics to be calculated. The “farm manager” is modelled using coded algorithms to specify field crop rotations and farmer’s preference for the allocation of land and water across alternative crop enterprises, risk attitude, cropping intensity, etc.

In this paper we demonstrate the value of developing and applying a more integrative and interdisciplinary approach to represent the whole farm system to support discussions in participatory research projects, aiming to design more profitable and sustainable farm businesses. Here we applied this framework to model a case study of an irrigated farm business near Dalby (151.27E - 27.17S), Queensland, Australia, to quantify the economic and environmental trade-offs of alternative business designs, under conditions of limited available water for irrigation.

Our model was able to answer two farmer's posed question; what is the relative profitability of two different crop rotations and the effect on relative whole-farm profitability of a small amount of additional irrigation water that is made available every day.

Introduction

Australian irrigators are under increasing pressure to maintain the viability of their farm business with pressure from reduced water allocations, receding water tables, increased competition from alternative users such as urban and industry, climate change, and the cost-price squeeze. While farmers continuously adapt their management practises in response to changes in their operational environment, medium and long term farm business planning requires greater levels of information and support to ensure success.

Desktop studies have long been used in the analysis of cropping systems to: explore the optimal allocation of limiting resources in farming systems; assist farmers in understanding and managing the complexity of their farming system; quantify impacts and identify optimum adaptations options to climate change and variability; as an aid in decision making or as discussion support tools. Typically these studies have involved the development and application of either whole-farm static equilibrium models (Pannel et al, 1990) or point scale bio-economic models that are scaled up to the whole farm (Brennan *et al*, 2008).

Static equilibrium or otherwise called mathematical models are limited in their applicability due to a reliance on assumptions made *a priori* about likely yields, prices, water allocations, etc.; and an inability to dynamically accommodate tactical and strategic responses to shifts in climate, seasonal climate forecasting tools, and market volatility. Dillon (1979) described their application to farm management as "*logically attractive but largely inapplicable theory*". However he conceded their suitability when modelling regional implication for policy. McCown (*et al* 2006) argue static equilibrium models fail when applied to the analysis of farm management because farms are: unique, dynamic, complex, exist in an uncertain environment, and farmers have different preferences. Here we present APSFarm a dynamic modelling framework that integrates multiple bio-physical models that operate at differing scales i.e. the management unit, the farm and the sub-catchment. We argue here that APSFarm adequately models the dynamics of farms and addresses the five factors raised by McCown (*et al* 2006) and there-by creating a more complex, dynamic whole farm model that are better able to generate relevant information and knowledge for growers.

In this paper we describe APSFarm and explain how it has been extended from rain-fed cropping to irrigated systems. We report on the results from participatory research project where APSFarm is applied to a case study farm near Dalby, Queensland, Australia to explore farm management options for increased profitability.

Material and Methods

Modelling Framework

When developing economic and bio-physical models of farms a three-way trade off exists between; generalisations so that conclusion and inferences may be made about other farms of similar type, a simplification of reality; and model complexity so that the model adequately represents the dynamics of the farm production system. The extension of APSIM (Keating *et al*, 2003) to APSFarm is described in de Voil, et al 2000 where it lists three components of the extension; multi-fields, farm level resources and manager and a module for economic analysis. Here-in we describe these extensions for an irrigated farming systems and a case study of an irrigated grain cotton farm business near Dalby, Queensland.

Firstly APSFarm has multi-fields where each field or management unit is an instance of APSIM, hence each field in our model can have different soil parameters, cropping history and areas. Typically the area for each field was chosen as the area that the existing farm infrastructure can irrigate in one day. Each of these *in silico* fields do not each map to a unique field on the physical farm but are instead a representation of an homogeneous irrigation management unit.

The management of these fields is achieved via a "*farm level manager"* and include two types of decisions, tactical and strategic, each with its own operational scope. Tactical decisions are field specific, such as fertiliser rates, sowing densities and irrigation management such as when and how much irrigation to apply. Secondly strategic management decisions, that operate at the whole farm level, such as setting crop priorities for irrigation water, specifying crop rotations for each field and the on farm movement of water between storages so that irrigation supply costs and water losses due to evaporation and drainage are minimised.

An example of the implementation of rotations in APSFarm is shown in Figure 1. The circles or nodes represent the states in which any management unit can be found such as planted to a crop or *Fallow* if no crop is planted. The arcs between nodes hold the description of the rules allowing the transition between the different states, such as rules for planting, and harvesting the different crops. For example to move from the *Fallow0* node to the *Maize* node in figure 1 it is necessary for all of the following sowing rules to be true: the date must be between September 15th and October 15th, the aggregate stored water in the field soil and corresponding farm storage must be grater the 4 ML/ha, the existing area planted to summer grain cannot exceed 50% of the total farm area and machinery capacity must be available to plant the proposed area. Table 1 has the complete list of sowing rules for each crop and these rules are executed every day in each field for all years of the simulation. A long term *patched* historical climate record (Jeffrey et al, 2001) from 1890 to 2008 for Dalby, Queensland was used and each fields initial state is one of the three different F*allow* nodes. These fields then become objects at the whole farm level in addition to whole farm resources such as on-farm water storages, source of irrigation water and farm machinery each of which are described in more detail below.

Water storages are subject to daily losses due to seepage and evaporation and are calculated via APSIM's *WaterSupply* module (Gaydon and Lisson 2005) using equations 1 and 2. The irrigation water stored is supplied to crops as needed and the number and timing of irrigation events is determined by crop demand. When extractable soil water falls below a critical value, water is pumped from storages to the field requiring the water and the crop is irrigated. If a field's corresponding storage is emptied and additional irrigation water is required other water-storages are queried to determine if they have water that is surplus to their requirement after considering an estimate of the irrigation needs for the remainder of the season.

This dynamic estimate of the irrigation water required from each water-storage is achieved by the implementation of a conceptual-water-storage. This is a model of the decision maker's mental representation of the seasonal requirement for irrigation water from each storage, that is updated through the growing season as rainfall, run off or irrigation events occur. For example Figure 2 shows a time series of the daily available water (blue series) and the water available from the conceptual storage (red series), which is a daily estimate of the required irrigation water for the remained of the season. This shows a sowing event in October when the conceptual-storage (red series), increased from 0 to 250 ML, which represents an estimate of the irrigation water required for the area planted to this particular crop. These values are obtained via interviews with the farmers and correspond to the required stored water per area planted for each crop and appear in table 1. For example cotton requires 4ML/ha and, depending on the area planted, this estimate of the required amount is then set-aside at sowing. Then, in Figure 2, more area is planted in early January and the estimate increases to almost 700ML. At each irrigation event the farmer updates his estimate of the required irrigation water and the amount required is reduced and the physical storage (blue series) is reduced as irrigation water is pumped out. If a water-storage receives a request from another storage to transfer water and its capacity is currently greater than the capacity of its corresponding conceptual-storage then it has irrigation water that is a surplus to its current seasonal requirements, and water is transferred to the requesting storage. This is subject to a constraint i.e. pumping capacity, and incurs in a cost in fuel and maintenance of the pumps.

In addition to facilitating the transfer of water between storages the inclusion of conceptual water storages allows for the prioritisation of irrigation-water at the whole farm level because it considers the irrigation requirement for all crops currently planted on the farm. For example if two fields are planted, one to cotton which has 4 ML/ha set aside and the other to sorghum which has no water set aside. Then all the stored water corresponding to the sorghum fields will be available to use to irrigate the cotton and only excess water not required by the cotton will be used to irrigate the sorghum.

Water-storage levels change dynamically through the season as reductions occur due to evaporation, drainage and irrigation events and additions are made from intercepted rainfall, captured runoff from fields and ‘top-up’ events where overland flow is captured in a sump and pumped into storages. To generate a historical time series of overland flow a simple catchment model was used and calibrated against estimates for annual captured overland flow. The farmer provided the estimates for median captured annual overland flow of 700ML/year and 0 and 1350 ML/year for annual minimum and maximum respectively. These values represent estimates for the past 30 years which corresponds to the time the farmer has managed this farm. A 30 year simulation was conducted and when daily run-off was greater than some critical value the sump is assumed full and the water can be pumped into the storage. This critical value was chosen, via an iterative process, so that simulated captured annual overland flow matched as closely as possible the estimates provided by the farmer and was then used to generate a full historical record for the same duration as the historical climate series. This technique maintains both the necessary correlation between the over-land flow events and historical climate data and the temporal correlation within the overland flow time-series i.e. the tendency for ‘top-up’ events to be clustered together.

Irrigation infrastructure

Firstly, our model of the case study farm, as the real-world farm, has three on-farm water storages, (labelled in figure 2 as A, B and C) two with 500ML capacity (A and B) and a 300 ML storage (labelled C). Due to the constraints of irrigation channels, each water-storage can only supply irrigation water and collect runoff water from the following fixed areas of the farm; 252 ha, 314 ha and 215 ha respectively. The delivery of irrigation water to fields is restricted by the pumping capacities listed in Table 2 as out-flow rates for each water-storage. In addition to these water storages, the farm has 5 bores with a combined annual allocation of 610 ML/year and with the facility to carry-over 50% any unused allocations into consecutive years. Water from bores can be supplied to all fields, though at the considerably reduced flow rate of 2.6 ML/hr and hence time is a limiting resource when irrigating from bores.

This particular irrigator, as most irrigators in the region, uses a furrow-irrigation system which involves applying water at the top of a furrow between rows of plants and allowing it to flow to the end of the row via gravity. The system is inherently inefficient (Raine *et al* 2005) and more water than required is pumped from the storage so that the excess run-off is returned as tail water. To capture this in-efficiency in our model an additional 25% more water than is required to fill the profile is pumped, which is common in most furrow irrigation schemes. The actual amount reaching the field is less 5% due to evaporation and seepage while in the channels. Pumping costs are then incurred to return the tail water back to the water-storage, again less 5% for evaporation and seepage losses (see figure 2 for a schematic). These values for transfer losses and irrigation efficiency were determined in consultation with the farmer and irrigation engineers.

Economics

The third component of the extension of APSIM to APSFarm is the inclusion of an economic module. However, its implementation here is different to that described previously in de Voil, 2009; Rodriguez 2007, 2010; Cox 2010 and Owens, 2009. Firstly the economic analysis is kept separate whereas previously it was included as an additional module within the APSFarm model. Here the economics analysis is conducted post simulation and hence it is possible to change cost and price scenarios and perform simple ‘what ifs’ without the need to re-run the simulation. For long-term simulations, using approximately 110 years of climate data and with multiple fields, this can save considerable computing time. This approach however does have its limitation because it is not suitable when decisions are made depending on the current cash balance of the farm business for example, crop choice that depends on farm liquidity. Secondly, gross margins are calculated and not whole farm cash-flows for the following reasons. Gross margins are simpler and are appropriate here because we are comparing the relative profitability of scenarios that have similar farm resource utilisations. Also, overhead costs and hence whole farm economics are specific to a particular farm where as gross margins are specific to an activity but more general to the farm (Malcolm et al, 2005). Since the long term goal of this work is to draw conclusions that are relevant to other farms of similar type, whole farm gross margin or total gross margin (TGM) are more appropriate. This approach also has the advantage in that it does away with the need for acquiring potentially sensitive information about farm financing and equity from collaborating farmers.

Values for variable costs and commodity prices for each enterprise were obtained via interviews with the collaborating farmer and appear in tables 4 to 8. These values represent what the farmer expects over the long term and hence exclude any recent movements. The 'event' column indicates the timing of income and costs for each simulated field. For example when harvesting a field planted to maize its simulated tonnage is multiplied by the expected on-farm price of $250/tonne less costs due to cartage ($11/tonne), levies ($2.50/tonne), contract harvester (270$/hr), fuel (1.31 $/L) and irrigation cost form the bores (30$/ML) and water storages. The cost to supply irrigation varies depending on the water storage used and is shown in Table 9. The fuel spent and hours required for a contract header to harvest a 60ha field is a function of the yield for each crop and is given by the step functions in figures 3 and 4 respectively. Similarly when sowing maize in a field all the costs listed in table 4 under event *sowing* and units in $/ha are multiplied by the field's area, in addition to fertiliser and fallow costs (described below).

The daily net balance of the soil nitrogen is modelled by APSIM's nitrogen module SOILN (Probert et al 1997). The fertiliser is applied at sowing at a rate that top up soil nitrogen to a set amount. The fertiliser costs for each crop is then the difference between the current soil nitrogen level (kg/ha) and the corresponding rate in table 3. Fertiliser costs then vary with each season and for each field due to their different cropping history. The fallow costs for each activity is given by the number of weed events during the fallow that precedes the crop's sowing event multiplied by herbicide spraying costs (listed in tables 5 to 9 with units dollars per weed event). A weed event occurs when sufficient rainfall for weeds to germinate (i.e. greater than 25 mm over 4 days) has fallen and the following 250 thermal degree days has sufficient soil water (i.e. the soil water profile is greater than 50% full). This model gave values for weed event counts that agreed with the data supplied by the farmer. The aggregate of these costs and prices represents this field's contribution to the whole-farm gross margin and likewise for all other fields and crop combinations.

Results and Discussion

The APSFarm model was run with Crop Rotation 1 in figure 1 and using almost 120 years of patched climate data (Jeffrey et al, 2001) for Dalby, Queensland, Australia. The resulting distributions of yields of each crop across all fields and seasons are shown in the box plot in figure 3. The red lines show the farmer estimates for average, minimum and maximums for each crop and the box plot shows the ability of APSFarm to adequately simulate yields in individual fields. Figure 4 shows the corresponding distributions of applied irrigation water (ML/ha) used to achieve the yields in figure 1. Wheat intentionally has no corresponding *box* to highlight that it is not irrigated and its inclusion in the rotation is to provide cover after the cotton. The total crop water use (ML/ha) is shown in figure 5 and its calculation is shown in equation 4. Both the applied irrigation water and crop water-use distributions for each crop were in agreement with what the farmer and irriigation engineer expected.

The economic analysis described previously was applied to the production data and seasonal gross margins (i.e. gross margins calculated from the beginning of the summer planting window) for each cropping enterprise in Crop Rotation 1 (see figure 1) was calculated. The results are plotted in Figure 8 which shows distributions of these gross margins from a simulation of 119 years of historical climate data. Cotton is clearly the most profitable crop with a mean gross margin of \$1734/ha (+/- \$110, 95% confidence interval) followed closely by maize \$1366/ha. Wheat is relatively unprofitable in this rotation with a gross margin of \$135ha. Again wheat is grown without irrigation (Table 3) and its inclusion in the rotation is for environmental reason to provide soil cover after the cotton crop.

When these results were presented to the collaborating farmer he was surprised and made comments such as "*… these results confirm why I grow cotton ...*" and *"... if cotton is the most profitable crop would I be better off with more cotton in my rotation ….*" To test this comment and to demonstrate the ability of the model to perform "what ifs" we re-ran APSFarm with a crop rotation that the farmer had previously implemented and one that he described as a more typical rotation for cotton and grain farmers in the Dalby region and is shown as Rotation 2 in Figure 1. It involves a summer grain crop, either maize or sorghum followed by two successive cotton crops. The arc from *Fallow_0* to *Fallow_1* indicates that if neither the maize nor sorghum planting rules are satisfied then the summer grain crops can be passed over this season for this particular field. However the two cotton nodes have no by-passing arc and hence if their planting rules are not satisfied this field will fallow through to the following season where the model will attempt to plant cotton again. This technique gives cotton priority in the rotation and is in agreement with the farmer's decision framework. Each crops planting rules, agronomy, fertiliser rates and irrigation management are the same as that described previously for the rotation 1 (table 3) except cotton which is planted with 1 meter row spacing instead of 2 meters.

Figure 8 shows the whole farm gross margins for the two rotations and depicts little difference between the two distributions. Hence there is no evidence to suggest that one rotation is more profitable than the other and this was confirmed by a statistical t-test (p.value > 0.1). However the area planted to each crops is a function of its planting rules and hence these areas vary from season to season as is shown in the time-series of total farm area planted to each summer crop for the last 10 years of the simulation in figure 9. These areas were then averaged over the whole 119 years for each rotation and plotted in figure 10. This plot shows the mean area planted every season to cotton is approximate the same for the two rotations however due to the difference in cotton row spacing their mean yields in the historical rotation (figure 11) are approximately 10 bales/ha. This is almost two bales per hectare more than the 2 meter cotton planted in the current *rotation* an it explains why the two rotations have similar returns with approximately 100ha difference in mean seasonal planting areas. The collaborating farmer was satisfied with his choice in rotation and cotton row spacing because it gave him more flexibility in marketing and the inclusion of legume crops in his rotation   had the added advantage of improved soil health without a loss in returns.

A second question posed by the farmer "*…what is the value to my farm of extra irrigation water made available every day, such as that available from coal seam gas production?"* To answer this we re-ran the APSFarm model, parameterised for this case study farm and using Rotation 1 in figure 1, a number of times. Each simulation had additional irrigation water, 1 ML to 10ML, delivered daily to a water storage. Current farm management such as agronomy, sowing rules (table 1) and irrigation management (table 3) and farm infrastructure (table 2 and 9) was used. Because water is delivered every day any water not immediately used is stored and subject to losses due drainage and evaporation. It was assumed that there is no problems with the quality if the water delivered and no cost were incurred in the deliver of the water. Figure 12 shows the change in farm gross margin where farm profitability increased by approximately $160/ML up to 4ML/day when system capacity is reached. This value can then be used to compare to the market price, should this water become available.

Conclusions

Here we have introduced APSFarm and shown how it has been extended to simulate irrigated farm businesses. In this paper we provided examples of how a whole farm simulation model can be used in close interaction between farmers and researchers, to test and learn about improved farm business tactics and strategies. The use of the model in collaboration with the farmers allowed for better informed discussions on the performance of a complicated farm business, helped both farmers and researchers identify feasible changes in the system towards increases in resilience and capacity to adapt to reduced allocations of water. Technologically, APSFarm proved to be a solid performer and a good alternative to static equilibrium models, with the additional benefit of allowing for dynamically integrating the multiple dimensions of highly complicated irrigated farm businesses.

References

Beeton RJS, Buckley KI, Jones GJ, Morgan D, Reichelt RE, TrewinD(2006) Australian State of the Environment Committee, Australia State of the Environment 2006. Independent report to the Australian Government Minister for the Environment and Heritage, Department of the Environment and Heritage, Canberra, ACT.

Dillon JL (1965) Farm Management in Australia as an academic discipline. Review of Marketing and Agricultural Economics 33, 175–189.

de Voil D, Rodriguez D, Power B. Simulation of whole farm management decisions. MODSIM 2009

Gaydon DS & Lisson SN (2005) APSIM WaterSupply, chapter in “Inventory of Australian Software tools for Best Use of Water On-Farm” – Final Report for Project 3.08, CRC for Irrigation Futures, G Inman-Bamber, S Attard - eds.

Jeffrey, S.J., Carter, J.O., Moodie, K.M and Beswick, A.R.. "Using spatial interpolation to construct a comprehensive archive of Australian climate data", *Environmental Modelling and Software*, Vol 16/4, pp 309-330, 2001.

Keating, BA, P. S. Carberry, G. L. Hammer, M. E. Probert, M. J. Robertson, D. Holzworth, N. I. Huth, J. N. G. Hargreaves, H. Meinke, Z. Hochman, G. McLean, K. Verburg, V. Snow, J. P. Dimes, M. Silburn, E. Wang, S. Brown, K. L. Bristow, S. Asseng, S. Chapman, R. L. McCown, D. M. Freebairn, C. J. Smith, An overview of APSIM, a model designed for farming systems simulation, European Journal of Agronomy, Volume 18, Issues 3-4, Modelling Cropping Systems: Science, Software and Applications, January 2003, Pages 267-288, ISSN 1161-0301, DOI: 10.1016/S1161-0301(02)00108-9.

McCown RL, Parton KA. Learning from the historical failure of farm management models to aid management practice. Part 2. Three systems approaches. Australian Journal of Agricultural Research. 2006:157-172.

Pannell, D. J. (1990). MIDAS Model of an Integrated Dryland Agricultural System: A Brief Introduction, Dryland Research Institute, Department of Agriculture Merredin.

Pannell, D.J. (1996). Lessons from a decade of whole-farm modelling in Western Australia. Review of Agricultural Economics 18: 373-383.

Probert ME, Dimes JP, Keating BA, Dalal RC, StrongWM(1997) APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agricultural Systems 56,1–28. doi: 10.1016/ S0308-521X(97)00028-0

Rodriguez, D., de Voil, P., and H.W. Cox (2007), Helping practical wisdom: a niche for whole-farm systems, In: Modelling farming systems design 2007, In proceedings : International symposium on methodologies on integrated analysis on farm production systems, September 10-12, 2007, Catania, Italy.

Smith RJ, Raine SR, Minkevich J. Irrigation application efciency and deep drainage potential under surface irrigated cotton. Agricultural Water Management. 2005;71:117-130.

Van Eijk T (2000) Holism and FSR. In 'A history of farming systems research'. (Ed.MCollinson) pp. 323–334. (FAOand CABI Publishing:Wallingford, UK)

deVoil P, Rodriguez D, Power B. Simulation of whole farm management decisions. 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009. http://mssanz.org.au/modsim09

Table 1: Sowing rules for each crop in current rotation.

Crop	Planting Rules
Maize	Date between Sep 15 - Oct 15
	Combined stored water in soil and water storage >= 4ML/ha
	Proportion of existing farm area planted to Maize or Sorghum <= 50%
	Days since last harvest > 14 days
	Machinery available
Sorghum	Date between Oct 16 - Jan 14
	Combined stored water in soil and water storage >= 0 ML/ha
	Sum of last 4 days rain >= 25mm
	Proportion of existing farm area planted to Maize or Sorghum <= 50%
	Days since last harvest > 14 days
	Machinery available
Cotton	Date between Oct 16 - Nov 15\
	Combined stored water in soil and water storage >= 4 ML/ha
	Proportion of existing farm area planted to cotton<= 50%
	Days since last harvest > 14 days
	Machinery available
Wheat	Date between Apr 16 - Jul 1
	Combined stored water in soil and water storage >= 0 ML/ha
	Sum of last 4 days rain >= 10
	Soil water >= 100 mm
	Days since last harvest > 14 days
	Machinery available
Soybean	Date between Dec 1 - Jan 15
	Combined stored water in soil and water storage >= 3 ML/ha
	Days since last harvest > 14 days
	Machinery available
Mungbean	Date between Dec 15 - Jan 15
	Combined stored water in soil and water storage >= 1.5 ML/ha
	Days since last harvest > 14 days
	Machinery available

Table 2: Water-storage parameters

Water storage	Capacity (ML)	Surface area (ha)	Cropping area (ha)	Out-flow rate (ML/hr)
A	500	12	252	7
B	500	11	314	8.5
C	300	8	215	5.3

Table 3: Crop agronomy parameters: Fraction of full profile - when soil water, expressed here as a proportion of a full profile, fall below these value for each crop irrigation is applied (wheat is not irrigated); Soil N at sowing - the soil nitrogen rate at which fertiliser is applied to reach this level; cultivars and sowing densities.

Crop	Fraction of full profile	Soil N at sowing (kg/ha)
Maize	40%	240
Sorghum	50%	220
2m Cotton	40%	140
Wheat	NA	160
Soybean	70%	0
Mungbean	60%	0

Table 4: Variable cost and prices for maize

Event	Description	dollars	units
harvest	Crop price	$418.00	$/bale
harvest	Cottonseed (31% @ 125/tonne)	$38.31	$/bale
harvest	Cartage	-$8.00	$/bale
harvest	Pick-up fee ($65/module)	-$3.25	$/bale
harvest	Ginning	-$55.00	$/bale
harvest	Cotton Research Levy	-$2.25	$/bale
harvest	Cotton Australia Levy	-$2.25	$/bale
harvest	Cottonseed storage fee	-$3.68	$/bale
harvest	Cottonseed loading fee	-$4.60	$/bale
harvest	Tarps	-$2.90	$/bale
harvest	Defoliation (Aerial spray)	-$28.00	$/ha
harvest	Defoliation (Dropp Ultra)	-$13.50	$/ha
harvest	Defoliation (ethephon (eg Prep))	-$11.70	$/ha
harvest	Defoliation (DC-Tron Oil)	-$4.44	$/ha
harvest	Defoliation (Dropp Ultra)	-$6.75	$/ha
harvest	Defoliation (CottonQuik)	-$27.60	$/ha
harvest	Cultivation (Stalk pull and mulch)	-$49.64	$/ha
harvest	Contract header	-$270.00	$/hr
harvest	fuel	-$1.31	$/L
harvest	Bore pumping costs	-$30.00	$/ML
sow	Preparation and Cultivation	-$48.46	$/ha
sow	Planter	-$9.39	$/ha
sow	Seed	-$91.00	$/ha
sow	Anhydrous ammonia	-$1.58	$/kg
sow	Liquifert Emerald	-$16.00	$/ha
sow	Foliar Triple 7	-$13.13	$/ha
sow	Herbicide & application	-$154.67	$/ha
sow	Insecticide & application	-$154.00	$/ha
sow	Crop Conditioning	-$9.81	$/ha
sow	Consulting	-$71.00	$/ha
sow	Bollguard II Licence Fee	-$250.00	$/ha

Table 5 Variable cost and prices for cotton at 2m row spacing.

Event	Description	dollars	units
harvest	Crop price	$200.00	$/tonne
harvest	Cartage (Farm to depot)	-$11.00	$/tonne
harvest	Freight (Rail)	-$19.40	$/tonne
harvest	Levies	-$2.00	$/tonne
harvest	Pre Harvest spray (ariel spray + glyphosate)	-$41.00	$/ha
harvest	Contract header	-$270.00	$/hr
harvest	fuel	-$1.31	$/L
harvest	Bore pumping costs	-$30.00	$/ML
sow	Primary tillage	-$8.76	$/ha
sow	Secondary tillage	-$6.98	$/ha
sow	Fertiliser application	-$6.98	$/ha
sow	Big N	-1.5	$/kg
sow	Strater Z (40 kg @ $957 / tonne)	-38.28	$/ha
sow	Inter-row tillage	-$3.34	$/ha
sow	Planting	-$6.98	$/ha
sow	Seed (7kg x $9.50/kg)	-$66.50	$/ha
sow	weeds spray - glyphosate and boomspraying	-$22.99	$/weed event
sow	Herbicide (Atrazine @ 3.5L x $5.50/L + bs)	-$20.64	$/ha
sow	Insecticide (NPV @ 0.4L x $55/L + bs)	-$23.39	$/ha

Table 6: Variable cost and prices for sorghum

Event	Description	dollars	units
harvest	Crop price	$300.00	$/tonne
harvest	Cartage (Farm to depot)	-$11.00	$/tonne
harvest	Levies	-$3.00	$/tonne
harvest	Contract header	-$270.00	$/hr
harvest	fuel	-$1.31	$/L
harvest	Bore pumping costs	-$30.00	$/ML
sow	Primary tillage	-$8.76	$/ha
sow	Secondary tillage	-$6.98	$/ha
sow	Fertiliser application	-$6.98	$/ha
sow	Big N	-$1.50	$/kg
sow	Strater Z (30 kg @ $957 / tonne)	-$28.71	$/ha
sow	Inter-row tillage	-$3.34	$/ha
sow	Planting	-$8.83	$/ha
sow	Seed (60kg x $1.00/kg)	-$60.00	$/ha
sow	weeds spray - glyphosate and boomspraying	-$22.99	$/weed event
sow	Herbicide (MCPA LVE @ 0.50L x $9.00/L + bs)	-$4.50	$/ha

Table 7: Variable costs and prices for wheat

Event	**Description**	**dollars**	**units**
harvest	Crop price	$720.00	$/tonne
harvest	Cartage (to Brisbane)	-$25.00	$/tonne
harvest	Levies	-$7.20	$/tonne
harvest	Pre Harvest spray (ariel spray + glyphosate)	-$41.00	$/ha
harvest	Contract header	-$270.00	$/hr
harvest	fuel	-$1.31	$/L
harvest	Bore pumping costs	-$30.00	$/ML
sow	Primary tillage	-$8.76	$/ha
sow	Secondary tillage	-$6.98	$/ha
sow	Strater Z (40 kg @ $957 / tonne)	-$38.28	$/ha
sow	Planting	$4.55	$/ha
sow	Seed (65kg x $1/kg)	-$65.00	$/ha
sow	Inoculum (.65 pkt x $6.05/pkt)	-$3.93	$/ha
sow	weeds spray - glyphosate and boomspraying	-$22.99	$/weed event
sow	Herbicide (trifluralin @ 2.1L x $7.25/L + bs)	-$16.65	$/ha
sow	Insecticide (thiodicarb @ 0.75L x $27.25/L + bs)	-$21.83	$/ha

Table 8: Variable costs and prices for soybean

Event	Description	dollars	units
harvest	Crop price	$600.00	$/tonne
harvest	Cartage	-$11.00	$/tonne
harvest	Bagging	-27	$/tonne
harvest	Grading	-$90.00	$/tonne
harvest	Levies	-$6.00	$/tonne
harvest	Contract header	-$270.00	$/hr
harvest	fuel	-$1.31	$/L
harvest	Bore pumping costs	-$30.00	$/ML
sow	Primary tillage	-$8.76	$/ha
sow	Secondary tillage	-$6.98	$/ha
sow	Inter-row tillage	-$3.34	$/ha
sow	Planting	$4.55	$/ha
sow	Seed (25kg x $1.75/kg)	-$43.75	$/ha
sow	Inoculum (.25 pkt x $6.05/pkt)	-$1.51	$/ha
sow	weeds spray - glyphosate and boomspraying	-$22.99	$/weed event
sow	Herbicide (Select @ .25L x $65/L + bs)	-$17.64	$/ha
sow	Insecticide (methomyl @ 1.8L x $10.5/L + bs)	-$20.29	$/ha
sow	Scouting	-$10.00	$/ha

Table 9: Costs and flow rates for pump operations for each water storage.

Water storage	flow direction	Capacity (ML/hr)	diesel (L/hr)	$/hr
A	in	7	40	-$52.40
B	in	8.5	49	-$63.63
C	in	5.3	30	-$39.67
A	out	1.75	10	-$13.10
B	out	2	11	-$14.97
C	out	1.5	9	-$11.23

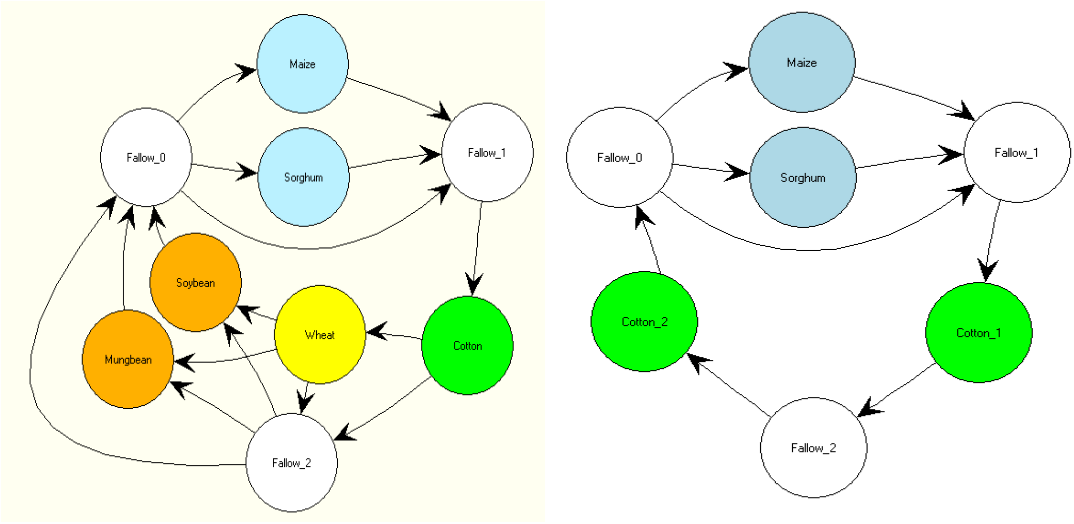

Figure 1: State diagram showing the implementation in APSFarm of Crop Rotation 1 (left) and Crop Rotation 2 (right). The state of each field is represented by nodes (circles), and the transitions between states by rules represented by the arcs connecting the nodes.

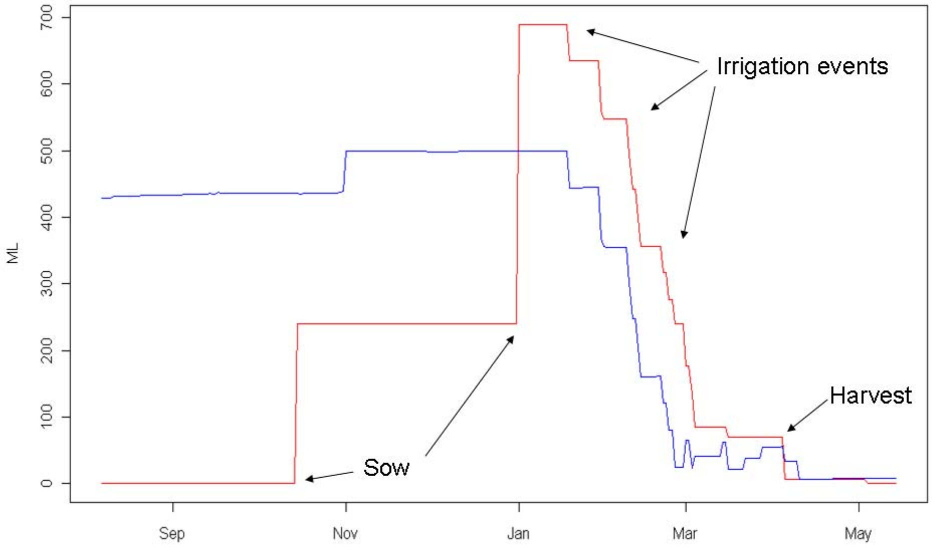

Figure 2: Time series of available water from the physical farm storage (blue series) and from the conceptual storage (red series) i.e. an estimate of the water required for a crop for the remainder of the season.

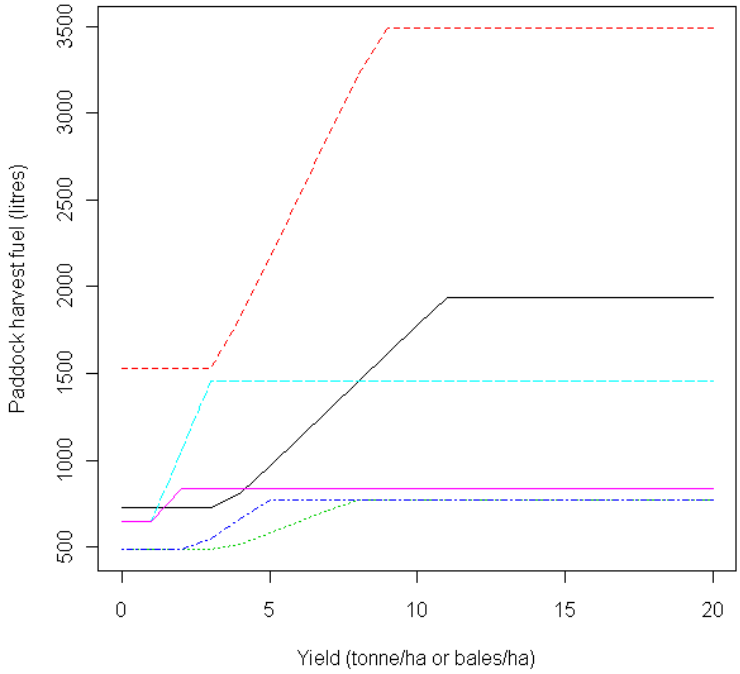

Figure 3: Fuel (litres) required to harvest a 60 ha field for a range of yields (tonnes/ha or bales/ha) and crops.

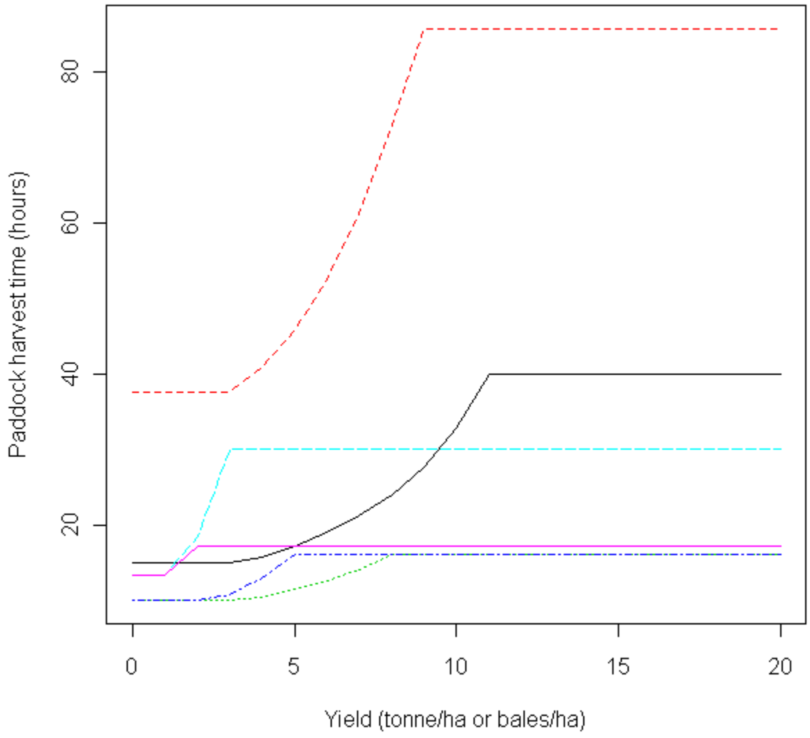

Figure 4: Response in time to harvest a 60 hectare field for a range of yields for each crop in the rotation.

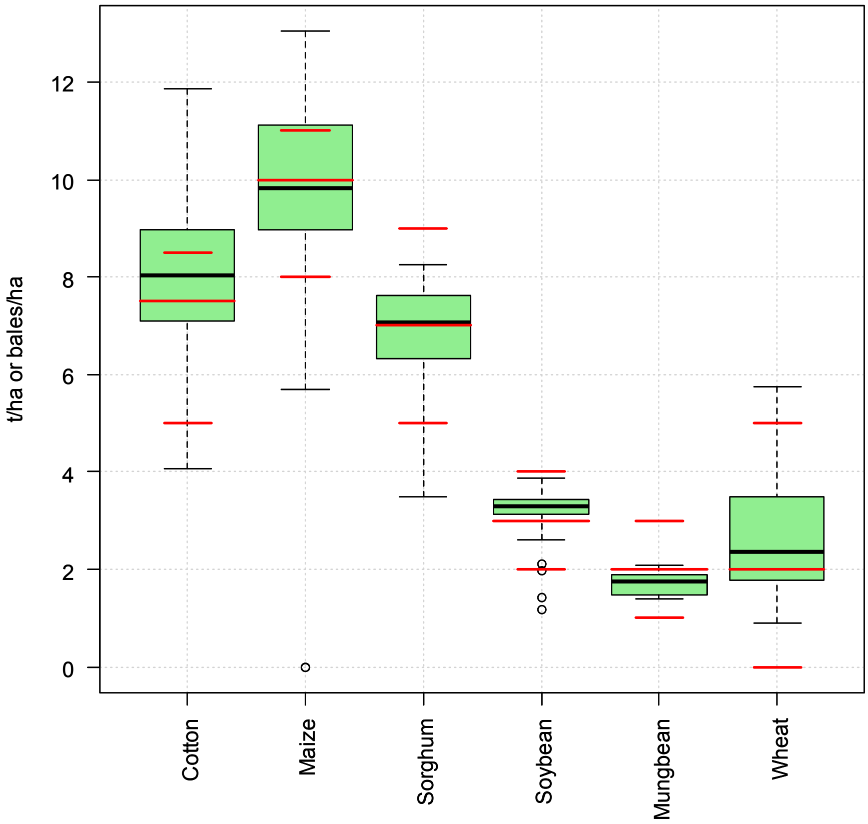

Figure 5: Box-plots of simulated yields derived from APSFarm simulation for years 1890 to 2007 with current rotation (see figure 1). Red lines show farmer expected distribution of yields.

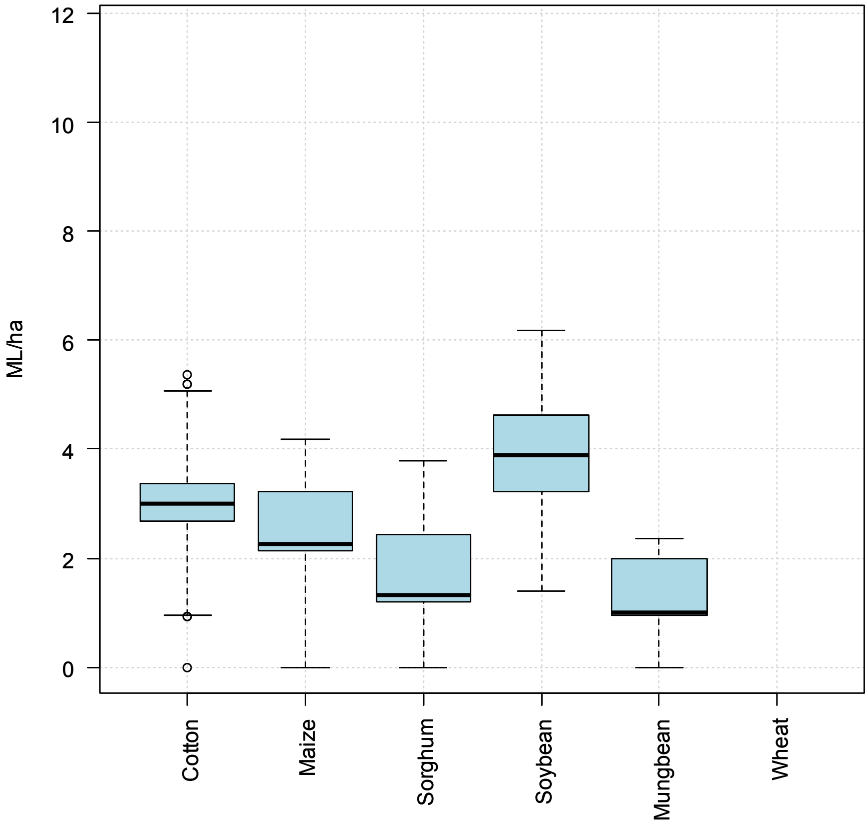

Figure 6: Applied irrigation (ML/ha) to the field for each crop in current rotation (figure 1). Wheat is not irrigated.

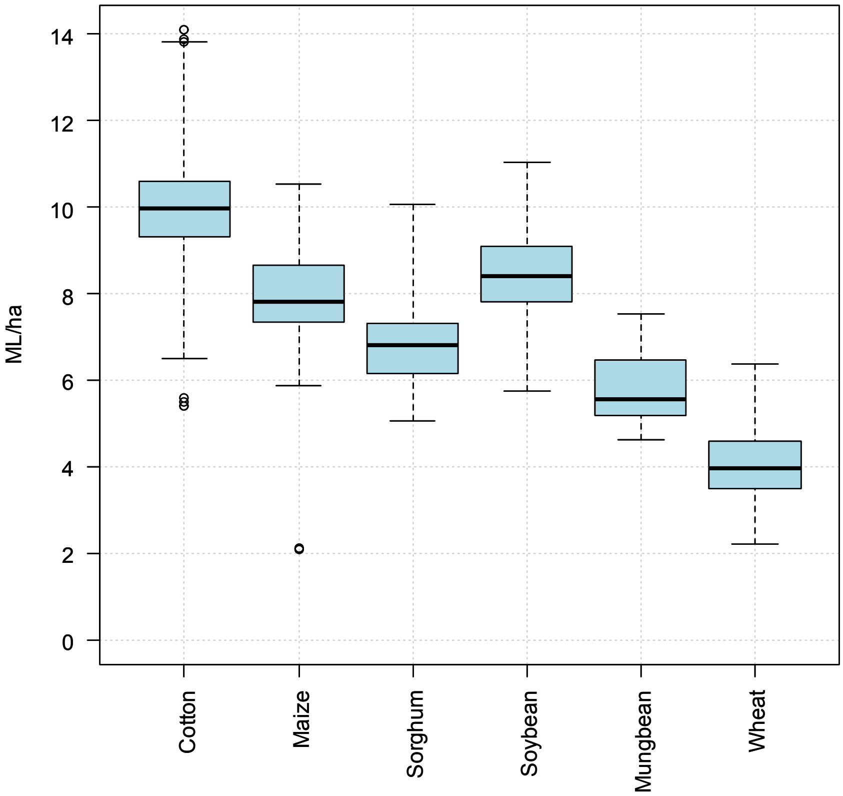

Figure 7: Total water use (ML/ha), includes applied irrigation, in-crop rainfall and soil water at sowing.

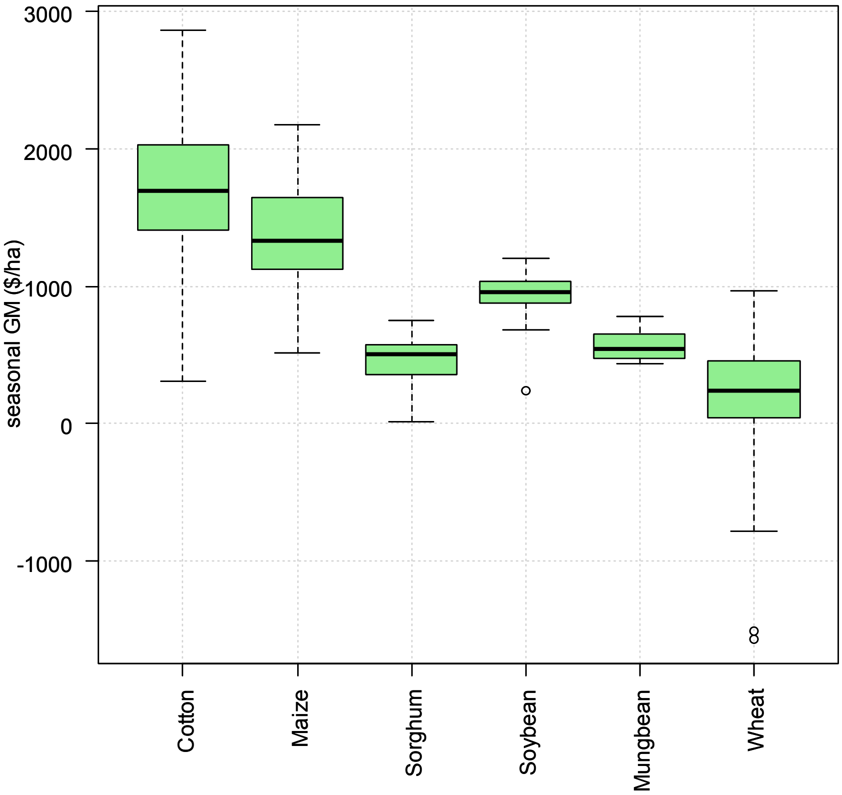

Figure 8: Gross margins ($/ha) for each crop using commodity prices and cost obtained from the farmer (table 4 to 9).

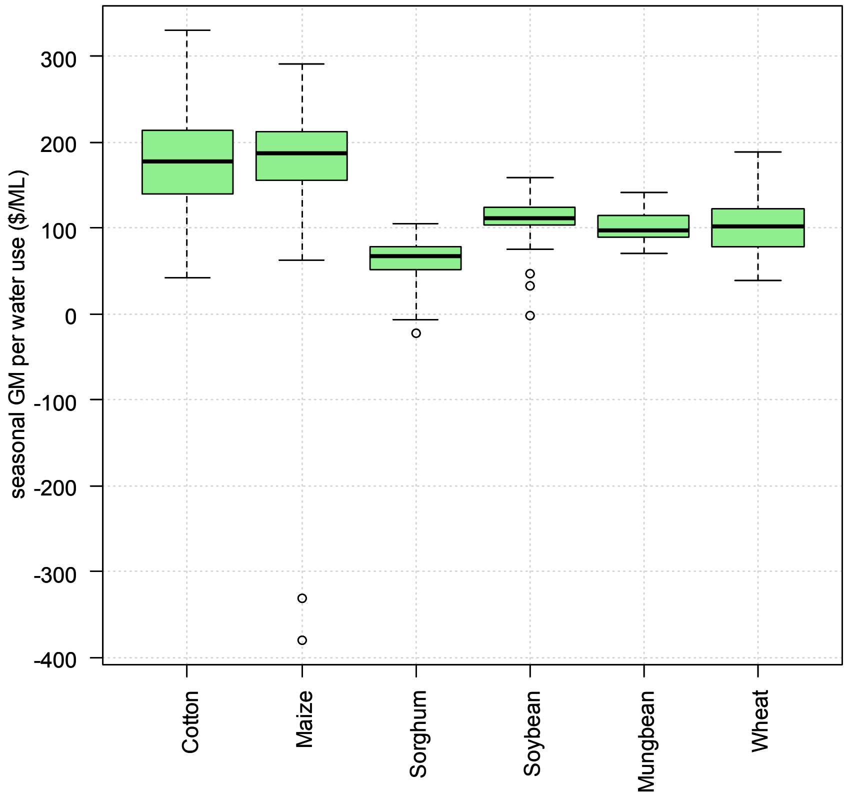

Figure 7: Seasonal gross margins per total crop water use ($/ML).

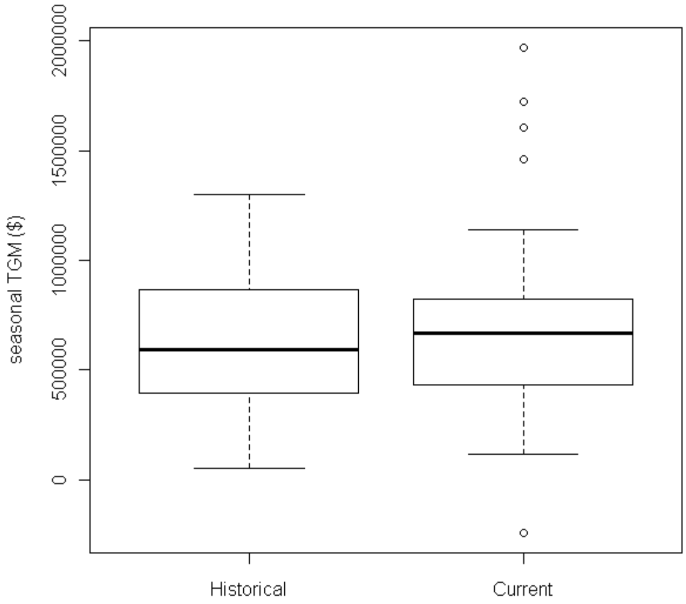

Figure 9: Distributions of seasonal whole farm gross margins (beginning at the summer planting window) for current rotation (figure 1) and historical rotations (figure 6).

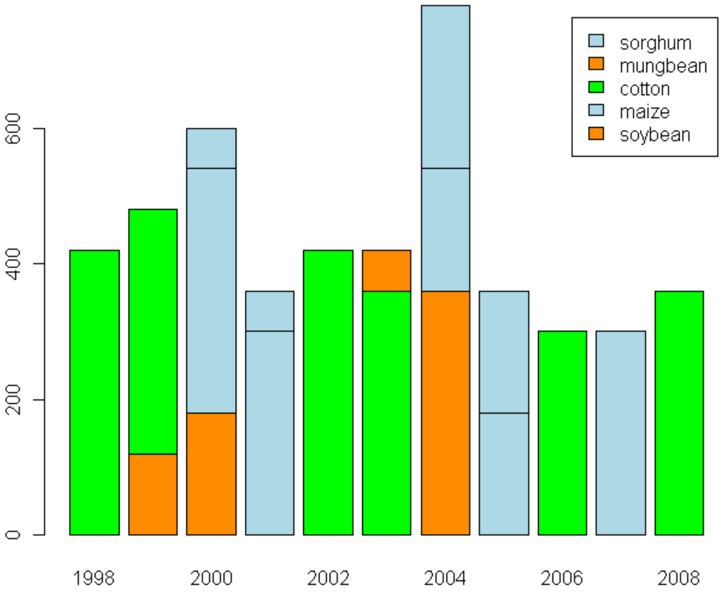

Figure 10: Summer crop planting areas for current rotation (figure 1) showing only last 10 years of simulation.

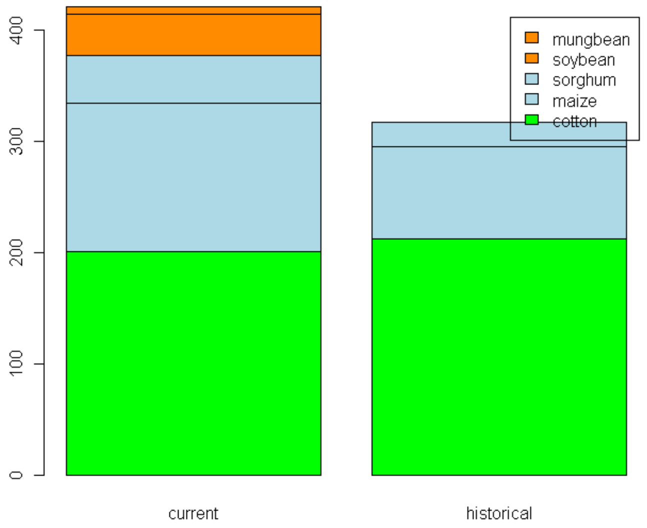

Figure 11: Summer crop planting areas for current rotation (figure 1) and historical rotation (figure 6) average over 119 seasons.

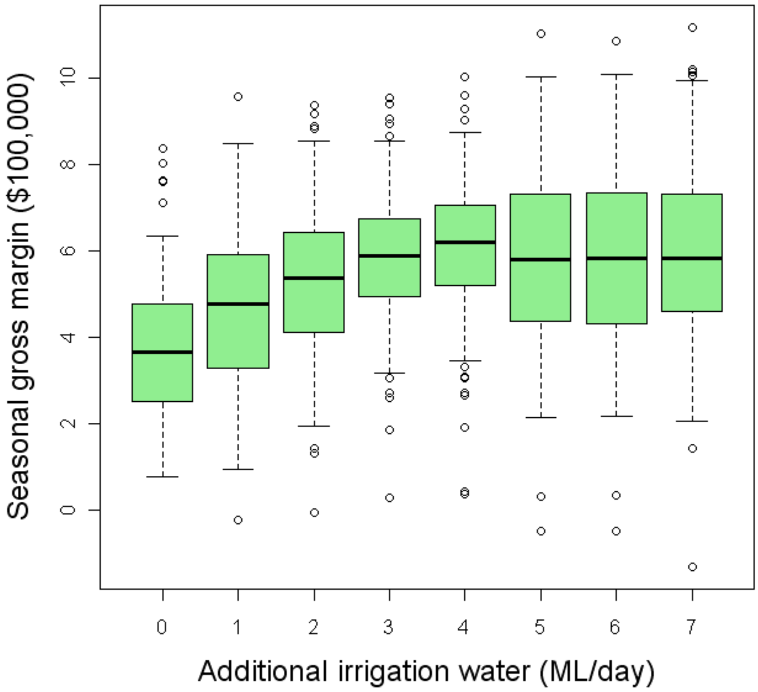

Figure 12: Whole farm gross margins for current rotation and additional daily irrigation water.

Appendix II

Using the farm-scale system model APSFarm to improve profitability of irrigation cropping enterprises.

Brendan Power*, Peter DeVoil, Jose Payero, Daniel Rodriguez and Graham Harris

Department of Primary Industries and Fisheries, PO Box 102, Toowoomba, Queensland. 4350.
*Author for correspondence Brendan.Power@dpi.qld.gov.au

Abstract

APSFarm is a whole farm systems simulation model derived from multiple instances of the paddock scale Agricultural Production System Simulator, APSIM. Here it is used to model a case study of an irrigated farm business near Dalby (151.27E - 27.17S), Queensland to try to identify optimum business strategies under conditions of limited available dam water. In this work we compared the long term impacts of reducing or maintaining planting areas of cotton, maize and wheat on the profitability of the farm business.

Interviews with the farmer provided farm specific data, such as water sources and their annual allocations, water storage capacities, cropping areas, agronomy, irrigation management and paddock layout relative to storages. Farm business constraints included: limited availability of land, irrigation water, finance, labour, machinery and time. In this paper we demonstrate the value of developing and applying whole farm systems models to support participatory research with the aim of designing more profitable and sustainable farm businesses.

Key Words
APSIM

Introduction

Irrigators are under increasing pressure to maintain profitability with reduced water allocations, rising input costs, and high market volatility. Desktop studies using crop simulation models are possible tools to assist in identifying more profitable management strategies. However the analysis and optimisation of irrigation enterprises with a point scale production model such as APSIM (Keating et al 2003) is problematic. For example, constraints such as dam capacities and water availability are not appropriate at the point scale. For this reason we used APSFarm, a whole farm systems simulation model derived from multiple instances of the paddock scale APSIM to model homogenous areas of the farm and hence it allows for the dynamics of area in the model

In APSFarm paddock level management rules (e.g. crop agronomy, irrigation scheduling), and farm level strategies (e.g. crop choice, water movement between storages, enterprise mix, risk attitude) are simulated across the whole farm. Model outputs include a wide range of bio-economical and environmental indicators of the farm business useful in trade-off analysis when comparing alternative farm business management strategies. The result is a whole farm model which can capture the dependencies and interactions of household budgets, soil types, climate variability, crop physiology, machinery, and labour It is also able to simultaneously take into account the effects of changes in climate, crop prices, variable costs, water allocations, and soils (e.g. salinity, N fertility). APSFarm has previously been used to identify possible farm business strategies to increase business viability (Cox et al., 2008; Rodriguez et al., 2007; Mayer et al., 2006). In this paper we used the model to explore a question from the farm manager i.e. *"…with lower dam levels,… am I better to reduce my planting area and apply more irrigation per hectare,… or should I maintain a maximum cropping area and rely more heavily on in-crop rain…"*.

Method

Case Study

Interviews with the farm managers of the property were used to describe the farm infrastructure, its management and long term business strategy. The farm business is located near Dalby Qld It has two 500 ML water storages supplying 252 and 314 hectare cropping areas, and a 300 ML storage supplying an area of 215 hectares. The storages are filled via overland flow and there is capacity to transfer water between them. It is possible to purchase an additional 100ML from a neighbour at a cost of $70/ML plus pumping. The farm has 5 bores with an annual allocation of 860ML/year, and can supply water to all paddocks, though at a considerably reduced flow rate compared to that of the storages. All paddocks are irrigated via furrows, and the run-off from paddocks and irrigation tail-water is captured.

Within the model a range of farm operating constraints were included e.g. sowing can only occur when relevant machinery is available. Prices and costs were relevant to the 2004/2005 cropping season. An example of the outputs from the farm cashbook appears in table 1.

Table 1. Example of the outputs from the cashbook calculations. Income, expenditure and cumulative balance ($).

date	income ($)	expenditure ($)	cumulative balance ($)	comment
15-Feb-07	316,756		25,296,781	cropprice (maize)what's cropprice
30-Jun-07		136,000	$25,160,781	Farm Overheads
30-Jun-07		$94,958	$25,065,823	Loan repayments for initial capital outlay
28-Sep-07		$4,309	$25,061,514	Dam_irrigation
9-Oct-07		$33,280	$25,028,234	Maize seed
9-Oct-07		$5,383	$25,022,851	Maize fertiliser Starter Z
9-Oct-07		$52,237	$24,970,614	Maize fertiliser Big N
9-Oct-07		$17,032	$24,953,581	Maize herbicide Primextra
9-Oct-07		$8,320	$24,945,261	Fertiliser
9-Oct-07		$509	$24,944,752	fuel & oil costs of tractor_1 + planter
9-Oct-07		$138	$24,944,613	Repairs & maintenance of tractor_1
9-Oct-07		$55	$24,944,558	Repairs & maintenance of planter
16-Oct-07		$9,828	$24,934,730	Cotton seed
16-Oct-07		$8,505	$24,926,225	Temik
16-Oct-07		$30,263	$24,895,961	Cotton Insurance
16-Oct-07		$1,351	$24,894,609	Cotton fertiliser application gas knife
16-Oct-07		$23,461	$24,871,148	Cotton fertiliser Anhydrous ammonia
16-Oct-07		$2,016	$24,869,132	Cotton fertiliser Liquifert Emerald
16-Oct-07		$4,536	$24,864,596	Cotton fertiliser Urea
16-Oct-07		$1,890	$24,862,706	Cotton fertiliser Foliar triple 7
16-Oct-07		$18,326	$24,844,379	Cotton herbicide and application
16-Oct-07		$14,279	$24,830,100	Cotton insecticides and application
16-Oct-07		$1,627	$24,828,472	Cotton conditioning
16-Oct-07		$8,946	$24,819,526	Cotton consulting fees
16-Oct-07		$31,500	$24,788,026	Cotton licence fees
16-Oct-07		$10,686.	$24,777,340	Cotton seed

Figure 1, shows the implementation of the rotation for the farm business in APSFarm. The circles, or nodes, indicate the states in which any management unit can be found, and the arcs between nodes holds the description of the rules allowing the transition between the connected states, i.e. rules for planting , and harvesting the different crops. The arc in blue shows an alternative path when the rules to plant wheat are not satisfied e.g. if there is insufficient soil moisture then wheat will not be planted and the system will go into fallow. Wheat is not irrigated and its inclusion in the rotation is to primarily provide ground cover.

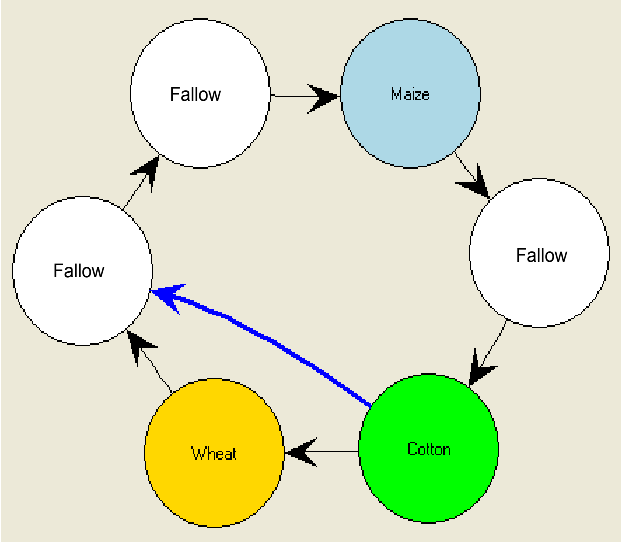

Figure 1. Crop rotation of the analysed farm business at Dalby, Qld.

Planting area

Each section of the farm serviced by one of the three dams is represented in the model by an APSIM paddock, which has planting area as an attribute that can vary from season to season. The initial state of each of the paddocks, at the start of the simulation, is set to a different stage of the rotation to avoid the three parts of the farm being synchronous and causing a disproportionate demand on farm resources such as irrigation water.

Two scenarios were simulated, (i) *adaptive strategy:* the area to be planted was set at sowing as the product between the maximum allowable area for that paddock, and the fraction of available water for irrigation stored in its respective dam, to a minimum of 50%, i.e. having less crop that are more fully irrigated; and (ii) a *non-adaptive strategy:* in which the area to be planted was set as the maximum allowable area for that paddock i.e. relying more on in-crop rainfall. Each strategy was run with APSfarm for 117 years of available patchpoint climate data i.e. 1890 to 2007.

Results

From the cumulative cash flow output from the 117 year simulation for the two scenarios i (Figure 2) it appears that for this particular farm business and crop rotation the *non-adaptive strategy* (black line) outperformed the *adaptive strategy* scenario. This demonstrates the significant contribution to yields that in-crop rainfall has in this environment. The median annual return for *the non-adaptive strategy* was significantly greater than for the *adaptive strategy* (*p* value = 0.04)

(Figure 3), However, the *adaptive strategy* was less variable and hence slightly less risky as it relies less on highly variable in-crop rainfall.

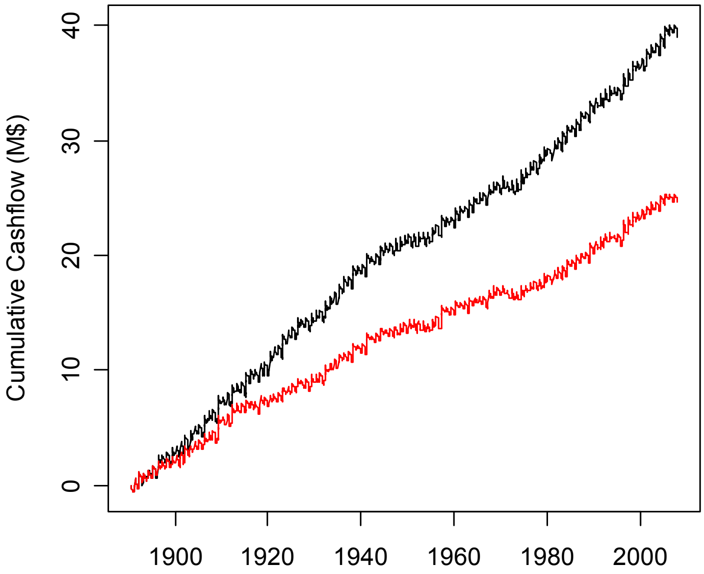

Figure 2. Cumulative cash-flow for the traditional (black line) and adaptive (red line) irrigation strategies for a farm at Dalby Qld.

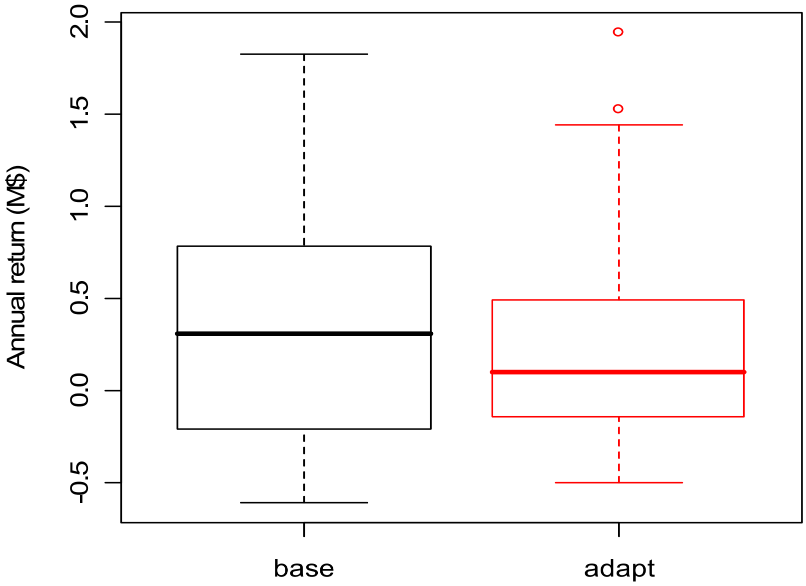

Figure 3. Annual returns for the traditional (black) and adaptive (red) irrigation strategies for afarm at Dalby Qld.

Conclusion

In this paper we provide an example of how a whole farm simulation model can be used to test farm business designs and strategies before they are implemented. The use of the model with the farmer permits more informed discussions and thus helps farmers increase their adaptive capacity to cope with changes in the availability of resources such as irrigation water.

Future work in this project will include the use of evolutionary optimisation techniques to identify farm business tactics and strategies that maximise trade-offs between alternative business outcomes e.g. profit, economic risk, and environmental impacts.

Acknowledgements

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References

Cox, HW, deVoil, P and Rodriguez, D (2008). Tools for managing farming risk in a variable and changing environment (Australia). In Proceedings 8th International Farming Systems Association Conference. Clermont-Ferrand, France.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. *Europ. J. Agron*., **18**: 267-288.

Mayer DG, Rossing DW, deVoil P, Groot JC, McPhee MJ, Oltjen JW (2008) Sustainable Management of Agricultural System`s*. (In press)*

Rodriguez D, deVoil P, Cox H (2007) Helping practical wisdom. A niche for whole farm systems modelling. International Conference on Farming Systems Design, Catania, Italy (http://www.iemss.org/farmsys07/)

Appendix III

A multi-paddock bio-economic model of irrigated grain-cotton farming systems

B Power* and D Rodriguez, P deVoil, G Harris, J Payero

Agri-science Queensland, Department of employment Economic Development and Innovation, 203 Tor St, Toowoomba, Qld 4350, Australia

* corresponding and presenting author, brendan.power@deedi.qld.gov.au

Introduction

Australian irrigators are under increasing pressure to maintain the viability of their farm business resulting from reduced water allocations, declining groundwater resources, increased competition from alternative water users such as urban and industry, climate change, and the cost-price squeeze. While farmers continuously adapt their management practises in response to changes in their operational environment, medium and long term farm business planning requires greater levels of information and support to ensure success.

Desktop studies using static-equilibrium models have long been used to model and explore the optimal allocation of limiting resources in farming systems. This approach however is limited in its applicability due to a reliance on assumptions made *a priori* about likely distributions for yields, prices, water allocations, etc.; and an inability to accommodate tactical and strategic responses to climate and markets. Here we present APSFarm, an alternative dynamic modelling framework that integrates multiple bio-physical models that operate at differing scales i.e. the management unit, the farm and the catchment.

Methods and Materials

Interviews with farmers provide farm specific data, such as water sources and their annual allocations, water storage capacities, cropping areas, agronomy, irrigation management and paddock layout relative to storages. Homogeneous irrigation management units (described here as paddocks) were modelled using the point scale Agricultural Production System sIMulator (APSIM: Keating et al., 2003). Multiple paddocks within the farm are then represented by various instances of APSIM using the farm scale model APSFarm (de Voil, 2009). This allows for: crop phenology, soil, climate and agronomy interactions; farm infrastructure, labour and time constraints; and whole farm economic analysis. The farm manager is modelled using coded algorithms to specify field crop rotations and farmer's preference for the allocation of land and water across alternative crop enterprises, risk attitude and cropping intensity.

We applied this modelling framework to a case study of an irrigated farm business near Dalby Queensland, to quantify the profitability and risk tradeoffs of alternative business designs, under conditions of limited available farm water. The farm description in APSFarm comprises three water storages, i.e. two 500ML water storages supplying a 252 and a 314 ha cropping area respectively; and a 300ML storage supplying an area of 215 ha. The storages are filled via overland flow and there is capacity to transfer water between them which incurs a cost for operation and maintenance of pumps. In addition, the farm has 5 bores with an annual allocation of 610 ML/year. Bore water can be supplied to all paddocks, though at a considerably reduced flow rate. All paddocks are irrigated via furrows, and the run-off from paddocks and irrigation tail-water is captured and recycled within the farm. To generate a historical time series of overland flow a simple catchment model was developed and calibrated against farmer estimates for annual captured overland flow.

Figure 1, shows the implementation of the crop rotation for the farm business in APSFarm. The circles or nodes represent the possible states in which any paddock can be found. The arcs between nodes hold the description of the rules allowing the transition between the different states, i.e. rules for planting, and harvesting the different crops. For example to plant maize between September 15th and October 15th, there needs to be available at least 4 ML/ha of aggregate stored water between the soil and storages, the area planted to summer grain cannot exceed 50% of the total farm area and machinery must be available. Whole farm gross margins were calculated using the farmer's long term expected variable costs and commodity prices in Table 1. A simple weed model was used to simulate the number of weed germination events in each fallow and from this fallow costs were calculated.

Table 1: Commodity prices used in the economic analysis.

Crop	**Cotton**	**Maize**	**Sorghum**	**Wheat**	**Soybean**	**Mungbean**
Price	$418 /t	$250 /bale	$200 /t	$300 /t	$720 /t	$600 /t

Results & Discussion

This economic analysis was applied to the production data generated from running APSFarm using 119 years of climate data. Figure 2 shows the relative profitability of each activity expressed as gross margins. Clearly cotton was the most profitable crop with a mean gross margin of $1734/ha followed closely by maize $1366/ha. Wheat is relatively unprofitable in this rotation with a gross margin of $135ha. This is due to it being grown without irrigation and its inclusion in the rotation is mainly to provide soil cover after the cotton. When these results were discussed with our collaborating farmer he made the comment*"… these results confirm why I grow cotton ..."*. Further interaction and engagement with this farmer is exploring questions of risk such as *"My planting rules are conservative because I don't want to be caught with not enough water to finish off my crop. What would be the effects of embracing some risk and changing my planting rules?"*

In this paper we present the value of developing and applying more integrative and interdisciplinary approaches to represent the whole farm systems to support better informed discussions in participatory research projects, with the aim of designing more profitable and sustainable farm businesses.

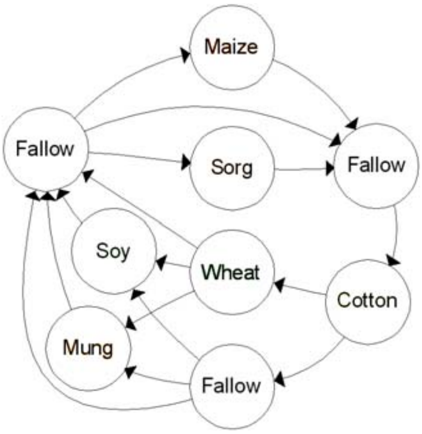


Figure 1: Crop implementation in APSFarm

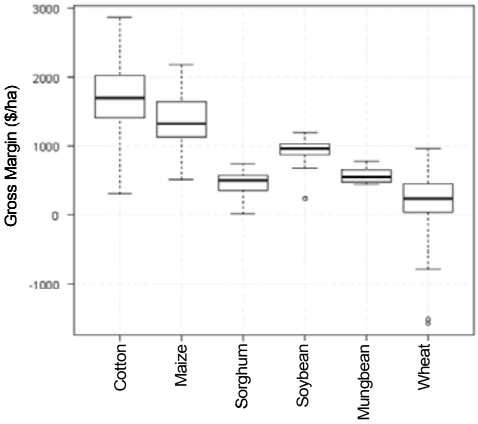


Figure 2: Gross margins ($/ha) for each crop.

References

de Voil D., Rodriguez D., Power B., (2009). Simulation of whole farm management decisions. 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, July 2009, pp. 2377-2383. ISBN: 978-0-9758400-7-8.

Keating B.A., Carberry P.S., Hammer G.L., Probert M.E., Robertson M.J., Holzworth D., Huth N.I., Hargreaves J.N.G., Meinke H., Hochman Z., McLean G., Verburg K., Snow V., Dimes J.P., Silburn M., Wang E., Brown S., Bristow K.L., Asseng S., Chapman S., McCown R.L., Freebairn D.M., Smith C.J. 2003. An overview of APSIM, a model designed for farming systems simulation, European Journal of Agronomy, 18, 267-288.

Appendix IV

Interviews with growers and crop consultants on the Darling Downs

Consultant 1 - Murray Boshammer, Dan Skerman

Key Cropping Systems Strategies

- A grower wants standing stubble- this helps establishment and is critical to getting water into the fallow- is Sorghum the best ?. Spray out the sorghum (1.8 Paramax).
- Plant Skip-row Cotton into stubble.

Strategies Within Each Crop

- **Sorghum** with limited water is planted on fallow and given one irrigation and can yield 7 to 7.5 t/ha. Putting water on at head emergence works well. Fallow gives a good soil water profile. Nutrition is planned to target 8t crops.
- **Cotton:** fallow through winter and spring plant sorghum. Population 70-80 000 plants/ha. In-row population 10 to 12 plants per metre for solid planting 12 to 14 for skip is a good dryland population. With a single irrigation it is critical when the irrigation applied. Variety is important (e.g. Bonus).Need varieties that perform well under difficult dryland conditions. Irrigation water less than 1.5 ML is normally scheduled. If applied early then another irrigation is required at heading. A maximum of three irrigations are applied. Pre-watering is considered a waste of water. A grower wants standing stubble which helps establishment and is critical to getting water into the fallow. If he has 500ML of water, instead of growing 100ha solid plant he should grow 150 ha skip with three irrigations and can obtain a yield of 7-8 bales/ha.
- With limited water skip- row cotton is grown to spread the crop over more land. If there is bore water then irrigate for high yields. If water source is from overland flows a different approach is needed. If grower has greater than 50% water in a ring tank he can grow solid cotton well . If less than 50% then use single skip- row for high yields.
- GPS helps by enabling grower to offset rows in standing sorghum stubble and keeps planting even. Roundup technology has helped with the weed problem. Atrazine is used in sorghum (Spring plant).
- Bollgard cotton needs to be watered when required- this is critical. Use Diviners are used to monitor water. 80-90 mm is the deficit for solid planted cotton. Skip-row deficit is half an irrigation less. First water 80mm on both. Prior to Bollgard 100 mm was used. Growers have to achieve 7 to 7.5 bales. They have to decide whether to use single skip or not. This depends on the starting water supply.
- **Corn:** This crop is not seen to be fitting in with limited water. It is grown when there is lots of water available. Growers should try to achieve 12 t . Plant nutrition: 300 units of N required. It probably needs more irrigations than cotton- 4 or 5 irrigations. After Corn, cotton is often grown and its nutrition must be watched because of stubble. It could probably need N: 250 units for cotton and for corn 200 immediately then top up to 250 if there is enough water.

Irrigation Systems and Management

- Optimising- most growers think they are doing the best they can- all clients have probes to monitor soil water.
- Changing irrigation systems- not an option.
- Some clients still need to optimize their irrigations.
- Very few fields are irrigated longer than 2 hours. There has been a decrease in the water application time over the past few years- this is progress.
- Overhead systems: Issues with bogging near towers. Machine sellers need to be educated.

- Storage management- not a lot of changes.
- There is seepage in some areas and leaky ring tanks are still problems.
- Key things- follow up sorghum stubble idea- don't have bare paddocks but there is still the question is Sorghum the best ?. Always spray out the Sorghum (1.8 Paramax) and use Skip-row cotton.

Consultant 2 - Geoff Rudd, John Fuelling

Key Cropping Systems Strategies

- Crop Choice- is the first strategy. Need a reasonably accurate measure of soil water. With limited water need good management from a dryland sense then a crop is guaranteed..
- Conservation tillage- leave stubble there as long as possible. Grower must have rotation at the back of the mind- 3 summer crops then winter crop usually- 3 years summer, 1 year winter.
- Unrealibility of rainfall drives growers out of rotations. With herbicide application it is difficult to go out of rotation- herbicide can lock you out. Hard to control weeds – this is a problem.

Strategies Within Each Crop

- **Cotton-** with limited water plant on rain. “Super, Super Single” configurations have made a difference. If coming out of late sorghum then double skip. 1.2m super single has yielded a bale. The question is, do we use a 3m skip or 5m skip ?
- Iirrigation strategy with Bollgard cotton – hold off irrigation until peak flower, if water is really limited. Usually plant double skip with one irrigation. Some growers plant solid then use the ‘plough out’ option if water is problem (i.e., no rain).
- Break even line is important e.g., if it is 2 bales/ac they will take a punt (if they have their own equipment and the line moves up a bit). If growers get late water they will use the water rather than sit it in the dam where it will evaporate.
- **Soybeans-** early plant in January- if no rain, then fallow. Plant on rain then choose a planting configuration. Soybeans are not an option with limited water. If you start to irrigate soybeans, you need to keep going.
- Late or real early **Corn** is an option with limited water. Mid September to late October with low population corn is ok. With corn on limited water, plant 25 000 plants/ha and if irrigate returns are reasonable , but this needs a reasonable soil moisture profile. However, Sorghum is the choice because you can get quality easily with sorghum.
- Sorghum, Mung Beans, Soybeans for late cropping.
- Sorghum: the target is 6-12 plants per metre. One watering with sorghum- it is amazing what can be done- pull back to 60-65mm deficit for one watering.
- With limited water price is the driver- sorghum can achieve 3 tons and Wheat 2 tons .
- Mung Bean is an option with limited water but it is inefficient in the use of water on heavy black soil. Expected yield with irrigation is 0.7 tons, best is 0.8 tons with one water. Chick Pea is similar. The return per ML for Mung Bean is not good but when the price was $600-$800 per ton, this made the difference !

Irrigation Systems and Management

- For cotton the changes to overhead irrigation with limited water include the use of lepa socks. These direct water into the furrow, 30 mm per pass, i.e., just survival, therefore deficits are ‘through the floor’ all the time. Some success stories with 3 bales but 2.25 is acceptable.
- Farm designs have not changed with limited water.
- First irrigation is important: 50mm deficit – get off the paddock quickly then stretch out the next irrigation to 11 nodes.
- If two waterings- the first is a quick irrigation, then stretch out the next.

- Strategy: - reduce the area and look after what you have left. With sorghum it is easy, one watering and apply at flowering.
- Other Strategies: - Overhead systems: problem is deficits too low and bogging is common. There is a lot to learn. 50mm per pass should be the maximum with socks. If 30mm pass when spread over crop it is not even. Between socks spacing is about 1 m. If full irrigation is managed well, yield can be greater than 5 bales . Soil type and season influences what happens. Design of systems and how quickly water can be applied is important.
- Slope and crusting soil important. Have to be able to drain water from the field.
- Must go for max capacity now. Flood irrigators who change to overhead will level the paddock.
- Agronomic Research : With overhead systems in light country issues can't be fixed . On box soils timing is important. Water quickly but there are flow on effects from flood irrigation and don't know how to fix. Salt is a problem but cotton is ok . However with Cotton and Corn the irrigator must use socks because salty water cannot be sprayed over the crop.
- Scheduling Irrigation: soil moisture probes are being used. Put 4 probes in each paddock. Diviners (capacitance probes) are being used.
- For the better use of rain, fallows and cover crops are used. Irrigation with zero till is difficult to manage when growers shift from grain to cotton.
- Hills were a nightmare ! Couldn't wet up hills. However, with stubble they wet up easily.
- With overhead irrigation growers use flat beds because level beds have drainage problems.

Consultant 3 - Graham Bolton

Key Cropping Systems Strategies

- Overland flows and bore water give some security. Water security is and issue with Cotton. Economics are very tight. The grower has to diversify to other crops such as early Corn. Plant mid-September and it finishes before Cotton. Last year (2008) Soybeans were planted as it was too late for Cotton. Growers have to look for opportunities. This consultant is dedicated to minimum till and zero till farming. However this locks out Cotton a bit. Minimum till helps to store soil water.
- Some growers are using pivots. Over- head watering is good because only half an inch is needed to get the crop up. Roundup-Ready Cotton has been a saving for water conservation. Minimum till and lateral moves have been good. More growers are expected to use them.
- This consultant uses soil moisture probes. He explained that you don't need profile full, but you don't want it to dry out either.

Strategies Within Each Crop

- Coming out of Cotton- Bollgard and pupae busting can be a problem. Growers dislike cultivating and cotton is really the only crop that has to be cultivated. Pupae busting can lose 25mm of soil water through cultivation. It also closes the soil cracks which assist in soil water penetration.
- Strategy is to minimize water use. Skip row with cotton assists. Having bore water helps. The grower has 7 to 10 days to get irrigation over the field. With bores he can stretch out water. However he must not stretch out the first watering with cotton,particularly with the new short varieties.
- Bollgard uses one or two post-plant waterings in the furrow. With overhead systems it is recommended to use 40mm irrigations and don't let the profile dry out too much. Some subsoil moisture is required.
- Corn strategies: need to water early 4-6 leaf stage if no rain. With the furrow system it is wasteful to water early just to stand the plant up.
- Cotton vs Corn: water usage is about the same. With the furrow system, solid cotton and corn, soil moisture probes are needed in both.
- Irrigated Sorghum: one watering at flowering or at boot stage yields 2 to 2.5 tons/ac. 3 to 4 tons/ac with good rainfall. Fertilizer program is important, but don't over do it.
- Populations: 50000 to 75000 for sorghum, 50000 to 60000 for irrigated corn. Yields 3 to5.5 tons. It all depends on how much water is available..
- Predominately summer crops are grown in this region. Winter Crops grown lately have not been good. However, because it has rained recently there are more Wheat and Chick Pea crops.

Irrigation Systems and Management

- Planning for overhead systems: Standing Sorghum or Corn, N fertilizer and minimum till. Growers are using guided systems, so they can offset when planting.
- Bollgard uses one or two post- plant waterings in the furrow. With overhead systems 40mm irrigations are recommended but don't let the profile dry out too much. Some sub-soil moisture is needed.

- Changing irrigation systems: For overhead systems, this consultant does not see too many topics necessary for research. Fertigation is used only to a limited degree but is more difficult with laterals than pivots . It can also possibly reduce the life of machines. There is a 5:1 reduction in labour with overhead systems.

Business Strategies

- There have been changes due to limited water. Trying to keep key staff and succession planning is important.
- Marketing skills are a problem with some growers. Some training is needed here. A trading plan is important. A share trader is needed to teach the principles.
- Buying more land and water: this has been done years ago and is not a new strategy. There has been some buying upstream and ground water purchases. Hence some water trading has been going on.
- Some clients are growing Chick Pea rather than Sorghum because there is not a big volume of grain to shift at harvest and this reduces transport costs.. Also less labour is needed.
- A lot revolves around labour now and what can be physically done. New technologies have helped to reduce labour.

Consultant 4 - Matthew Holding

Key Cropping Systems Strategies

- Greatest improvements have been with the introduction of minimum till. The goal is to have more minimum till under irrigated cotton.
- Establishment is the biggest issue with stubble cover and how to successfully irrigate.Therefore establishment in zero till is the biggest problem under irrigated conditions.
- Sequencing crops: many growers follow a Sorghum/Chick Pea/ summer fallow/winter fallow/Cotton rotation. Cotton has been 20% of farm acres over the last 5 years.
- What is the benefit of a single irrigation is the question? So if you have a good profile from stubble fallow, how much do you get from one irrigation instead of say 4 e.g., with Soybeans ?
- How well are paddocks set up for irrigation with respect to soil type ? Laser leveling, slope , length of run are important. Therefore paddock layout and establishment with zero till are key issues.
- Implements for zero till need investigation.

Strategies Within each Crop

- Planting configurations with Cotton are still an issue. Single skip nearly needs the same water as solid planted crops. ‘Super single’ is also being used, one row every 80 inch i.e., every second hill. Irrigation management in cotton water strategies still needs research. With Bollgard Cotton you need to water a little earlier. New varieties are shorter, so one can manipulate more.
- Soybeans: how can we reduce water ?
- With beds: plant into Sorghum stubble slightly to the side. There are lots of issues here still to be dealt with.
- Sorghum and Cotton with water are the main crops with some Soybeans and Corn in this consultants region.
- Two to three in-crop irrigations are applied with Cotton. Most prefer a pre-irrigation but with zero-till rain is still required to reduce the pre-plant irrigation.
- Sorghum and Wheat benefit the next crop in terms of water capture. Growers are also trying Millet as a cover crop followed by Cotton.
- Plant populations: Reduction in Corn to 4 plants / metre , also Sorghum 4 plants/metre in 1 metre rows.
- Cotton fully irrigated: growers are still using high populations due to loss from disease.

Irrigation Systems and Management

- If clients are growing Cotton there is very little irrigation in other crops. But nearly all are overwatering their crops. It is difficult to get growers to water over a 12 hour period. Most water for 24 hours. This is due to is a labour problems. Gated pipes or lay-flat, with automated shutoff would help..
- With overhead systems: the benefit is you don’t have to worry about trash. Lateral move systems are popular.
- Pupae busting has moved growers from Cotton because they don’t want to cultivate. Therefore they plant Sorghum or Corn.

- Not many are using c-probes or neutron probes. They are irrigation scheduling by crop stage. The position of probes in the crop is important. Most don’t put them in the right place. Growers need to look at what happened in the previous season.
- Evaporation rate information would be useful. A guide to mm/day would be very useful. Effective rainfall information would also be useful as would information sent to consultants such as a projection out 4-5 days.

Business Strategies

- Some growers are selling out and some are buying next door. There is amalgamation of farms.
- Growers zero- till and configure irrigation to smaller areas.
- There are a lot of lateral moves being used as they give better returns per ML. Laterals are there to be promoted, but price is an issue.
- Soil types and slopes are issues, as are issues with establishment with laterals. Channel/drainage/storage issues are still there.
- Too much fertilizer is being put on initially.
- Growers must start with a full soil moisture profile in a hot year.

Consultant 5 - Brad Tatzenko

Key Cropping Systems Strategies

- Most growers successful in Cotton and grain growing have been using Sorghum/cotton rotations and zero- till. This leaves the paddock with 2.5 inches of extra water leading to 0.5 bales/ac extra yield .Planting can be made directly into stubble.
- Growers are trying to avoid pre-irrigation.
- Disc openers are used and N is drilled into the plant row.
- Planting is offset using GPS guidance.

Strategies Within Each Crop

- 30-60 inch rows for single- skip Cotton, 40-60 inch double- skip Cotton, 40 inch for Sorghum.
- Irrigated Sorghum can yield 2.5 to 3.5 tons/ac depending on rainfall. Fleabane is controlled with Atrazine and Starain. This only possible with Roundup Ready Flex Cotton.
- With limited water, growers spread out the rows: solid 40 inch, single-skip single-row 40 inch or double-skip single-row 80 inch. With single-row 80 inch some is irrigated if there is a water opportunity i.e., overland flow from rain into a ring tank then plantings are made with no available water for irrigation.
- Cotton variety choice is critical. The determinate types are not used with limited water. Indeterminate types are used. Scheduling is difficult with limited water. Growers seem to think it is not important. The consultant puts in neutron probes and will stretch out the water, although sometimes he goes early with the irrigation. 90mm deficits for indeterminate types and 75-80mm for determinate types, measured with neutron probes.
- The variety 71BRF will be the most used variety this season (2009) on the Downs. It is a determinate variety.
- Determinates put on yield fast and can get maximum yield with stored water. If it rains there is an extra boost in yield. CSD is doing a lot of plant mapping. Node cut out number would be worth researching.
- Volumes of water used : Too much N and water is used in Corn, therefore it is not really worth growing. However, corn is good for the soil and growers like this. But the stubble is not good .
- Cotton into Sorghum stubble is improving yields. With Corn if have 3 in-crop irrigations, yield expected is 4 tons/acre.
- Growers are trying not to pre-irrigate anything. If there is 1.5 ft of water stored in the top of the profile then they go ahead and plant.
- For Cotton single-skip vs solid vs double- skip : Single-skip lasts 10 days longer than solid, saves about 2 inches of water. Double lasts 21 days longer. Skip-row is used to get water around the farm. Some growers are using a combination of configurations, which can be changed at will. Strategies change during planting depending on the situation. Insect spraying is not an issue with different configurations.
- Wheat and Barley are generally pre-irrigated because they follow a Cotton crop. Growers have to rip soil up to 4 inches after Cotton. However, growers don’t like to do this. Following harvest, growers mulch Cotton stubble and root cut, then work 4 inches deep and generally wait until August. Pupae busting is the problem, but they have to do it !

- Pre-water 1.5 to 1.75 ML/ha then plant Wheat. One irrigation is given at boot stage or the crop might fail. If there is some late water from rain, it is pumped on to the field and wheat planted- this is “opportunity cropping”. Therefore, water is not lost from ring tanks through evaporation.
- Fertilizer: growers put on two-thirds initially (for N, apply 200 units if aiming for 3 bales). N application needs to be increased because yields are increasing. Most growers split the N applications. If an irrigation is coming up they side dress with the required fertilizer then irrigate. (This consultant is starting to ignore deep soil tests. He tests to 0-15, 15-60). N at depth is a bonus if they get more water, then that is a back-up.
- With Sorghum a single irrigation is applied at booting to floweing.Timing important, 1.2 to 1.3 ML is being used.
- Growers could do better with Sorghum yields. It is “hit and miss”. Growers don’t have a great strategy for Sorghum. It is mostly being grown for stubble.
- Barley and Wheat are not grown much because the growing season is too long. If Wheat is grown then it is generally followed with Soybeans.
- With limited water they are growing more crops because they want something in the paddock in case of rain. Cropping is “opportunity cropping” these days and long fallow is not used much. Grain price is the driver.
- Corn is fully watered. It is treated as a fully irrigated crop whereas cotton is not. Usually 2 to 3 irrigations are applied to corn.

Irrigation Systems and Management

- There are changes in irrigation application methods: Syphons have changed from 2 inches to 3 inches due to use of Irrimates. Also, 12 hour shifts are used instead of 24hour. They have changed to double 2 inch or 3 inch siphons to get to 12 hour shifts. Irrimates have created the change .However, Irrimates give tail water information, so some growers tend to run water longer!
- Most would like to change to laterals. Cost is the problem.
- Ring tanks are managed to minimize evaporation. Water is accumulated into one ring tank or into sumps. The pumping of water from bores into ring tanks in August has stopped. Water is pumped from bores into ditches then onto fields.
- Tops of peaked hills are cut off after irrigation with mesh sheets . The practice is called “meshing”. This is done in dryland cropping also.
- Alternative systems: Trickle has been tried but is not satisfactory because of mice. Pigs are also a problem, as are crickets. (The consultant has only one grower with trickle- T Tape. It is too expensive to set up).
- Overhead systems: The consultant has only one grower using this with Cotton. There are still many questions to be answered. In the past with determinate varieties, overhead systems were ok, but now with indeterminate varieties there are problems e.g., when using lepa socks. The plant will shut down (71BR and 71BRF varieties) if water is applied to one side, because it is stressed on the other side. This is a variety problem. Growers can lose 1 bale/ac because of this problem. The consultant is aiming for 5 bales/ac. Growers won’t agree that spraying directly on to the crop is not as good as using lepa socks.
- Growers would all like to change to overhead systems because of the water saving, however cost is the restriction.

Business Strategies

- Most growers have share portfolios. Some do contracting. They are not buying more land for more water. Land is too expensive and everyone is very conservative.
- All have dryland areas but these are only 10 to 15 % of the farm. Most farms can be fully irrigated. The dryland growers use irrigation for “opportunity cropping”.
- Labour costs have been reduced with overhead systems with the new varieties e.g., Roundup Ready Cotton.
- Growers get a lot of their information from neighbours and consultants and especially talking to their colleagues after church on Sundays !

Grower 1 - Scott Seis

Key Cropping Systems Strategies

- Trickle irrigation saves 1 ML/Ha over flood irrigation and gives an improvement in yields. However, this year (2009) there was a problem with root rot. Last year the grower achieved 4.4 bales from flood irrigation and 5 bales from trickle with 1ML saved. This year he had 4.3 bales/ac on back to back Cotton. He has 36ha of trickle irrigation on the property.
- He uses 1.5m (60 inch) rows in Cotton because the farm is mostly dryland. He grows single-skip. Under irrigation he grows 30 inch rows with Corn or Sorghum and 15 inch rows in winter crops. He uses beds with a furrow down the centre in case he needs to pre-irrigate.
- This grower fallows and tries to plant on moisture with no pre-irrigation. He likes to grow Cotton and double crop to Wheat or Barley, then fallow into Cotton. But this is not always the case.
- The cropping sequence is: Cotton/winter Barley/Corn/fallow/Cotton in dryland and flood irrigation. Last year the sequence was, Cotton/Sorghum/fallow. He root cuts, pupae busts, bed rolls. If it rains the winter crop is dryland. He keeps cultivation to a minimum.
- The grower's bore water is salty, so he uses a combination of 50/50 bore to overland flow water. A fine ground formulation of gypsum is used through the trickle tape. His current tape has had two Cotton crops and he hopes it will go on to 5 years.
- Soil water probes are used and he has found the crops are not drawing well at depth. Suspects a Cl-salt bulge at depth. He finds that the probes are especially useful in trickle irrigation.

Strategies Within Each Crop

- Irrigation strategies with Cotton: stretch out the first irrigation with flood irrigation. He splits the irrigation country in half, so he can have fallow in between crops. With flood: 2 to 3 irrigations in-crop, pre-apply all the fertilizer before planting. Under trickle, 50% N and other requirements applied before planting. Tissue analysis determines the rest and it is put on through the tape.
- Corn: under irrigation he has no real strategies. Supplementary irrigation yields 7.5 to 10 tons/ha. The aim with trickle is to apply fertilizer through the tape. Corn and winter crops are treated as rotation crops.
- Sorghum is treated as a dryland crop with probably one in-crop watering. It has produced 3 tons/ac when watered at grain fill.
- This grower has half the area in Cotton each year. Plant populations are 10 plants/m and he usually gets 9 emerging. Therefore, if he is short of water he does not have too many plants. With Corn and Sorghum he plants dryland areas as well.
- Yields: Cotton target is 4+ bales/ac, Corn 3-4 tons/ac, Sorghum 2.5 to 3 tons/ac, Barley and Wheat 1to1.5 tons/ac.

Irrigation Systems and Management

- Trickle will remain part of this grower's system. Trickle tape is on the surface and he is now using a heavier walled tape. With Bollgard Cotton, if water is limited he blends bore and dam water and stretches out the water, hence both fibre and yield are ok. Wider spacing helps with fibre length. Every second row is watered.

- The grower times his furrow irrigation for16 hours for 800m runs and limits tail water as much as possible. Every second furrow is watered and water subs across the rows. He feels that a study is needed on this as it might be better to water each furrow to get water through quicker.
- If he did not have a drip expert on hand he would have been interested in overhead irrigation systems. He thinks long term trickle has a future. There is starting to be a lot more interest in trickle (T- Tape). He would like to go to 4to4.5 inches in depth with the tape. He links the tapes with lay flat and will probably expand his drip system.
- He uses a controlled traffic system. He picks 4 rows (6m) and runs wheel track down every second one. GPS has been important with his tram tracking system.

Business Strategies

- Irrigation allows pre-selling the crop. This helps because he can guarantee production and it lessens the risk. If there is no ground water to commence the season, he puts some bore water into the ring tank, but only about half fills it to cut down evaporation. He has limited water at present (September 2009). His soil type allows for good dryland yields.
- This grower also does contract work.
- Research to be done: Fertigation needs work. Trickle is better than overheads for fertigation. It needs to be linked to tissue tests.
- Better education in reading soil moisture probes (Diviners) is needed.
- 60 inch row cotton works well for this grower. It works well within his Bollgard licences.
- Roundup-Ready Cotton over the last 2 years was good with trickle and flood. He has to watch rotations for re-growth. Atrazine and Starain on Sorghum work well. Fleabane is a major weed problem for him.
- Pupae busting is a problem and more research is needed on this. Are the pupae there ? Do we need to cultivate?
- This grower also has a piggery with 280 sows to take the grain..
- Other problems are the loss of water through evaporation and seepage and these need research . The grower estimates that he has a net 4 foot evaporation loss.

Grower 2 - Nev Walton

Key Cropping Systems Strategies

- Growers must have a 5 to10 year plan. One year is no good because e.g., this year (2008-09) ran at a loss. Due to limited water a 10 year strategy would probably be ok.
- The main issue revolves around standing stubble. In a dry season coming out of cotton nothing can be grown (average rainfall is 450mm per year on his farm). It is necessary to put in sorghum to get stubble, it turns 'hard' rain into 'soft' rain. Wheat is not a good option. Don't make decisions in Spring, wait until January. Grow stubble, spray out, then plant beside it. Wait for rain to get a yield advantage and go back to cotton. Need to be in a position that when you do get water you can capture it and go forward. Pre-irrigation is no good. Skip- row cotton is always an option e.g., single skip.
- On the Jimbour plain with 400mm of rain you won't do any good. 550mm will produce a stream flow. There is no stream flow with less than 540mm of rain.
- How does a farm survive 10 years ? That is the study needed. Farmers need to know how they are to be farming in 10 years time !!
- To see how to manage the drought look at a dryland farm !

Strategies Within Each Crop

- This grower had Soybeans about 10 years ago.
- Corn sets its potential in the first 6 weeks. Do not stress it in the first six weeks as it will take the top off the yield. 80 to100mm irrigation deficits are used.
- Winter crop is not an option as diseases are a problem. The year before last he planted wheat but with a diseasedncrop produced 1 ton instead of 1.5 tons. He had to spray Tilt.
- With Corn , logistics are a problem, unless sales are local. It is a ' nightmare' at harvest, because of the volume grown.
- N and Cotton: Do a soil test, put on at the last working or close to planting and you get more out of the N. Split application in December. Urea probably the best. After fallow with wheat use 90 kilos of N. If following corn, use 200 kilos of urea. If side dressing use half rate. In total 200 kilos of urea is needed. He is now trying other forms of N- grow the N e.g., Vetch.

Irrigation Systems and Management

- Plant on rain, apply N, use a determinate variety of Cotton. Four irrigations only, will give best return per ML. With new varieties expect 4.2 to 4.3 bales to be produced, all on long fallow.
- Seven days pumping is the average for 7 years in 10. Probably down to 5.2 days now i.e., 20% cut due to weather and that is 6 years in 10.
- Irrigations: When to irrigate depends on rainfall. Usually rain starts in November and cotton does not start using water until the second week in December. Side dress fertilizer, insert soil moisture probes (consultant reads them). The grower has 8 days to get around the watering to flower 6 nodes from the top. Work on smaller deficits and finish quickly. The determinate varieties need to be irrigated as needed. Cluster grub infestations make the season go a bit longer.
- This year all the farm will be cotton. Next year the decision will be single skip cotton or soybean (if no rain), then sorghum for stubble.

- Everything depends on the budget. The consultant runs the “Ham” program processing the numbers to produce the budget. Results are sent monthly.
- Options are soybeans, corn, sorghum, single skip cotton. It is important to have a good budget for all the crops you are capable of growing. The budget needs constantly updating.
- The grower gets an aerial photo taken each year. Mapping equipment is installed in the picker to produce yield maps. Soil on the property is classified into 7 types. He has had an EM survey done. He also has a fertilizer sampling site to show trends. Sap tests are also carried out. Soil moisture probes are put in key sites which helps in field sequencing. Probes give information so irrigation can start early. It takes 8 days to get around the crop.
- Changes : Bigger syphons being used. Water through in 10 hours is the goal. It takes half an hour for a syphon to get through. About 1 ML is used per irrigation event. If it rains it will be a bit less.
- Alternate Systems: Trickle is too expensive. Pivots and laterals: investing in these and might only irrigate part of the property, therefore only putting half to two thirds of water through it. Looking at it with a neighbour as a long term thing. He has water only 4 years in 10 and therefore the machine will not pay for itself. Bogging is a problem, levelling to drain the land is an issue.
- If he is to grow Wheat or Chick Peas the figures will have to be looked at.
- Coal seam gas: this water is a possibility to be available. Water quality will be an issue. It can burn the plant, damage equipment and soil. But 400 to 800 ppm salt has been quoted and this would be ok. There is an RO (reverse osmosis) plant near the grower’s property.
- Evaporation: The grower has two storage cells, 640 ML and 500ML. He siphons over then back. Evaporation is very high so he has experimented to reduce evapaporation loss using “Aquatain”. The loss has been reduced by 50% on a small water holding tank.

Business Strategies

- Value of the property important. What is the return from an asset ? He looks at the best farm on the Jimbour plain and asks what is the return from the asset? What is the real estate value of the land? Need a business strategy to determine how to minimize a backward step over a period of time? The near-by mines are a good asset in spite of what people say. He could make a 50% gain in the asset with a mine .
- Other strategies: Need more area that you don’t have to irrigate. Single-skip is the best way to go. Need to rent land so the business is not land limited. But leasing land leads to a few issues, such as, what happens if leased land is sold? Leasing is a way to go forward as economics get tighter. Need long term leases.
- Bigger area, reduce evaporation, stubble, grow high value crop when one comes out of a drought. These are the strategies to use.

Grower 3 - Andrew Bartley

Key Cropping Systems Strategies

- Changes over the last 5 years: plant populations reduced slightly, sorghum reduced from 4 kg to 2.5 kg per ha. Cotton in 60inch rows and sorghum in 30 inch rows.
- “Tram Tracking” being used is the biggest change. 40 ft equipment has been standardized. GPS is used. The benefit is compaction reduction and better water penetration.
- Grower has not adopted a structured rotation. This depends on commodity prices and water availability. Cotton has not been grown lately because of the price reduction and lack of water.
- The grower uses push probes to determine profile water depth i.e., “gut feeling” is used.

Strategies Within Each Crop

- Main crops are Cotton and Sorghum. Grower has moved from winter crops.
- Reduced tilling used in the last 10 years . The grower doesn’t have a reduced till wheat planter.
- Long fallow is used. Irrigation is handled the same as for raingrown crops.
- Cotton: Bollgard varieties are used.
- Sequence is: cotton/winter fallow/summer fallow/wheat/summer fallow/winter fallow/cotton or sorghum.
- Thoughts on drip: He is replacing the system . If water is available he would would use a lateral move system, because the infra structure is there. T- Tape would be replaced with an overhead system.
- Irrigation is not a large part of the grower’s operation. He has 3500 acres of raingrown crops and plants Cotton if water is sufficient. Plant populations are reduced and grass is controlled with Roundup.
- For Sorghum, stored water is needed to plant. It is usually less than 3 ft deep in the profile. The acreage planted is reduced if conditions are dry. If planted on 1.5 ft of profile water he can produce 1.5 tons. Zero till increases yields. He works on yields of 2 tons/acre sorghum or 1.5 for wheat.
- Irrigated Cotton yields 3 to 3.5 bales/ac irrigated, wheat probably 2 to 2.5 tons/ac.

Irrigation Systems and Management

- The grower has 500 acres of drip irrigation (T-Tape) on the farm. This is supplied with bores. He uses rain to get the crop up. Cotton is successful under this system. It is a permanent system and has been in for 18 years. However tape lines are too long and there has been a worry about getting water to the end of the line. Tape is placed every 60 inches and over 500m long, 18 inches deep. The pipe is one and one eighth inch. There have been problems with mice damage. He did well using dam water and high pressure.- 3.5 bales yield on 60inch cotton . Low population rates are planted. Water used was 250ML on 120 ha i.e., 2ML/ha (if surface irrigating 4 to 5 ML would be used).
- Strategy: no probes are used. Timing is based on the stage of the crop. The grower said that he is not really a serious irrigator. He is trying not to use bores as there are some problems with water quality.

- Tram Tracking gives a better strike. He can plant on less moisture and plants alongside plant lines. He can offset by “nudging” across a bit but a guidance system is needed. A zero till planter is used and he uses a 120 ft sprayer.
- He has a ‘weed seeker’ and can manage fleabane with it. 24D and Roundup works well. Dicamba is also used. He is trying to reduce operations.

Business Strategies

- With limited water, zero till is used as much as possible. Have to manage crop conservatively with limited water. Plant a ground cover crop and spray out. He said a neighbour plants French Millet for cover.
- For Dryland: Chick Peas and Mung Beans are treated similarly to Cotton. Chick peas dry the ground out because of its deep tap root. It takes moisture from depth. Chick pea yields just over a ton in wet years and Mung Beans 0.3 to 0.5 tons.
- Mung Beans are an opportunity crop- late plant in summer (Feb). Some powdery mildew occurs but is not a big problem (variety grown recently was Crystal).
- About one eighth of the grower’s farm is irrigated.
- The grower has a track harvester being made in Germany and is due in September.
- In future he will be retaining sorghum stubble (this also reduces sand blasting of an emerging crop).
- Planting into sorghum stubble is an issue. Some growers still burn . Another issue he has is applying fertilizer .
- Hills, beds : the grower has more hills than beds. How to wet these up is an issue. Also wheel tracks and stubble result in watering problems. Much controlled trafficking is being used.

Grower 4 - Stuart Armitage

Key Cropping Systems Strategies

- Solid Cotton is grown, followed by fallow for two years to get a full profile. The grower crops half tor 40% of the farm. From Cotton he fallows a summer and two winters then it is back to Cotton.
- Some Sorghum is grown for use as a stubble cover. At $300 per ton and average rainfall it is profitable. Present stubble on the farm (September 2009) is two years old. He says that he is " land rich" and "water poor" and most farms are.
- This grower tries not to grow other crops besides Cotton.
- Labour is a significant issue as he is on his own.

Strategies Within each Crop

- Cotton is grown on 40inch rows, solid and fully irrigated. This grower is trying some on 80 inch rows with a single irrigation only. He mainly uses bores for water.
- He does 3 irrigations for solid planted Cotton and one irrigation for skip-row (prior to flower, 0.4ML / ac (1 ML/ha). The first irrigation is timed for prior to first flower.
- The grower tries not to pre-irrigate, but if needed, 0.2ML is applied. He needs 1 to 1.5 inches of rainfall to plant. Stubble is a big help as it holds the water. He uses 8 to 12 hour shifts. Roundup-Ready Flex is the variety used. He said that Bollgard is so different to past varieties.
- He usually plants and waters up, depending on rainfall. He does not use soil moisture probes (because he said that you get false readings if you receive rain). He pays consultants for nutrient and watering advice.
- Varieties 70 and 71 BRF are big yielders for single-skip cotton (which is one row out and two rows in). He usually does two waterings in drought with 80 inch rows. Usually only one watering and three for solid planting.
- Cotton is his key crop because of the returns. He has 160 to 200 ha of Cotton per year. This grower has 500ml of water available (that is his ground water licence). Quality and availability of water is good. He has had 100 to 150 ML from overland flows over the past five years but reliability is poor.
- Cotton target yields are: single-skip, 2 waterings- 3.5 to 4 bales/ac, solid , 3 waterings- 4.5 to 5 bales/ac, dryland 80 inch no water- 2 bales/ac- if long fallow.
- Nutrition: The grower uses sewage sludge. He uses 60 tons/ac at approximately $2 to $3 per ton. This has 6% N. Phosphate is high, but potash is lacking. Zinc etc are good. One application lasts 2 to 3 years. One application of sewage will produce 3 crops of Cotton., and no other fertilizer is required. He replaces the nutrients the crop takes out. Soil tests are used.
- Sorghum: dryland mostly 40 inch rows, yields 2.5 tons/ac
- Soybeans: irrigated 40 inch rows- needs more water than Cotton, yields 1.2 to 1.4 tons/ac.
- Wheat and Chick Pea: used to even up paddocks. Wheat is used to provide stubble for Cotton and will have Roundup applied if the crop is poor.
- Millet is also used to provide stubble- he is trialling this. White French is the variety used.

Irrigation Systems and Management

- Alternative Irrigation Systems: This grower does not think there is an alternative. Although centre pivot systems might be, but not laterals. Laterals can't keep up the water and maintenance costs are high. The grower said that he needs information on laterals which are are probably satisfactory for winter crops but not for Cotton.
- He uses 10 to 12 hour shifts and short runs (less than 500 metres). This is cost effective.

Business Strategies

- Buying more water: If neighbours do not use their full allocation they will sell ($160 per ML for the water, $60 for pumping).
- The grower pre-sells the Cotton. It is good business to have adequate water. If solid planted Cotton is grown properly, it produces good yields and quality. Full water allocations can be carried over 3 years.
- His strategy is to use the dam first if it has water. This saves losing water through evaporation. If the dam is full he will water a winter crop to produce stubble and he has the equipment to handle the stubble.
- His water allocation is 60% this year (2009) but it might go back to 50 %. DERM reads the water meters about 3 times per year.

Grower 5 - Neil Pfeffer

Key Cropping Systems Strategies

- It comes down to the question, what is the risk you want to take?. For the last 4 years the grower has planted on rain with no water in storage. He had to do a lot with little water and said he pushed the envelope a bit far. Now (September 2009) he has water in the ground and it is a long time since that has happened.
- He does a water budget: 2 in-crop waterings for Cotton gives a profitable yield. One crop watering for Sorghum, but Cotton usually gets preference. He does a minimum 2 ML/ha in-crop watering with cotton.
- Pre- plant water: 1.4 ML/ha, 2 in-crop waterings of 2ML/ha to average 4 bales/ac. 1 m row spacing is used. He always plants solid . If he thinks he might skip he grows Sorghum or other grains instead of Cotton. With Bollgard cotton, he is tending to planting on rain. With Bollgard Roundup-Ready, he will water following planting to emerge the crop ('watering up').
- Some of the grower's land has not been cultivated for 3 years. He zero-tills dryland areas GPS equipment has helped with tracking.
- He shreds the stubble: Following harvest, Cotton is shredded and ground is gassed at first working, then he might put in opportunity Wheat.
- This grower has shifted from having back to back Cotton, because of Fusarium Wilt and the grain prices have been good.. He will put in some Sorghum and Corn after Cotton. Sometimes he will fallow from Wheat then will go to Cotton. He plants a crop in most years and does not fallow very much.
- Direct drilling Soybeans into standing Wheat stubble works well on 2 m beds.

Strategies Within Each Crop

- Cotton/Wheat/Sorghum/Corn on one paddock. Average yield of Cotton is getting better each year, probably because of varieties, 4.3 bales average.
- Yields are :8 tons/ha Sorghum, 10 tons/ha Corn, with 2 to 3 in-crop irrigations. Soybeans 3.5 tons/ha. This was with an older variety with 3 in-crop irrigations. This is good at $700 per ton, but price is falling.
- Irrigated Wheat planted on rain yielded approximately 5 tons/ha. He waits until flowering to irrigate if possible. He waters when still in the boot stage, but considers it best when showing a few heads.

Irrigation Systems and Management

- Irrigation practice with Bollgard Cotton: delay the first irrigation if ample water is available. 80mm applied in the first irrigation. He usually needs to get water on early. He sees this as a change with Cotton. He uses soil probes on 2 or 3 fields.
- Irrigation on other crops: Sorghum, one irrigation This year (2009) he irrigated late as the soil profile was well filled, but he said that he should have irrigated early. It depends on cropping history what is done. Fallow ground will hold the crop longer.
- Most runs are 600m. He uses yield monitors in the header.
- Alternate systems: With lateral moves a study showed that it would take 7 years to pay off the equipment, therefore he didn't proceed with purchasing. However, he thinks that maybe he should have. This study needs to be repeated.

- The grower said he is watering quicker for shorter durations by stacking up siphons. He generally uses a 24 hour cycle. He said that he is managing water better and has learnt when crops best respond to water.
- Key things with storage management is stopping evaporation. Covers would be good if possible. He has 3 cells, two full and one empty. He doesn't think he can do more here and said his distribution network is good. It costs $10/ML to pump out of storages. That is for one lift. Water costs need to be worked on $/ML and returns/crop.
- Coal seam water was discussed: If you have to pay $300/ML it would not be economical for broadacre crops but probably satisfactory for vegetables.
- Reduced till is an important part of his operation. GPS has improved operations on dryland areas, as has controlled trafficking.

Appendix V

Irrigation Guidelines for the Darling Downs

COPING WITH LIMITED WATER IN IRRIGATED FARMING SYSTEMS

Guidelines for the Darling Downs

Dr Phil Goyne, Graham Harris and Dr Jose Payero

Contents

Take Home Messages

Project Description and Detail

- Research component (lysimmetry, Eddy covariance)
- APSFARM Modelling (Fressers)
- Interviews – consultants and growers
- Development of Decision Aids (Crop Water Use tool, etc)

District Characteristics

Location

The Darling Downs region lies on the western slopes of the Great Dividing Range in southern Queensland. Irrigated cropping is practiced on the floodplains adjacent to the Condamine River and tributaries.

Climate

Climate statistics for the Darling Downs region are summarised in Table 1.

Table 1: Climate Statistics for selected Darling Downs centres

DALBY	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Temperature (C)													
Mean maximum	32.6	31.3	30.2	27.4	23.3	20.2	19.7	21.9	25.6	28.5	30.1	31.7	26.9
Mean number of days >= 30C	24.4	18.7	16.6	4.6	0.2	0	0	0.5	4.1	11.2	14.6	22.1	117
Mean number of days >= 35C	6.8	4.3	1.8	0.1	0	0	0	0	0.2	1.3	3.2	5.7	23.4
Mean number of days >= 40C	0.4	0.2	0	0	0	0	0	0	0	0	0.2	0.3	1.1
Mean minimum	18.8	18.6	16.2	12.5	8.5	5.5	4.1	4.8	8.8	12.6	15.6	17.6	12
Mean number of days <= 2C	0	0	0	0.2	2.5	8.5	11.5	9.8	1.5	0.1	0	0	34.1
Mean number of days <= 0C	0	0	0	0	0.8	4.9	7.3	5.4	0.6	0.1	0	0	19.1
Rainfall (mm)													
Mean rainfall	70.4	87.8	44.1	20.3	38.3	33.7	24	24.4	30.1	58.2	83.1	98.2	608.9
Highest rainfall	226.4	224.8	174.2	91.2	216.2	146.6	77.6	103.2	96.2	166.4	150.6	174.4	847
Lowest rainfall	7.4	11.2	0.6	0	5.8	0.4	0	1.2	1.2	0.4	10.4	26.8	421
Decile 1 monthly rainfall	11.6	24	5.9	0.3	7.6	2	0.6	1.7	6.2	19.5	26.9	51.3	461
Decile 5 (median) monthly rainfall	42.8	80.6	23.4	14	15.4	27	16.4	11.6	24.7	44.7	81.2	98.3	591.1
Decile 9 monthly rainfall	162.5	172.2	106.3	46.4	80.6	80.8	63.6	63.8	53.6	103.9	142.2	144.8	795.9
Mean daily evaporation (mm)	9.2	7.8	7.3	5.9	3.7	3	3	4.2	5.9	7.4	8.1	9.1	6.2

PITTSWORTH	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Temperature (C)													
Mean maximum	29.9	29.1	27.8	24.7	20.5	17.3	16.7	18.6	22.1	25.6	28.4	29.8	24.2
Mean number of days >= 30C	10.1	9.5	5.9	2.2	0	0	0	0.1	0.2	2	7.2	9.9	47.1
Mean number of days >= 35C	0.9	1.1	0.3	0	0	0	0	0	0	0.3	1.3	1.2	5.1
Mean number of days >= 40C	0	0.1	0	0	0	0	0	0	0	0	0	0.1	0.2
Mean minimum	17	16.9	15.4	12	8.4	6.1	5	5.9	8.7	11.9	14.4	16.1	11.5
Mean number of days <= 2C	0	0	0	0	1.1	3	7.2	3.6	1.2	0	0	0	16.1
Mean number of days <= 0C	0	0	0	0	0.1	0.7	2.6	0.5	0.1	0	0	0	4
Rainfall (mm)													
Mean rainfall	92.1	76.8	62.7	38.5	40.6	40.7	40.5	30.4	36.6	63.4	76.6	96	694.2
Highest rainfall	264.8	359.7	321.8	281.2	325.4	172.7	141.8	117.4	148.9	251	302	297.5	1072.7
Lowest rainfall	2.4	0.8	0	0	0	0	0	0	0	0	4.9	5.7	328.2
Decile 1 monthly rainfall	33.4	20.2	10.3	2.2	3	6.1	4.4	2.5	5.4	17	18.1	31	477.3
Decile 5 (median) monthly rainfall	83.4	66.9	50.3	27.5	32.9	30.2	34.2	23	34.8	54.8	68.9	82.2	701.2
Decile 9 monthly rainfall	172.7	146	132.6	86.2	81.1	82.2	89.3	64.4	67	108.7	139.3	171.5	887.5
Mean daily evaporation (mm)													

WARWICK	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Temperature (C)													
Mean maximum	30.1	29.5	27.7	25.1	21.2	18.5	18	20.1	23.7	26	27.5	29.4	24.7
Mean number of days >= 30C	15.1	12.3	6.3	1.1	0	0	0	0.4	2	4.9	8	12.7	62.8
Mean number of days >= 35C	2.7	1.3	0.7	0	0	0	0	0	0	0.5	1.4	2.4	9
Mean number of days >= 40C	0.1	0	0	0	0	0	0	0	0	0	0	0	0.1
Mean minimum	16.9	17	14.8	11.3	6.9	4.8	2.9	3.1	7.1	10.4	13.7	15.9	10.4
Mean number of days <= 2C	0	0	0	0.5	6.2	9.5	13.6	13.2	3.5	0.1	0.1	0	46.7
Mean number of days <= 0C	0	0	0	0.1	2.9	6	9.5	8.9	1.1	0	0	0	28.5
Rainfall (mm)													
Mean rainfall	81.4	68.9	52	31	40	33.1	26.9	23.2	32.6	74.4	98.5	98.7	655.6
Highest rainfall	176.2	171.6	163	74.6	187.6	94.1	101.6	77.6	90.2	183.5	198.6	201.2	950.4
Lowest rainfall	3.6	12	13.4	0.6	0	3	0	0	2.6	0.6	26	57	465.7
Decile 1 monthly rainfall	24.6	27.3	15.6	1.3	4.4	3.6	1.8	1	8.4	16.2	35.1	60.6	481
Decile 5 (median) monthly rainfall	76.6	57.6	32.1	31.2	34.6	27.9	7.6	15.6	27.7	49	95.4	81.6	616.4
Decile 9 monthly rainfall	127.8	110.9	103.9	57.2	69	61.4	73.4	52.4	58.7	162	170.8	159.8	796.5
Mean daily evaporation (mm)	6.7	6.1	5.1	4.2	2.9	2.3	2.4	3.5	5	6.2	6.4	6.8	4.8

Irrigation Industry

In 2007-08 there were 1,443 agricultural businesses irrigating on 103,846ha of land within the Darling Downs. Water use in that year was 279,535ML (an average of 2.7 ML/ha).

Map

Add in the Land Resource Area and Soils map developed for the report by Wendy Casey, DEEDI

Soils

There are a number of soil types in which crops are planted on the Darling Downs. The water holding capacity of the soils associated with the growers surveyed in this report are presented in Table 1. The information in this table are a guide only as individual fields vary.

Water

(groundwater resource issues, surface water issues, water requirements of crops – use CropWaterUse to generate this data)

Table 1: Characteristics of Irrigated Cropping Soils for Darling Downs growers and consultants interviewed

Anchorfield (Black Vertosol)									**PAWC mm**	**Grower No.**	**Consultant No.**
Depth :	**cm**	**0-15**	**15-30**	**30-60**	**60-90**	**90-120**	**120-150**	**150-180**		3, 5	3, 4, 5
Saturation	% vol water	50	48	51	50	50	49	48			
Drained upper limit	% vol water	45	43	46	45	45	44	43			
Bulk density	g/cc	1.25	1.31	1.23	1.24	1.25	1.26	1.29			
Barley											
LL	%vol	23	25	29	30	35	38	43			
PAWC	mm	32	27	49	45	30	19	2	204		
Cotton											
LL	%vol	23	24	23	26	30	33	37			
PAWC	mm	32	27	67	59	44	35	19	282		
Sorghum											
LL	%vol	23	24	29	34	37	38	39			
PAWC	mm	32	28	50	34	24	19	12	199		

Saturation	maximum water held in the soil before drainage takes place.
Gravimetric water %	(wet soil weight-dry soil weight)/dry soil weight) x100
Bulk Density	weight of solid material in a unit volume of soil (as g/cc).
% Vol Water	gravimetric water % x Bulk Density
Drained upper limit (UL)	amount of water a soil holds after drainage has practically ceased.
Crop lower limit (LL)	lower limit of water extraction for a particular crop and soil.
PAWC	maximum water available to a crop - difference between UL and LL.

Bongeen (Black Vertosol)									PAWC mm	Grower No.	Consultant No.
Depth :	**cm**	**0-15**	**15-30**	**30-60**	**60-90**	**90-120**	**120-150**	**150-180**		1, 4	1
Saturation	% vol water	57	57	55	55	54	53	52			
Drained upper limit	% vol water	52	52	50	50	49	48	47			
Bulk density	g/cc	1.05	1.06	1.11	1.02	1.13	1.17	1.20			
Wheat											
LL	%vol	22	22	31	33	37	42	47			
PAWC	mm	45	45	57	51	37	16	0	252		
Cotton											
LL	%vol	22	22	35	36	37	38	38			
PAWC	mm	45	45	44	40	37	30	25	267		
Chickpea											
LL	%vol	22	22	37	38	40	40	41			
PAWC	mm	45	45	40	34	28	24	16	231		
Sorghum											
LL	%vol	26	32	33	36	38	39	40			
PAWC	mm	39	31	50	42	34	25	20	241		

Saturation	maximum water held in the soil before drainage takes place.
Gravimetric water %	(wet soil weight-dry soil weight)/dry soil weight) x100
Bulk Density	weight of solid material in a unit volume of soil (as g/cc).
% Vol Water	gravimetric water % x Bulk Density
Drained upper limit (UL)	amount of water a soil holds after drainage has practically ceased.
Crop lower limit (LL)	lower limit of water extraction for a particular crop and soil.
PAWC	maximum water available to a crop - difference between UL and LL.

Waco (Black Vertosol)									**PAWC mm**	**Grower No.**	**Consultant No.**
Depth :	**cm**	**0-15**	**15-30**	**30-60**	**60-90**	**90-120**	**120-150**	**150-180**		2	1
Saturation	% vol water	57	57	55	55	54	53	52			
Drained upper limit	% vol water	52	52	50	50	49	48	47			
Bulk density	g/cc	1.05	1.06	1.11	1.12	1.13	1.17	1.20			
Wheat											
LL	%vol	31	29	31	33	37	42	47			
PAWC	mm	31	34	57	51	37	16	0	227		
Cotton											
LL	%vol	22	22	35	36	37	38	38			
PAWC	mm	42	45	44	40	37	30	25	263		
Chickpea											
LL	%vol	33	33	37	38	40	40	41			
PAWC	mm	28	29	40	34	28	24	16	198		

Saturation	maximum water held in the soil before drainage takes place.
Gravimetric water %	(wet soil weight-dry soil weight)/dry soil weight) x100
Bulk Density	weight of solid material in a unit volume of soil (as g/cc).
% Vol Water	gravimetric water % x Bulk Density
Drained upper limit (UL)	amount of water a soil holds after drainage has practically ceased.
Crop lower limit (LL)	lower limit of water extraction for a particular crop and soil.
PAWC	maximum water available to a crop - difference between UL and LL.

Reference Dalgliesh N. and Foale M. (1980) Soil Matters- monitoring soil water and nutrients in dryland farming. Australian Productions Systems research Unit Toowoomba, Queensland, Australia.

Limited Water Strategies

Irrigation management of individual crops

fully irrigated vs limited water ie critical phases and response to water (include Alan Peake's maize work, APSIM?, etc). Use international data plus what we have found from research (lysimeter and eddy covariance results). Include economics.

Barley

(Phil Goyne)

- The seasonal water requirements for barley depends on variety, target yield and crop management. Generally barley requires 390 - 430 mm for optimum yield.
- In soils well suited to irrigation, barley develops an active rooting depth of approximately 1.0 m.
- To optimize yield, soil moisture levels should remain above 50 % of available moisture in the active root zone from seeding to the soft dough stage.
- Barley is not tolerant of prolonged or excessive drought. However it will tolerate soil moisture depletion to 30-35 % of available moisture during grain formation and 10-20 % near maturity.
- Research indicates that stress prior to, or just after, the onset of flowering, reduces yields the most.
- The yield-reducing effects of stress can be offset somewhat if the stress is relieved later in the season, but the yield recovery from stress near flowering stage is lower than recovery from stress in the vegetative stages of earlier growth.
- Moisture stress can also result in higher protein content and a shortening of the grain filling period, leading to earlier maturity.

(photo of barley crop)

Ref. Sutton, D (2008) Irrigation Management of Barley. Government of Alberta, Agric. and Rural Development.

Chickpea

(to be determined)

Cotton

(Steve Yeates, Kingsthorpe)

Maize

(Allen Peake, Jose Payero)

Mungbeans

(Mike Lucy)

Sorghum

(Phil Goyne)

- Sorghum is noted for its ability to produce grain when subjected to water and temperature stresses as compared with other cereals.
- It is usually grown under conditions of less than optimum water supply so crop water stress is a major yield limiting factor.
- Stress during certain critical growth stages reduces yield more than other stages therefore managing water supply is important in increasing the efficient use of limited water.
- Critical growth stages for water supply are head initiation to flowering and flowering to grain maturity. However, it is important to have a continuous water supply although it might not completely replace that lost by evapotranspiration.
- Generally 50% of the volumetric soil water between permanent wilting point and field capacity can be depleted before growth reduction is observed.
- Total water requirement for grain sorghum is 6-7 ML, with average irrigation requirement of 4 ML per hectare.
- Management strategies such as choice of hybrid (maturity group), planting time, planting rate, irrigation schedule and fertilizer application, can be developed to use limited water supplies efficiently.

(photo of sorghum crop here)

Ref Irrigation of Agricultural Crops. ASA, CSSA,and SSSA., Madison, WI. 1990

Soybeans

(Jose Payero)

Sunflower

(Phil Goyne)

- Sunflower is known to yield relatively high under soil water deficit due to its increased rooting depth (80 to 180 cm over five Queensland soils) and greater ability of roots to extract water to a lower soil water potential.
- Sunflower has been shown to extract more soil water than many other crops including, maize, sorghum and soybean
- Because it is deep rooting and water extraction characteristics, crops following sunflower may be expected to have low yields where soil water is limiting.
- Sunflower responds positively to irrigation in both vegetative growth and seed yield where lack of water is retarding normal plant development.
- Under limited water conditions sunflower should be irrigated during early growth to promote adequate leaf expansion and at flowering to assist seed yield.
- Research under raingrown conditions indicates that approximately 75% to 80% of the seasonal water use had occurred by flowering.
- Sunflower water use has been shown to vary widely from<200mm to >900mm. Water use efficiency increases with decreased irrigation efficiency especially when crops are irrigated at critical stages of growth (budding and flowering to grain filling).
- Models are available to estimate water use, under water limited conditions, based on the calculation of crop growth rate as a function of water supply and transpiration efficiency.

(Insert sunflower crop photo here)

Ref Sunflower Technology and Production. ASA, CSSA,and SSSA., Madison, WI. 1997

Irrigation of Agricultural Crops. ASA, CSSA,and SSSA., Madison, WI. 1990

Wheat

(Graham Harris – from info being prepared for High Yielding Grains Project, Kingsthorpe)

APSFARM model of Fressers as a case study

- (summarise the study into useful information that includes economics)

Consultant District Strategies

Consultant 1 - Murray Boshammer, Dan Skerman

Key Cropping Systems Strategies

- A grower wants standing stubble- this helps establishment and is critical to getting water into the fallow- is Sorghum the best ?. Spray out the sorghum (1.8 Paramax).
- Plant Skip-row Cotton into stubble.

Strategies Within Each Crop

- **Sorghum** with limited water is planted on fallow and given one irrigation and can yield 7 to 7.5 t/ha. Putting water on at head emergence works well. Fallow gives a good soil water profile. Nutrition is planned to target 8t crops.
- **Cotton:** fallow through winter and spring plant sorghum. Population 70-80 000 plants/ha. In-row population 10 to 12 plants per metre for solid planting 12 to 14 for skip is a good dryland population. With a single irrigation it is critical when the irrigation applied. Variety is important (e.g. Bonus).Need varieties that perform well under difficult dryland conditions. Irrigation water less than 1.5 ML is normally scheduled. If applied early then another irrigation is required at heading. A maximum of three irrigations are applied. Pre-watering is considered a waste of water. A grower wants standing stubble which helps establishment and is critical to getting water into the fallow. If he has 500ML of water, instead of growing 100ha solid plant he should grow 150 ha skip with three irrigations and can obtain a yield of 7-8 bales/ha.
- With limited water skip- row cotton is grown to spread the crop over more land. If there is bore water then irrigate for high yields. If water source is from overland flows a different approach is needed. If grower has greater than 50% water in a ring tank he can grow solid cotton well . If less than 50% then use single skip-row for high yields.
- GPS helps by enabling grower to offset rows in standing sorghum stubble and keeps planting even. Roundup technology has helped with the weed problem. Atrazine is used in sorghum (Spring plant).
- Bollgard cotton needs to be watered when required- this is critical. Use Diviners are used to monitor water. 80-90 mm is the deficit for solid planted cotton. Skip-row deficit is half an irrigation less. First water 80mm on both. Prior to Bollgard 100 mm was used. Growers have to achieve 7 to 7.5 bales. They have to decide whether to use single skip or not. This depends on the starting water supply.
- **Corn:** This crop is not seen to be fitting in with limited water. It is grown when there is lots of water available. Growers should try to achieve 12 t . Plant nutrition: 300 units of N required. It probably needs more irrigations than cotton- 4 or 5 irrigations. After Corn, cotton is often grown and its nutrition must be watched because of stubble. It could probably need N: 250 units for cotton and for corn 200 immediately then top up to 250 if there is enough water.

Irrigation Systems and Management

- Optimising- most growers think they are doing the best they can- all clients have probes to monitor soil water.
- Changing irrigation systems- not an option.
- Some clients still need to optimize their irrigations.
- Very few fields are irrigated longer than 2 hours. There has been a decrease in the water application time over the past few years- this is progress.
- Overhead systems: Issues with bogging near towers. Machine sellers need to be educated.
- Storage management- not a lot of changes.
- There is seepage in some areas and leaky ring tanks are still problems.
- Key things- follow up sorghum stubble idea- don't have bare paddocks but there is still the question is Sorghum the best ?. Always spray out the Sorghum (1.8 Paramax) and use Skip-row cotton.

Consultant 2 - Geoff Rudd, John Fuelling

Key Cropping Systems Strategies

- Crop Choice- is the first strategy. Need a reasonably accurate measure of soil water. With limited water need good management from a dryland sense then a crop is guaranteed..
- Conservation tillage- leave stubble there as long as possible. Grower must have rotation at the back of the mind- 3 summer crops then winter crop usually- 3 years summer, 1 year winter.
- Unrealibility of rainfall drives growers out of rotations. With herbicide application it is difficult to go out of rotation- herbicide can lock you out. Hard to control weeds – this is a problem.

Strategies Within Each Crop

- **Cotton-** with limited water plant on rain. "Super, Super Single" configurations have made a difference. If coming out of late sorghum then double skip. 1.2m super single has yielded a bale. The question is, do we use a 3m skip or 5m skip ?
- Iirrigation strategy with Bollgard cotton – hold off irrigation until peak flower, if water is really limited. Usually plant double skip with one irrigation. Some growers plant solid then use the 'plough out' option if water is problem (i.e., no rain).
- Break even line is important e.g., if it is 2 bales/ac they will take a punt (if they have their own equipment and the line moves up a bit). If growers get late water they will use the water rather than sit it in the dam where it will evaporate.
- **Soybeans-** early plant in January- if no rain, then fallow. Plant on rain then choose a planting configuration. Soybeans are not an option with limited water. If you start to irrigate soybeans, you need to keep going.
- Late or real early **Corn** is an option with limited water. Mid September to late October with low population corn is ok. With corn on limited water, plant 25 000

plants/ha and if irrigate returns are reasonable , but this needs a reasonable soil moisture profile. However, Sorghum is the choice because you can get quality easily with sorghum.

- Sorghum, Mung Beans, Soybeans for late cropping.
- Sorghum: the target is 6-12 plants per metre. One watering with sorghum- it is amazing what can be done- pull back to 60-65mm deficit for one watering.
- With limited water price is the driver- sorghum can achieve 3 tons and Wheat 2 tons .
- Mung Bean is an option with limited water but it is inefficient in the use of water on heavy black soil. Expected yield with irrigation is 0.7 tons, best is 0.8 tons with one water. Chick Pea is similar. The return per ML for Mung Bean is not good but when the price was $600-$800 per ton, this made the difference !

Irrigation Systems and Management

- For cotton the changes to overhead irrigation with limited water include the use of lepa socks. These direct water into the furrow, 30 mm per pass, i.e., just survival, therefore deficits are ‘through the floor’ all the time. Some success stories with 3 bales but 2.25 is acceptable.
- Farm designs have not changed with limited water.
- First irrigation is important: 50mm deficit – get off the paddock quickly then stretch out the next irrigation to 11 nodes.
- If two waterings- the first is a quick irrigation, then stretch out the next.
- Strategy: - reduce the area and look after what you have left. With sorghum it is easy, one watering and apply at flowering.
- Other Strategies: - Overhead systems: problem is deficits too low and bogging is common. There is a lot to learn. 50mm per pass should be the maximum with socks. If 30mm pass when spread over crop it is not even. Between socks spacing is about 1 m. If full irrigation is managed well, yield can be greater than 5 bales . Soil type and season influences what happens. Design of systems and how quickly water can be applied is important.
- Slope and crusting soil important. Have to be able to drain water from the field.
- Must go for max capacity now. Flood irrigators who change to overhead will level the paddock.
- Agronomic Research : With overhead systems in light country issues can’t be fixed . On box soils timing is important. Water quickly but there are flow on effects from flood irrigation and don’t know how to fix. Salt is a problem but cotton is ok . However with Cotton and Corn the irrigator must use socks because salty water cannot be sprayed over the crop.
- Scheduling Irrigation: soil moisture probes are being used. Put 4 probes in each paddock. Diviners (capacitance probes) are being used.
- For the better use of rain, fallows and cover crops are used. Irrigation with zero till is difficult to manage when growers shift from grain to cotton.
- Hills were a nightmare ! Couldn’t wet up hills. However, with stubble they wet up easily.

- With overhead irrigation growers use flat beds because level beds have drainage problems.

Consultant 3 - Graham Bolton

Key Cropping Systems Strategies

- Overland flows and bore water give some security. Water security is and issue with Cotton. Economics are very tight. The grower has to diversify to other crops such as early Corn. Plant mid-September and it finishes before Cotton. Last year (2008) Soybeans were planted as it was too late for Cotton. Growers have to look for opportunities. This consultant is dedicated to minimum till and zero till farming. However this locks out Cotton a bit. Minimum till helps to store soil water.
- Some growers are using pivots. Over- head watering is good because only half an inch is needed to get the crop up. Roundup-Ready Cotton has been a saving for water conservation. Minimum till and lateral moves have been good. More growers are expected to use them.
- This consultant uses soil moisture probes. He explained that you don't need profile full, but you don't want it to dry out either.

Strategies Within Each Crop

- Coming out of Cotton- Bollgard and pupae busting can be a problem. Growers dislike cultivating and cotton is really the only crop that has to be cultivated. Pupae busting can lose 25mm of soil water through cultivation. It also closes the soil cracks which assist in soil water penetration.
- Strategy is to minimize water use. Skip row with cotton assists. Having bore water helps. The grower has 7 to 10 days to get irrigation over the field. With bores he can stretch out water. However he must not stretch out the first watering with cotton,particularly with the new short varieties.
- Bollgard uses one or two post-plant waterings in the furrow. With overhead systems it is recommended to use 40mm irrigations and don't let the profile dry out too much. Some subsoil moisture is required.
- Corn strategies: need to water early 4-6 leaf stage if no rain. With the furrow system it is wasteful to water early just to stand the plant up.
- Cotton vs Corn: water usage is about the same. With the furrow system, solid cotton and corn, soil moisture probes are needed in both.
- Irrigated Sorghum: one watering at flowering or at boot stage yields 2 to 2.5 tons/ac. 3 to 4 tons/ac with good rainfall. Fertilizer program is important, but don't over do it.
- Populations: 50000 to 75000 for sorghum, 50000 to 60000 for irrigated corn. Yields 3 to5.5 tons. It all depends on how much water is available..
- Predominately summer crops are grown in this region. Winter Crops grown lately have not been good. However, because it has rained recently there are more Wheat and Chick Pea crops.

Irrigation Systems and Management

- Planning for overhead systems: Standing Sorghum or Corn, N fertilizer and minimum till. Growers are using guided systems, so they can offset when planting.
- Bollgard uses one or two post- plant waterings in the furrow. With overhead systems 40mm irrigations are recommended but don't let the profile dry out too much. Some sub-soil moisture is needed.
- Changing irrigation systems: For overhead systems, this consultant does not see too many topics necessary for research. Fertigation is used only to a limited degree but is more difficult with laterals than pivots . It can also possibly reduce the life of machines. There is a 5:1 reduction in labour with overhead systems.

Business Strategies

- There have been changes due to limited water. Trying to keep key staff and succession planning is important.
- Marketing skills are a problem with some growers. Some training is needed here. A trading plan is important. A share trader is needed to teach the principles.
- Buying more land and water: this has been done years ago and is not a new strategy. There has been some buying upstream and ground water purchases. Hence some water trading has been going on.
- Some clients are growing Chick Pea rather than Sorghum because there is not a big volume of grain to shift at harvest and this reduces transport costs.. Also less labour is needed.
- A lot revolves around labour now and what can be physically done. New technologies have helped to reduce labour.

Consultant 4 - Matthew Holding

Key Cropping Systems Strategies

- Greatest improvements have been with the introduction of minimum till. The goal is to have more minimum till under irrigated cotton.
- Establishment is the biggest issue with stubble cover and how to successfully irrigate.Therefore establishment in zero till is the biggest problem under irrigated conditions.
- Sequencing crops: many growers follow a Sorghum/Chick Pea/ summer fallow/winter fallow/Cotton rotation. Cotton has been 20% of farm acres over the last 5 years.
- What is the benefit of a single irrigation is the question? So if you have a good profile from stubble fallow, how much do you get from one irrigation instead of say 4 e.g., with Soybeans ?
- How well are paddocks set up for irrigation with respect to soil type ? Laser leveling, slope , length of run are important. Therefore paddock layout and establishment with zero till are key issues.
- Implements for zero till need investigation.

Strategies Within each Crop

- Planting configurations with Cotton are still an issue. Single skip nearly needs the same water as solid planted crops. ‘Super single’ is also being used, one row every 80 inch i.e., every second hill. Irrigation management in cotton water strategies still needs research. With Bollgard Cotton you need to water a little earlier. New varieties are shorter, so one can manipulate more.
- Soybeans: how can we reduce water ?
- With beds: plant into Sorghum stubble slightly to the side. There are lots of issues here still to be dealt with.
- Sorghum and Cotton with water are the main crops with some Soybeans and Corn in this consultants region.
- Two to three in-crop irrigations are applied with Cotton. Most prefer a pre-irrigation but with zero-till rain is still required to reduce the pre-plant irrigation.
- Sorghum and Wheat benefit the next crop in terms of water capture. Growers are also trying Millet as a cover crop followed by Cotton.
- Plant populations: Reduction in Corn to 4 plants / metre , also Sorghum 4 plants/metre in 1 metre rows.
- Cotton fully irrigated: growers are still using high populations due to loss from disease.

Irrigation Systems and Management

- If clients are growing Cotton there is very little irrigation in other crops. But nearly all are overwatering their crops. It is difficult to get growers to water over a 12 hour period. Most water for 24 hours. This is due to is a labour problems. Gated pipes or lay-flat, with automated shutoff would help..
- With overhead systems: the benefit is you don’t have to worry about trash. Lateral move systems are popular.
- Pupae busting has moved growers from Cotton because they don’t want to cultivate. Therefore they plant Sorghum or Corn.
- Not many are using c-probes or neutron probes. They are irrigation scheduling by crop stage. The position of probes in the crop is important. Most don’t put them in the right place. Growers need to look at what happened in the previous season.
- Evaporation rate information would be useful. A guide to mm/day would be very useful. Effective rainfall information would also be useful as would information sent to consultants such as a projection out 4-5 days.

Business Strategies

- Some growers are selling out and some are buying next door. There is amalgamation of farms.
- Growers zero- till and configure irrigation to smaller areas.
- There are a lot of lateral moves being used as they give better returns per ML. Laterals are there to be promoted, but price is an issue.
- Soil types and slopes are issues, as are issues with establishment with laterals. Channel/drainage/storage issues are still there.

- Too much fertilizer is being put on initially.
- Growers must start with a full soil moisture profile in a hot year.

Consultant 5 - Brad Tatzenko

Key Cropping Systems Strategies

- Most growers successful in Cotton and grain growing have been using Sorghum/cotton rotations and zero- till. This leaves the paddock with 2.5 inches of extra water leading to 0.5 bales/ac extra yield .Planting can be made directly into stubble.
- Growers are trying to avoid pre-irrigation.
- Disc openers are used and N is drilled into the plant row.
- Planting is offset using GPS guidance.

Strategies Within Each Crop

- 30-60 inch rows for single- skip Cotton, 40-60 inch double- skip Cotton, 40 inch for Sorghum.
- Irrigated Sorghum can yield 2.5 to 3.5 tons/ac depending on rainfall. Fleabane is controlled with Atrazine and Starain. This only possible with Roundup Ready Flex Cotton.
- With limited water, growers spread out the rows: solid 40 inch, single-skip single-row 40 inch or double-skip single-row 80 inch. With single-row 80 inch some is irrigated if there is a water opportunity i.e., overland flow from rain into a ring tank then plantings are made with no available water for irrigation.
- Cotton variety choice is critical. The determinate types are not used with limited water. Indeterminate types are used. Scheduling is difficult with limited water. Growers seem to think it is not important. The consultant puts in neutron probes and will stretch out the water, although sometimes he goes early with the irrigation. 90mm deficits for indeterminate types and 75-80mm for determinate types, measured with neutron probes.
- The variety 71BRF will be the most used variety this season (2009) on the Downs. It is a determinate variety.
- Determinates put on yield fast and can get maximum yield with stored water. If it rains there is an extra boost in yield. CSD is doing a lot of plant mapping. Node cut out number would be worth researching.
- Volumes of water used : Too much N and water is used in Corn, therefore it is not really worth growing. However, corn is good for the soil and growers like this. But the stubble is not good .
- Cotton into Sorghum stubble is improving yields. With Corn if have 3 in-crop irrigations, yield expected is 4 tons/acre.
- Growers are trying not to pre-irrigate anything. If there is 1.5 ft of water stored in the top of the profile then they go ahead and plant.
- For Cotton single-skip vs solid vs double- skip : Single-skip lasts 10 days longer than solid, saves about 2 inches of water. Double lasts 21 days longer. Skip-row is used to get water around the farm. Some growers are using a combination of

configurations, which can be changed at will. Strategies change during planting depending on the situation. Insect spraying is not an issue with different configurations.

- Wheat and Barley are generally pre-irrigated because they follow a Cotton crop. Growers have to rip soil up to 4 inches after Cotton. However, growers don't like to do this. Following harvest, growers mulch Cotton stubble and root cut, then work 4 inches deep and generally wait until August. Pupae busting is the problem, but they have to do it !
- Pre-water 1.5 to 1.75 ML/ha then plant Wheat. One irrigation is given at boot stage or the crop might fail. If there is some late water from rain, it is pumped on to the field and wheat planted- this is "opportunity cropping". Therefore, water is not lost from ring tanks through evaporation.
- Fertilizer: growers put on two-thirds initially (for N, apply 200 units if aiming for 3 bales). N application needs to be increased because yields are increasing. Most growers split the N applications. If an irrigation is coming up they side dress with the required fertilizer then irrigate. (This consultant is starting to ignore deep soil tests. He tests to 0-15, 15-60). N at depth is a bonus if they get more water, then that is a back-up.
- With Sorghum a single irrigation is applied at booting to floweing.Timing important, 1.2 to 1.3 ML is being used.
- Growers could do better with Sorghum yields. It is "hit and miss". Growers don't have a great strategy for Sorghum. It is mostly being grown for stubble.
- Barley and Wheat are not grown much because the growing season is too long. If Wheat is grown then it is generally followed with Soybeans.
- With limited water they are growing more crops because they want something in the paddock in case of rain. Cropping is "opportunity cropping" these days and long fallow is not used much. Grain price is the driver.
- Corn is fully watered. It is treated as a fully irrigated crop whereas cotton is not. Usually 2 to 3 irrigations are applied to corn.

Irrigation Systems and Management

- There are changes in irrigation application methods: Syphons have changed from 2 inches to 3 inches due to use of Irrimates. Also, 12 hour shifts are used instead of 24hour. They have changed to double 2 inch or 3 inch siphons to get to 12 hour shifts. Irrimates have created the change .However, Irrimates give tail water information, so some growers tend to run water longer!
- Most would like to change to laterals. Cost is the problem.
- Ring tanks are managed to minimize evaporation. Water is accumulated into one ring tank or into sumps. The pumping of water from bores into ring tanks in August has stopped. Water is pumped from bores into ditches then onto fields.
- Tops of peaked hills are cut off after irrigation with mesh sheets . The practice is called "meshing". This is done in dryland cropping also.
- Alternative systems: Trickle has been tried but is not satisfactory because of mice. Pigs are also a problem, as are crickets. (The consultant has only one grower with trickle- T Tape. It is too expensive to set up).
- Overhead systems: The consultant has only one grower using this with Cotton. There are still many questions to be answered. In the past with determinate

varieties, overhead systems were ok, but now with indeterminate varieties there are problems e.g., when using lepa socks. The plant will shut down (71BR and 71BRF varieties) if water is applied to one side, because it is stressed on the other side. This is a variety problem. Growers can lose 1 bale/ac because of this problem. The consultant is aiming for 5 bales/ac. Growers won’t agree that spraying directly on to the crop is not as good as using lepa socks.

- Growers would all like to change to overhead systems because of the water saving, however cost is the restriction.

Business Strategies

- Most growers have share portfolios. Some do contracting. They are not buying more land for more water. Land is too expensive and everyone is very conservative.
- All have dryland areas but these are only 10 to 15 % of the farm. Most farms can be fully irrigated. The dryland growers use irrigation for “opportunity cropping”.
- Labour costs have been reduced with overhead systems with the new varieties e.g., Roundup Ready Cotton.
- Growers get a lot of their information from neighbours and consultants and especially talking to their colleagues after church on Sundays !

Summary of Grower strategies

Key Cropping Systems Strategies

- A long term cropping plan (preferably 10 years) needs to be developed for farms.
- Having standing stubble (Sorghum preferred although Millet, Wheat and Barley are used) to help establishment and water penetration.
- A reasonably accurate measure of soil water is required.
- Bore water gives some security to supplement overland flow.
- Greatest improvements in cropping have been with the practice of minimum till.
- Sequencing crops has been a key strategy e.g., Sorghum/Chick Pea/summer fallow/winter fallow/Cotton.
- There has been a slight reduction in plant populations over the last five years.
- The introduction of GPS has improved “tram tracking” which allows accurate planting beside the stubble row. Water penetration is improved.

Strategies Within each Crop

- Growers practice “opportunity cropping”- season and commodity prices determine crops grown.
- Pre-plant watering Cotton is avoided where possible. This is a recent change.
- Skip-row Cotton (usually single-skip) is being used with limited water so the crop is spread over more land.
- Bollgard Cotton has to be managed carefully and watered when needed. Irrigation is held off until peak flower if water is really limited.
- Some growers don’t see Corn as fitting in with limited water strategies.
- Soybeans, Mung Beans, Chick Peas, Wheat and Barley are not preferred if water is really limiting. Disease can be a problem with the winter crops.
- Pupae busting following Cotton is a problem for growers who practice minimum till. It leads to soil water loss.
- Growers require more information on skip-row Cotton.
- Cotton variety choice is critical. Indeterminate types are preferred.

Irrigation Systems and Management

- Growers are reducing the length of furrow irrigation runs and reducing the application times of irrigation.
- There are issues with overhead systems: bogging near towers, cost of equipment, fertigation damage to equipment and LEPA socks have problems with the indeterminate Cotton varieties. Operators and sellers of systems need educating.

- Some growers are having success with trickle systems. Expense is an issue as are mice and other pests. However growers reported a saving in water and increase in yields.
- Ring tank evaporation still needs attention. Growers with bore water will use ring tank water first to cut down evaporation losses.
- Growers still tend to over-water their crops.
- Few growers are using probes to schedule irrigation.
- There have been changes in siphon sizes and numbers per furrow.
- Coal seam gas water is a possible future water supply.

Business Strategies

- Growers need education in marketing skills.
- Education in the principles of share trading required.
- There has been a significant reduction in farm labour. This and transport costs determines to some extent the grain crops grown e.g., one grower prefers not to grow Corn because of the volume of crop yield or would rather grow Chick Pea instead of Sorghum.
- Trying to keep key staff and succession planning is a problem.
- Cotton is generally forward sold.
- Most growers have share portfolios.
- Some growers do contracting.
- Growers obtain their information from consultants and neighbours.
- Growers consider the value of their property as an important investment. Mines are a good asset in spite of the recent controversy.
- Growers are increasing their property size by buying from neighbours.

One grower summed up the strategies to use as: ” Have a bigger area, reduce evaporation, retain stubble and grow a high value crop when you come out of a drought”.

Grower 1 - Scott Seis

Key Cropping Systems Strategies

- Trickle irrigation saves 1 ML/Ha over flood irrigation and gives an improvement in yields. However, this year (2009) there was a problem with root rot. Last year the grower achieved 4.4 bales from flood irrigation and 5 bales from trickle with 1ML saved. This year he had 4.3 bales/ac on back to back Cotton. He has 36ha of trickle irrigation on the property.
- He uses 1.5m (60 inch) rows in Cotton because the farm is mostly dryland. He grows single-skip. Under irrigation he grows 30 inch rows with Corn or Sorghum and 15 inch rows in winter crops. He uses beds with a furrow down the centre in case he needs to pre-irrigate.
- This grower fallows and tries to plant on moisture with no pre-irrigation. He likes to grow Cotton and double crop to Wheat or Barley, then fallow into Cotton. But this is not always the case.
- The cropping sequence is: Cotton/winter Barley/Corn/fallow/Cotton in dryland and flood irrigation. Last year the sequence was, Cotton/Sorghum/fallow. He root cuts, pupae busts, bed rolls. If it rains the winter crop is dryland. He keeps cultivation to a minimum.
- The grower's bore water is salty, so he uses a combination of 50/50 bore to overland flow water. A fine ground formulation of gypsum is used through the trickle tape. His current tape has had two Cotton crops and he hopes it will go on to 5 years.
- Soil water probes are used and he has found the crops are not drawing well at depth. Suspects a Cl-salt bulge at depth. He finds that the probes are especially useful in trickle irrigation.

Strategies Within Each Crop

- Irrigation strategies with Cotton: stretch out the first irrigation with flood irrigation. He splits the irrigation country in half, so he can have fallow in between crops. With flood: 2 to 3 irrigations in-crop, pre-apply all the fertilizer before planting. Under trickle, 50% N and other requirements applied before planting. Tissue analysis determines the rest and it is put on through the tape.
- Corn: under irrigation he has no real strategies. Supplementary irrigation yields 7.5 to 10 tons/ha. The aim with trickle is to apply fertilizer through the tape. Corn and winter crops are treated as rotation crops.
- Sorghum is treated as a dryland crop with probably one in-crop watering. It has produced 3 tons/ac when watered at grain fill.
- This grower has half the area in Cotton each year. Plant populations are 10 plants/m and he usually gets 9 emerging. Therefore, if he is short of water he does not have too many plants. With Corn and Sorghum he plants dryland areas as well.
- Yields: Cotton target is 4+ bales/ac, Corn 3-4 tons/ac, Sorghum 2.5 to 3 tons/ac, Barley and Wheat 1to1.5 tons/ac.

Irrigation Systems and Management

- Trickle will remain part of this grower's system. Trickle tape is on the surface and he is now using a heavier walled tape. With Bollgard Cotton, if water is limited he blends bore and dam water and stretches out the water, hence both fibre and yield are ok. Wider spacing helps with fibre length. Every second row is watered.
- The grower times his furrow irrigation for16 hours for 800m runs and limits tail water as much as possible. Every second furrow is watered and water subs across the rows. He feels that a study is needed on this as it might be better to water each furrow to get water through quicker.
- If he did not have a drip expert on hand he would have been interested in overhead irrigation systems. He thinks long term trickle has a future. There is starting to be a lot more interest in trickle (T- Tape). He would like to go to 4to4.5 inches in depth with the tape. He links the tapes with lay flat and will probably expand his drip system.
- He uses a controlled traffic system. He picks 4 rows (6m) and runs wheel track down every second one. GPS has been important with his tram tracking system.

Business Strategies

- Irrigation allows pre-selling the crop. This helps because he can guarantee production and it lessens the risk. If there is no ground water to commence the season, he puts some bore water into the ring tank, but only about half fills it to cut down evaporation. He has limited water at present (September 2009). His soil type allows for good dryland yields.
- This grower also does contract work.
- Research to be done: Fertigation needs work. Trickle is better than overheads for fertigation. It needs to be linked to tissue tests.
- Better education in reading soil moisture probes (Diviners) is needed.
- 60 inch row cotton works well for this grower. It works well within his Bollgard licences.
- Roundup-Ready Cotton over the last 2 years was good with trickle and flood. He has to watch rotations for re-growth. Atrazine and Starain on Sorghum work well. Fleabane is a major weed problem for him.
- Pupae busting is a problem and more research is needed on this. Are the pupae there ? Do we need to cultivate?
- This grower also has a piggery with 280 sows to take the grain..
- Other problems are the loss of water through evaporation and seepage and these need research . The grower estimates that he has a net 4 foot evaporation loss.

Grower 2 - Nev Walton

Key Cropping Systems Strategies

- Growers must have a 5 to10 year plan. One year is no good because e.g., this year (2008-09) ran at a loss. Due to limited water a 10 year strategy would probably be ok.
- The main issue revolves around standing stubble. In a dry season coming out of cotton nothing can be grown (average rainfall is 450mm per year on his farm). It is necessary to put in sorghum to get stubble, it turns 'hard' rain into 'soft' rain. Wheat is not a good option. Don't make decisions in Spring, wait until January. Grow stubble, spray out, then plant beside it. Wait for rain to get a yield advantage and go back to cotton. Need to be in a position that when you do get water you can capture it and go forward. Pre-irrigation is no good. Skip- row cotton is always an option e.g., single skip.
- On the Jimbour plain with 400mm of rain you won't do any good. 550mm will produce a stream flow. There is no stream flow with less than 540mm of rain.
- How does a farm survive 10 years ? That is the study needed. Farmers need to know how they are to be farming in 10 years time !!
- To see how to manage the drought look at a dryland farm !

Strategies Within Each Crop

- This grower had Soybeans about 10 years ago.
- Corn sets its potential in the first 6 weeks. Do not stress it in the first six weeks as it will take the top off the yield. 80 to100mm irrigation deficits are used.
- Winter crop is not an option as diseases are a problem. The year before last he planted wheat but with a diseasedncrop produced 1 ton instead of 1.5 tons. He had to spray Tilt.
- With Corn , logistics are a problem, unless sales are local. It is a ' nightmare' at harvest, because of the volume grown.
- N and Cotton: Do a soil test, put on at the last working or close to planting and you get more out of the N. Split application in December. Urea probably the best. After fallow with wheat use 90 kilos of N. If following corn, use 200 kilos of urea. If side dressing use half rate. In total 200 kilos of urea is needed. He is now trying other forms of N- grow the N e.g., Vetch.

Irrigation Systems and Management

- Plant on rain, apply N, use a determinate variety of Cotton. Four irrigations only, will give best return per ML. With new varieties expect 4.2 to 4.3 bales to be produced, all on long fallow.
- Seven days pumping is the average for 7 years in 10. Probably down to 5.2 days now i.e., 20% cut due to weather and that is 6 years in 10.
- Irrigations: When to irrigate depends on rainfall. Usually rain starts in November and cotton does not start using water until the second week in December. Side dress fertilizer, insert soil moisture probes (consultant reads them). The grower has 8 days to get around the watering to flower 6 nodes from the top. Work on

smaller deficits and finish quickly. The determinate varieties need to be irrigated as needed. Cluster grub infestations make the season go a bit longer.

- This year all the farm will be cotton. Next year the decision will be single skip cotton or soybean (if no rain), then sorghum for stubble.
- Everything depends on the budget. The consultant runs the “Ham” program processing the numbers to produce the budget. Results are sent monthly.
- Options are soybeans, corn, sorghum, single skip cotton. It is important to have a good budget for all the crops you are capable of growing. The budget needs constantly updating.
- The grower gets an aerial photo taken each year. Mapping equipment is installed in the picker to produce yield maps. Soil on the property is classified into 7 types. He has had an EM survey done. He also has a fertilizer sampling site to show trends. Sap tests are also carried out. Soil moisture probes are put in key sites which helps in field sequencing. Probes give information so irrigation can start early. It takes 8 days to get around the crop.
- Changes : Bigger syphons being used. Water through in 10 hours is the goal. It takes half an hour for a syphon to get through. About 1 ML is used per irrigation event. If it rains it will be a bit less.
- Alternate Systems: Trickle is too expensive. Pivots and laterals: investing in these and might only irrigate part of the property, therefore only putting half to two thirds of water through it. Looking at it with a neighbour as a long term thing. He has water only 4 years in 10 and therefore the machine will not pay for itself. Bogging is a problem, levelling to drain the land is an issue.
- If he is to grow Wheat or Chick Peas the figures will have to be looked at.
- Coal seam gas: this water is a possibility to be available. Water quality will be an issue. It can burn the plant, damage equipment and soil. But 400 to 800 ppm salt has been quoted and this would be ok. There is an RO (reverse osmosis) plant near the grower’s property.
- Evaporation: The grower has two storage cells, 640 ML and 500ML. He siphons over then back. Evaporation is very high so he has experimented to reduce evapaporation loss using “Aquatain”. The loss has been reduced by 50% on a small water holding tank.

Business Strategies

- Value of the property important. What is the return from an asset ? He looks at the best farm on the Jimbour plain and asks what is the return from the asset? What is the real estate value of the land? Need a business strategy to determine how to minimize a backward step over a period of time? The near-by mines are a good asset in spite of what people say. He could make a 50% gain in the asset with a mine .
- Other strategies: Need more area that you don’t have to irrigate. Single-skip is the best way to go. Need to rent land so the business is not land limited. But leasing land leads to a few issues, such as, what happens if leased land is sold? Leasing is a way to go forward as economics get tighter. Need long term leases.
- Bigger area, reduce evaporation, stubble, grow high value crop when one comes out of a drought. These are the strategies to use.

Grower 3 - Andrew Bartley

Key Cropping Systems Strategies

- Changes over the last 5 years: plant populations reduced slightly, sorghum reduced from 4 kg to 2.5 kg per ha. Cotton in 60inch rows and sorghum in 30 inch rows.
- "Tram Tracking" being used is the biggest change. 40 ft equipment has been standardized. GPS is used. The benefit is compaction reduction and better water penetration.
- Grower has not adopted a structured rotation. This depends on commodity prices and water availability. Cotton has not been grown lately because of the price reduction and lack of water.
- The grower uses push probes to determine profile water depth i.e., "gut feeling" is used.

Strategies Within Each Crop

- Main crops are Cotton and Sorghum. Grower has moved from winter crops.
- Reduced tilling used in the last 10 years . The grower doesn't have a reduced till wheat planter.
- Long fallow is used. Irrigation is handled the same as for raingrown crops.
- Cotton: Bollgard varieties are used.
- Sequence is: cotton/winter fallow/summer fallow/wheat/summer fallow/winter fallow/cotton or sorghum.
- Thoughts on drip: He is replacing the system . If water is available he would would use a lateral move system, because the infra structure is there. T- Tape would be replaced with an overhead system.
- Irrigation is not a large part of the grower's operation. He has 3500 acres of raingrown crops and plants Cotton if water is sufficient. Plant populations are reduced and grass is controlled with Roundup.
- For Sorghum, stored water is needed to plant. It is usually less than 3 ft deep in the profile. The acreage planted is reduced if conditions are dry. If planted on 1.5 ft of profile water he can produce 1.5 tons. Zero till increases yields. He works on yields of 2 tons/acre sorghum or 1.5 for wheat.
- Irrigated Cotton yields 3 to 3.5 bales/ac irrigated, wheat probably 2 to 2.5 tons/ac.

Irrigation Systems and Management

- The grower has 500 acres of drip irrigation (T-Tape) on the farm. This is supplied with bores. He uses rain to get the crop up. Cotton is successful under this system. It is a permanent system and has been in for 18 years. However tape lines are too long and there has been a worry about getting water to the end of the line. Tape is placed every 60 inches and over 500m long, 18 inches deep. The pipe is one and one eighth inch. There have been problems with mice damage. He did well using dam water and high pressure.- 3.5 bales yield on 60inch cotton . Low population rates are planted. Water used was 250ML on 120 ha i.e., 2ML/ha (if surface irrigating 4 to 5 ML would be used).

- Strategy: no probes are used. Timing is based on the stage of the crop. The grower said that he is not really a serious irrigator. He is trying not to use bores as there are some problems with water quality.
- Tram Tracking gives a better strike. He can plant on less moisture and plants alongside plant lines. He can offset by “nudging” across a bit but a guidance system is needed. A zero till planter is used and he uses a 120 ft sprayer.
- He has a ‘weed seeker’ and can manage fleabane with it. 24D and Roundup works well. Dicamba is also used. He is trying to reduce operations.

Business Strategies

- With limited water, zero till is used as much as possible. Have to manage crop conservatively with limited water. Plant a ground cover crop and spray out. He said a neighbour plants French Millet for cover.
- For Dryland: Chick Peas and Mung Beans are treated similarly to Cotton. Chick peas dry the ground out because of its deep tap root. It takes moisture from depth. Chick pea yields just over a ton in wet years and Mung Beans 0.3 to 0.5 tons.
- Mung Beans are an opportunity crop- late plant in summer (Feb). Some powdery mildew occurs but is not a big problem (variety grown recently was Crystal).
- About one eighth of the grower’s farm is irrigated.
- The grower has a track harvester being made in Germany and is due in September.
- In future he will be retaining sorghum stubble (this also reduces sand blasting of an emerging crop).
- Planting into sorghum stubble is an issue. Some growers still burn . Another issue he has is applying fertilizer .
- Hills, beds : the grower has more hills than beds. How to wet these up is an issue. Also wheel tracks and stubble result in watering problems. Much controlled trafficking is being used.

Grower 4 - Stuart Armitage

Key Cropping Systems Strategies

- Solid Cotton is grown, followed by fallow for two years to get a full profile. The grower crops half tor 40% of the farm. From Cotton he fallows a summer and two winters then it is back to Cotton.
- Some Sorghum is grown for use as a stubble cover. At $300 per ton and average rainfall it is profitable. Present stubble on the farm (September 2009) is two years old. He says that he is " land rich" and "water poor" and most farms are.
- This grower tries not to grow other crops besides Cotton.
- Labour is a significant issue as he is on his own.

Strategies Within each Crop

- Cotton is grown on 40inch rows, solid and fully irrigated. This grower is trying some on 80 inch rows with a single irrigation only. He mainly uses bores for water.
- He does 3 irrigations for solid planted Cotton and one irrigation for skip-row (prior to flower, 0.4ML / ac (1 ML/ha). The first irrigation is timed for prior to first flower.
- The grower tries not to pre-irrigate, but if needed, 0.2ML is applied. He needs 1 to 1.5 inches of rainfall to plant. Stubble is a big help as it holds the water. He uses 8 to 12 hour shifts. Roundup-Ready Flex is the variety used. He said that Bollgard is so different to past varieties.
- He usually plants and waters up, depending on rainfall. He does not use soil moisture probes (because he said that you get false readings if you receive rain). He pays consultants for nutrient and watering advice.
- Varieties 70 and 71 BRF are big yielders for single-skip cotton (which is one row out and two rows in). He usually does two waterings in drought with 80 inch rows. Usually only one watering and three for solid planting.
- Cotton is his key crop because of the returns. He has 160 to 200 ha of Cotton per year. This grower has 500ml of water available (that is his ground water licence). Quality and availability of water is good. He has had 100 to 150 ML from overland flows over the past five years but reliability is poor.
- Cotton target yields are: single-skip, 2 waterings- 3.5 to 4 bales/ac, solid , 3 waterings- 4.5 to 5 bales/ac, dryland 80 inch no water- 2 bales/ac- if long fallow.
- Nutrition: The grower uses sewage sludge. He uses 60 tons/ac at approximately $2 to $3 per ton. This has 6% N. Phosphate is high, but potash is lacking. Zinc etc are good. One application lasts 2 to 3 years. One application of sewage will produce 3 crops of Cotton., and no other fertilizer is required. He replaces the nutrients the crop takes out. Soil tests are used.
- Sorghum: dryland mostly 40 inch rows, yields 2.5 tons/ac
- Soybeans: irrigated 40 inch rows- needs more water than Cotton, yields 1.2 to 1.4 tons/ac.

- Wheat and Chick Pea: used to even up paddocks. Wheat is used to provide stubble for Cotton and will have Roundup applied if the crop is poor.
- Millet is also used to provide stubble- he is trialling this. White French is the variety used.

Irrigation Systems and Management

- Alternative Irrigation Systems: This grower does not think there is an alternative. Although centre pivot systems might be, but not laterals. Laterals can't keep up the water and maintenance costs are high. The grower said that he needs information on laterals which are are probably satisfactory for winter crops but not for Cotton.
- He uses 10 to 12 hour shifts and short runs (less than 500 metres). This is cost effective.

Business Strategies

- Buying more water: If neighbours do not use their full allocation they will sell ($160 per ML for the water, $60 for pumping).
- The grower pre-sells the Cotton. It is good business to have adequate water. If solid planted Cotton is grown properly, it produces good yields and quality. Full water allocations can be carried over 3 years.
- His strategy is to use the dam first if it has water. This saves losing water through evaporation. If the dam is full he will water a winter crop to produce stubble and he has the equipment to handle the stubble.
- His water allocation is 60% this year (2009) but it might go back to 50 %. DERM reads the water meters about 3 times per year.

Grower 5 - Neil Pfeffer

Key Cropping Systems Strategies

- It comes down to the question, what is the risk you want to take?. For the last 4 years the grower has planted on rain with no water in storage. He had to do a lot with little water and said he pushed the envelope a bit far. Now (September 2009) he has water in the ground and it is a long time since that has happened.
- He does a water budget: 2 in-crop waterings for Cotton gives a profitable yield. One crop watering for Sorghum, but Cotton usually gets preference. He does a minimum 2 ML/ha in- crop watering with cotton.
- Pre- plant water: 1.4 ML/ha, 2 in-crop waterings of 2ML/ha to average 4 bales/ac. 1 m row spacing is used. He always plants solid . If he thinks he might skip he grows Sorghum or other grains instead of Cotton. With Bollgard cotton, he is tending to planting on rain. With Bollgard Roundup-Ready, he will water following planting to emerge the crop (‘watering up’).
- Some of the grower’s land has not been cultivated for 3 years. He zero-tills dryland areas GPS equipment has helped with tracking.
- He shreds the stubble: Following harvest, Cotton is shredded and ground is gassed at first working, then he might put in opportunity Wheat.
- This grower has shifted from having back to back Cotton, because of Fusarium Wilt and the grain prices have been good.. He will put in some Sorghum and Corn after Cotton. Sometimes he will fallow from Wheat then will go to Cotton. He plants a crop in most years and does not fallow very much.
- Direct drilling Soybeans into standing Wheat stubble works well on 2 m beds.

Strategies Within Each Crop

- Cotton/Wheat/Sorghum/Corn on one paddock. Average yield of Cotton is getting better each year, probably because of varieties, 4.3 bales average.
- Yields are :8 tons/ha Sorghum, 10 tons/ha Corn, with 2 to 3 in-crop irrigations. Soybeans 3.5 tons/ha. This was with an older variety with 3 in-crop irrigations. This is good at $700 per ton, but price is falling.
- Irrigated Wheat planted on rain yielded approximately 5 tons/ha. He waits until flowering to irrigate if possible. He waters when still in the boot stage, but considers it best when showing a few heads.

Irrigation Systems and Management

- Irrigation practice with Bollgard Cotton: delay the first irrigation if ample water is available. 80mm applied in the first irrigation. He usually needs to get water on early. He sees this as a change with Cotton. He uses soil probes on 2 or 3 fields.
- Irrigation on other crops: Sorghum, one irrigation This year (2009) he irrigated late as the soil profile was well filled, but he said that he should have irrigated early. It depends on cropping history what is done. Fallow ground will hold the crop longer.
- Most runs are 600m. He uses yield monitors in the header.

- Alternate systems: With lateral moves a study showed that it would take 7 years to pay off the equipment, therefore he didn't proceed with purchasing. However, he thinks that maybe he should have. This study needs to be repeated.
- The grower said he is watering quicker for shorter durations by stacking up siphons. He generally uses a 24 hour cycle. He said that he is managing water better and has learnt when crops best respond to water.
- Key things with storage management is stopping evaporation. Covers would be good if possible. He has 3 cells, two full and one empty. He doesn't think he can do more here and said his distribution network is good. It costs $10/ML to pump out of storages. That is for one lift. Water costs need to be worked on $/ML and returns/crop.
- Coal seam water was discussed: If you have to pay $300/ML it would not be economical for broadacre crops but probably satisfactory for vegetables.
- Reduced till is an important part of his operation. GPS has improved operations on dryland areas, as has controlled trafficking.

Further Reading & Tools

-crop water use

-web based ?

Appendix VI

Crop water use, water extraction distribution, crop development, lint yield and quality of cotton grown under four irrigation regimes in Queensland

Jose O. Payero[1], Geoff Robinson[1] and Graham Harris[1]

[1] **Agri-Science Queensland, Department of Employment, Economic Development & Innovation, www.deedi.qld.gov.au Email jose.payero@deedi.qld.gov.au**

Abstract

Water scarcity is the main limiting factor in cotton (Gossypium hirsutum L.) production in Australia. Therefore, sustaining or even increasing productivity and profitability with limited water resources is one of the biggest challenges facing the cotton industry. The objective of this study was to evaluate the evapotranspiration (ETc) water extraction distribution, crop development, lint yield and quality of Bollgard II cotton grown under different irrigation regimes. A field experiment with four irrigation treatments and three replications was conducted at Kingsthope, Queensland, during the 2007-08 season. It was found that the seasonal potential evapotranspiration (ETp) was about 750 mm. Cumulative daily ETp increased linearly from sowing to 60 days after sowing (DAS) at 2.4 mm d^{-1} and at 5.29 mm d^{-1} after that. All treatments received some stress, which affected ETc, resulting in seasonal ETc of 417 to 628 mm (56 to 84% of ETp). A computer model based on the FAO-56 procedure estimated the seasonal ETc of all treatments to within 3% compared with a seasonal water balance estimate. The crop extracted soil water from as deep as 150 cm, but about 80% of the seasonal extraction was from the top 60 cm and 90% from the top 80 cm. Also, from about 32 DAS to 100 DAS, the depth of soil water extraction increased almost linearly at a rate of 1.89 cm d^{-1} or 2.36 times the crop canopy height. Irrigation affected crop development, for example, daily accumulation in above-ground dry biomass was linearly related to daily cumulative ETc (11.28 g m^{-2} mm^{-1}) and to cumulative transpiration (12.08 g m^{-2} mm^{-1}). Crop stress affected reproductive development and lint quality, but did not affect lint yield. Severe stress caused the crop to stop producing bolls, while the mildly stressed plants kept producing bolls until the end of the season. Bolls produced late in the season did not develop and mature properly. Crop stress and delay in crop maturity significantly affected lint quality. Several indicators of lint quality, including micronaire, were linearly related to seasonal ETc.

Keywords: Cotton, evapotranspiration, dry biomass, soil water, lint quality

Introduction

Water scarcity is the main limiting factor in cotton (*Gossypium hirsutum L.*) production in Australia. Therefore, sustaining or even increasing productivity and profitability with limited water resources is one of the biggest challenges facing the cotton industry. This requires increasing the beneficial use of water, which is producing more crop quantity and quality with the same amount or even less water. Some workers refer to this concept as to increase crop water productivity. According to (Ali and Talukder, 2008), increasing crop water productivity (CWP) requires increasing transpiration while minimising unwanted water losses, exchanging transpired water for CO_2 more efficiently in producing crop biomass, and converting more of the produced biomass into harvestable yield. They also suggested that to improve CWP, the most promising and efficient proven techniques were limited supplemental irrigation for optimizing the use of limited water, and water harvesting to improve farm income in drier environments. Improving the beneficial use of water requires improving water management at different scales, including the basin, the farm and the field. At the field scale, one of the important issues includes knowing how much water to apply and when to apply it. If water is limited, then it is important to know the impact of crop stress at different times during the season, so that irrigation is applied when benefits to the crop are maximized and/or negative impacts are minimized.

Another important aspect to water management is its impact on crop quality, which can affect profitability. According to (Bange and Constable, 2006), fibre quality issues affecting the Australian cotton industry include maintaining fibre length, prevalence of high micronaire, and perception of high levels of neps. These quality issues translate into significant economic losses for Australian producers due to price discount for sub-standard fibre quality. Fibre quality is determined by a variety of factors, including crop variety, environmental factors, crop management practices, etc. Other factors include disease and insect damage, sowing date, harvest timing, timing of defoliation, crop nutrition and ginning procedures. Fibre length is determined during the period from flowering until about twenty days after flowering. During this stage, water stress is the critical factor affecting fibre length. They reported good positive correlation (R^2 = 0.66-0.96) between micronaire and average daily temperature during boll filling at three different sites. (Yeates et al., 2009) found that water stress significantly affected fibre quality parameters over two seasons. Parameters affected included fibre length, strength and micronaire. They found that micronaire increased with water stress, which they suggested was due to high boll loads as water availability increased.

To be able to properly manage water under limited water situation, it is therefore important to know how much water the crop needs at different times during the season and how crops subjected to different irrigation regimes respond in terms of growth, reproductive development, water extraction patter, yield and yield quality. The objective of this study was to evaluate the evapotranspiration (ETc), water extraction distribution, crop development, lint yield and quality of Bollgard II cotton grown under different irrigation regimes in a sub-tropical climate.

Methods

Site description

For this study, a field experiment was conducted during the 2007-08 cotton season at the Agri-Science Queensland, Department of Employment, Economic Development & Innovation (DEEDI) Kingsthorpe research station. The station is located in a sub-tropical climatic zone, about 20 km north-west of the city of Toowoomba, Queensland, Australia (27°30’44.5” Latitude South, 151°46’54.5” Longitude East, 431 m above mean sea level). The soil at the site is a haplic, self-mulching, black, vertisol. It has a heavy clay texture in the 1.5 m root zone profile, with a distinct change in soil colour from brownish black (10YR22) in the top 90 cm to dark brown (7.5YR33) deeper in the profile. The soil is of alluvial fan and basalt rock origin, slowly permeable, with a surface slope of about 0.5%. Physical and chemical characteristics of the soil profile are shown in Table 1. Bore water was used for irrigation. Results of quality analysis of the bore water (Table 2) shows that the water was of salinity class 3, which is only suitable for irrigating medium to high salt tolerant crops. Poor irrigation water quality is typical of bore water on the Darling Downs area.

Table 1. Soil properties at Kingsthorpe, Australia (data provided by Jenney Foley).

Depth	pH	EC	BD	Cl	N	P	SO_4-S	Ca	Mg	Na	K	CEC	ADMC	C. Sand	F. Sand	Silt	Clay
(m)		(mS/cm)	(g cm^{-3})	mg/kg				meq/100g					%				
0-0.1	7.3	0.239	0.89	92	28	110	24	36	30	1.5	1.8	71	13.1	< 1	8	17	76
0.1-0.2	7.2	0.416	1.03	183	86	77	35										
0.2-0.3	7.5	0.345	1.02	153	61	25	29										
0.3-0.4	7.9	0.348	1.03	126	49	19	27										
0.4-0.5	8.1	0.355	1.03	118	39	32	24	36	31	2.2	0.71	71	13.8	< 1	7	18	76
0.5-0.6	8.2	0.349	1.05	104	36	40	23										
0.6-0.7	8.3	0.334	1.05	104	34	45	20	32	31	2.5	0.83	65	13	2	8	19	72
0.7-0.8	8.5	0.320	1.01	99	28	49	17										
0.8-0.9	8.5	0.314	1.02	110	24	46	16										
0.9-1.0	8.5	0.363	1.06	97	25	41	15										
1.0-1.1	8.6	0.308	1.07	76	21	43	14	28	29	3.4	0.88	56	12.8	2	10	17	73
1.1-1.2	8.6	0.336	1.08	78	18	35	16										
1.2-1.5	8.6	0.401	1.08	78	19	36	18	28	31	4.5	1.2	58	13.1	3	7	17	73

Table 2. Results of water quality analysis from bore water sample collected at Kingsthorpe during March 2009.

Analysis	Result	Units
pH	8.1	pH units
Electrical Conductivity	2048	µS/cm
Total dissolved ions	1311	mg/L
Bicarbonate Alkalinity	277.5	mg $CaCO_3$/L
Total Alkalinity	281	mg $CaCO_3$/L
Total Hardness	691	mg $CaCO_3$/L
Sodium Absorption Ratio	1.2	
Calcium	102	mg/L
Magnesium	110	mg/L
Sodium	75	mg/L
Phosphorus	<1	mg/L
Potassium	11	mg/L
Sulphur	40	mg/L
Aluminium	<0.1	mg/L
Zinc	<0.01	mg/L
Iron	<0.01	mg/L
Copper	<0.01	mg/L
Manganese	<0.01	mg/L
Boron	0.05	mg/L
Molybdenum	0.05	mg/L
Salt from Chloride	747	mg/L
Chloride	452	mg/L
Corrected SAR	1.6	
Effective Conductivity	1540	µS/cm
Residual Alkali	<0.01	meq/L

Experimental design

The cotton experiment was conducted using four irrigation treatments and three replications arranged in a randomized complete block design. Each experimental plot was 13 m wide x 20 m long, with the crop planted in the North-South direction. A 4-m border was allowed between plots and a 4 m road was located at the centre of the research area. A refuge crop (6 rows) was planted at the East and West sides of the plots. The plots were irrigated individually with bore water using a sprinkler system. The irrigation treatments included:

1. Fully-irrigated (T50%). Irrigation applied when 50% of the plant available water capacity (PAWC) was depleted.
2. Deficit-irrigated 1 (T60%). Irrigation applied when 60% of the PAWC was depleted.
3. Deficit-irrigated 2 (T70%). Irrigation applied when 70% of the PAWC was depleted.
4. Deficit-irrigated 3 (T85%). Irrigation applied when 85% of the PAWC was depleted.

A concurrent experiment was also conducted to compare water extraction pattern and crop development of single-skip and solid row configurations. For this experiment, each plot for the T85% treatments was divided into two. Half of the plot was kept as a solid row configuration and in the other half a single-skip configuration was established by eliminating some of the crop rows. The experimental plot layout and row configurations are shown in Figure 1 and Figure 2, respectively.

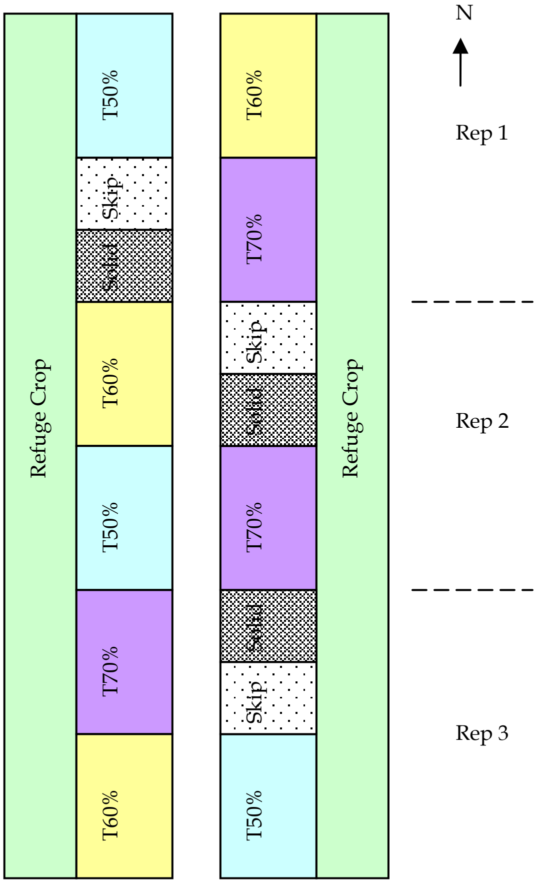


Figure 1. Field experimental layout at Kingsthorpe. The T85% treatment was split into "Solid" and "Skip" row configurations.

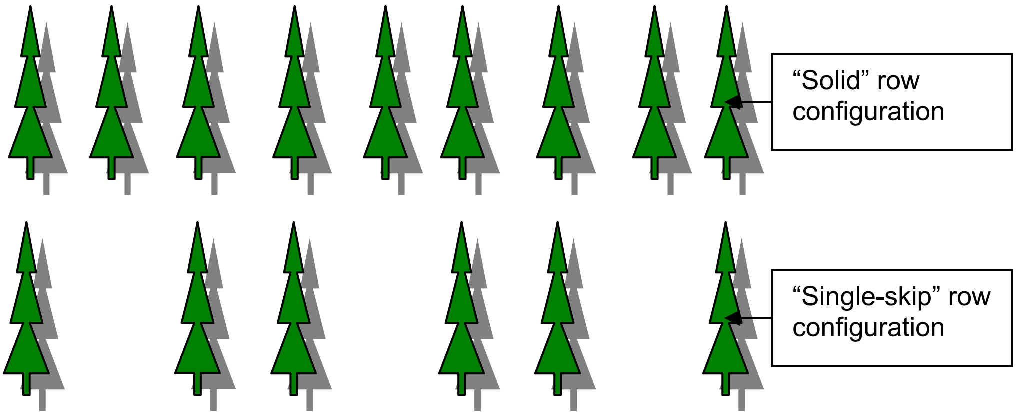


Figure 2. "Solid" and "Single-skip" row configurations.

Sowing

In 2007-08 cotton was planted on 12 November 2007 after the soil received several small rainfall events during the previous week. The crop was planted within the Bollgard® II cotton planting window for the Darling Downs, which was from 15 October to 26 November (variation granted) and 1 December (under permit).

Late sowing can significantly reduce yields due to excessive vegetative growth promoted by higher than normal temperatures early in the season. It can also impact yield due to an increased risk of insect attacks, such as silverleaf whitefly and aphids, late in the season. Fibre quality can also be impacted due to immature fibre and difficult defoliation and picking in cooler and/or wetter conditions. Because of the late planting, selecting a short or medium maturity variety was important to complete fibre maturity and boll opening before first frost.

In 2007-08, the cotton hybrid Sicala 60 BRF, which is a Bollgard® II Roundup Ready Flex® variety, was planted. Six rows of the conventional (non-Bollgard) variety Sicot 43 RRF were planted as the refuge crop on each of the two long sides of the experimental block. Sicala 60 BRF is classified as a medium maturity variety with very good yield potential for late planting, excellent fibre quality characteristics, and a long and strong fibre with mid range micronaire (Cotton Seed Distributors, 2007)

Seeds were planted at about a density of 17 seeds/m, a depth of 4 cm and a row spacing of 1 m. The aim was to get an established stand of 11-12 plants/m, which is the recommended density for Bollgard II varieties, which is higher than the 5-10 plant/m recommended for conventional varieties. The seeds were rated at a germination rate of at least 70% and were coated with the “Peridiam” seed treatment that included protection with fungicide and insecticide.

Fertilizer application

Starter fertilizer (10.5% N-19.5%P- 0%K-2.2%S) and granular Urea (46% N) were applied with the seed at sowing. A total of 120 kg of starter and 80 kg of Urea were applied in the experimental area (including the refuge area), which had a total area of 0.64 ha. Therefore, the fertilizer rate was 188 kg/ha starter (20 kg N/ha), and 126 kg/ha Urea (58 kg N/ha), for a total of 78 kg N/ha. An additional 87 kg N/ha (190 kg/ha of Urea) was applied on 18/1/2008, for a total seasonal nitrogen application of 165 kg N/ha.

Weed Control

Problem weeds during the experiment were mainly of two species, Dwarf amaranth (*Amaranthus macrocarpus*) and Tarvine (*Boerhavia dominii*), which were controlled by a combination of manual chipping (3/12/2007), mechanical cultivation (9/1/2008), and a chemical control of 1 kg/ha of Roundup (15/1/2008).

Insect control

Although they did not reach the economic threshold, several insect species were present during the study. These include the Black sunflower scarab (*Pseudoheteronyx basicollis*) during the emergence stage, the sucking insect Pale Cotton Stainer (*Dysdercus sidae*) during the boll development stage, and the Cotton Harlequin Bug (*Tectocoris diophthalmus*), at squaring, flowering and boll development stages. The insecticide Decis (deltamethrin) was applied on 15 March 2008 at a dose of 200 mL/ha to control the Pale Cotton Stainer and avoid its negative impact on fibre quality.

Irrigation

The plots were irrigated individually with bore water using a hand-shift sprinkler system (Figure 3). Partial-circle sprinkler heads were used to avoid irrigating adjacent plots. Irrigations were applied during times with low wind speeds, to assure good application uniformity. Irrigation depths were measured using a rain gauge installed at the centre of each plot. Irrigations were scheduled based on neutron probe soil water content measurements.

Figure 3. Irrigation system used in 2007-08 at Kingsthorpe.

Defoliation

The crop was defoliated when it reached 4 nodes above cracked boll (NACB). NACB measurements were taken on 4 April (all treatments), 14 April (for T85% only), 22 April (for T85% only), 28 April (all treatments), and 7 May 2008 (for T50% only). Defoliant was applied on 29-30 April 2008 to all treatments, except the T50% treatment. The defoliant consisted of 20 mL Dropp Ultra + 50 mL Canopy Oil + 50 mL Sticker Spreader mixed in 15 L of water. The defoliant was applied with a single nozzle knapsack to the yield sampling area. Because of delay in maturity of the T50% treatment, defoliant to this treatment was applied on 7 May, 2008. A second defoliant application to the T50% treatment was applied on 15 May 2008. One dose was sufficient to defoliate the other treatments.

Harvest and pupae busting

A hand-harvested sample from each plot was taken to determine crop yield. All treatments, except T50%, were harvested on 12-14 May, 2008. The T50% treatment was harvested on 22 May 2008. After cotton harvest, the soil moisture monitoring equipment and the irrigation system were removed from the site (23 May 2008). A frail mower with catcher on the back was used to cut the remaining crop and remove the residue from the field. The soil was then tilled twice (27 and 28 May 2008) to comply with pupae busting requirements and to prepare the soil for the winter crop (wheat).

Measurements

Soil moisture monitoring

Soil moisture was manually measured using the neutron probe method and was continuously recorded using capacitance probes (EnvironScan).

<u>Neutron Probe</u>: A neutron access tubes was installed in each plot. Also, for the row configuration comparison, six neutron tubes were installed in each T85% plot, with three in the solid configuration and three in the single-skip configuration. The three tubes were installed in a row at 0.5 m spacing, two in the plant line (P1 and P3) and one in the middle of the furrow (P2) (Figure 4 and Figure 5).

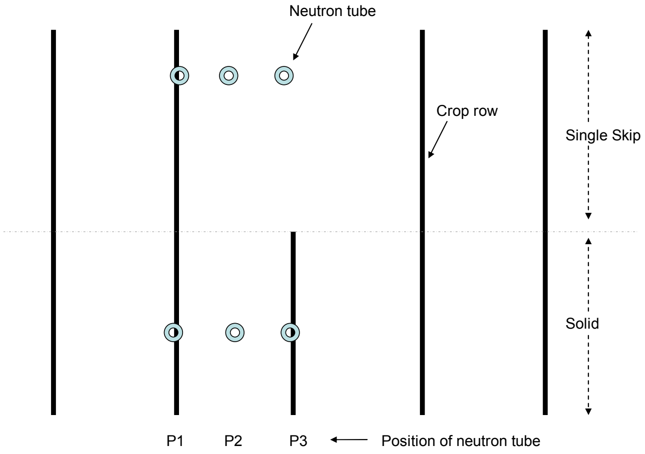


Figure 4. Positions of neutron tubes in the solid and single skip cotton row configurations compared at Kingsthorpe during 2007-08.

Figure 5. Solid and Skip row configurations compared at Kingsthorpe during 2007-08.

Neutron readings were taken at least weekly at 0.10 m depth increments to a depth of 1.5 m. Measurements were taken with a 503DR Hydroprobe (CPN International, Inc., Martinez, CA, USA), using integration periods of 16 seconds for normal counts and 240 seconds for standard counts. Standard counts were taken from air with the neutron source inside the shield and with the neutron probe mounted on an access tube standing 1 m above ground. Standard counts were also taken on water by lowering the neutron source on an access tube installed in the middle of a water drum (≈ 200 L) (Figure 6).

Figure 6. Taking neutron probe water standard count reading.

The neutron probe was calibrated against soil water contents determined using the gravimetric method. For this, soil cores to 1.5 m depth were taken from each treatment. The cores were divided into 10 cm depth increments, which were used to determine soil water content and bulk density (BD). The resulting profile BD and the calibration equation for the neutron probe are shown in Figure 7 and Figure 8.

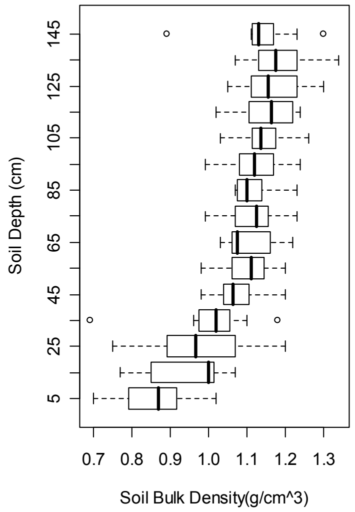


Figure 7. Soil bulk density at Kingsthorpe, obtained from samples taken on 8/5/2009.

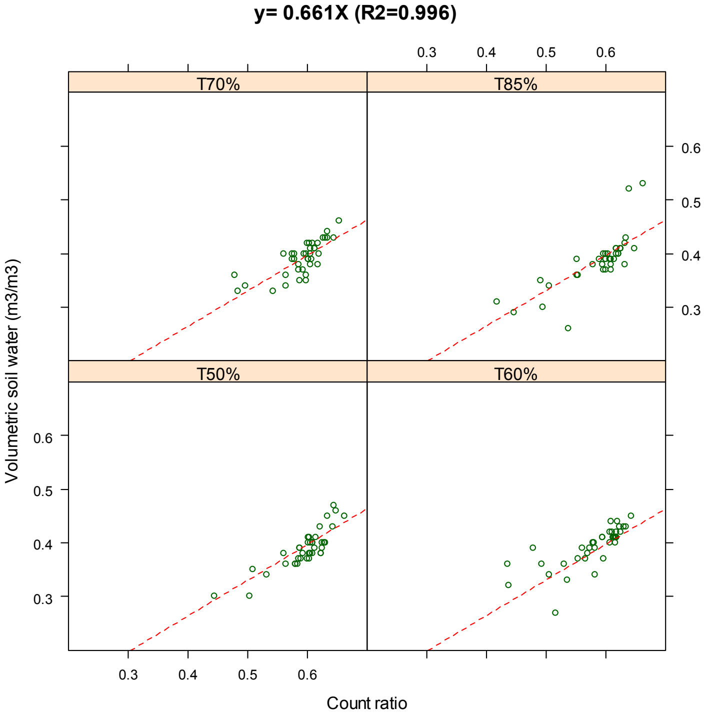


Figure 8. Relationship between count ratio and volumetric soil water content by irrigation treatment (T50%-T85%) for soil at Kingsthorpe. Soil water was determined from soil samples taken from different depths on 8/5/2009. The count ratio was calculated with respect to the water standard counts. The dotted line is the regression line (intercept = 0).

The neutron probe data obtained at the start and end of season were used to estimate the seasonal crop evapotranspiration using a water balance approach as:

$$\mathrm{ETc} = (\mathrm{P} + \mathrm{I} + \mathrm{U}) - (\mathrm{R} + \mathrm{D} + \Delta \mathrm{S}) \qquad \textbf{(1)}$$

where, ETc = crop evapotranspiration (mm), P = precipitation (mm), I = irrigation (mm), U = capillary rise (mm), R = runoff (mm), D = deep drainage (mm) and ΔS = change in profile soil water (mm). In this study, U, R, and D were assumed to be negligible.

Capacitance probes: Soil water was also monitored using capacitance probes (Figure 9). An EnviroScan® *Solo* (Sentek sensor technologies, Stepney, South Australia) was installed in one replication of each treatment (Rep 2). Each unit measured soil water every 30 minutes at twelve soil depths, including 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7,0.8, 0.9,1.0, 1.2, and 1.5 m. The EnviroScan® manufacturer indicates that a single sensor records moisture data from a soil volume outside the access tube with a sphere of influence of 10 cm vertical height and a radial distance from the outer wall of the access tube of 10 cm.

Figure 9. EnvironScan probes used to measure soil water at Kingsthorpe.

Each sensor of each probe was normalized by taking raw counts (RC) readings with the probe in the PVC access tube while suspended in air (air count) and in a water bath or normalization container (water count). Sample air and water counts obtained are shown in **Error! Not a valid bookmark self-reference.**.

Table 3. Example of readings in air and water obtained during the EnviroScan® *Solo* probe normalization.

Depth (cm)	Air Count	Water Count
20	36797	26285
40	36661	26242
60	37463	26712
80	37269	26434
100	36686	26318
120	36758	26301

The raw soil counts from each sensor were converted to volumetric soil water contents as (Sentek Sensor Technologies, 2001):

$$\mathrm{SF} = \frac{(\mathrm{Fa} - \mathrm{Fs})}{(\mathrm{Fa} - \mathrm{Fw})} \tag{2}$$

$$\mathrm{SF} = \mathrm{A}\theta_{\mathrm{v}}^{\mathrm{B}} + \mathrm{C} \tag{3}$$

$$\theta_{\mathrm{v}} = \left(\frac{\mathrm{SF} - \mathrm{C}}{\mathrm{A}}\right)^{\frac{1}{\mathrm{B}}} \tag{4}$$

Where, θ_v = volumetric soil water content ($m^3\ m^{-3}$), SF = scaled frequencies, Fa = air count, Fs = soil count, Fw = water count. SF, Fa, Fs, and Fw are all unitless and A, B, and C are empirical factors that depend on soil type. We used values of A = 0.0254, B = 1.00, and C = 0.011, recommended by the manufacturer for soils similar to the soil at the research site.

The EnvironScan data was used to evaluate and quantify the fraction soil water extraction from the different soil depths as a function of DAS and for the whole season. The data was also used to develop relationships between depth of soil water extraction, days after sowing when extraction starts from a given depth, and plant canopy height.

Weather data and reference evapotranspiration

An EnviroStation (ICT International Pty Ltd, Armidale, NSW, Australia) weather station was installed next to the research plots. The station recorded hourly values of solar radiation, air temperature (maximum, minimum, and average), relative humidity, wind speed, and rainfall. From the weather data, daily grass-reference ET were calculated using the standardized FAO-56 Penman-Monteith method (Allen et al., 1998) as:

$$\mathrm{ETo} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T + 273} U_2\,(e_s - e_a)}{\left[\Delta + \gamma\,(1 + C_d U_2)\,\right]} \tag{5}$$

where, Eto = grass-reference evapotranspiration (mm d^{-1}), Δ = slope of the saturation vapor pressure versus air temperature curve (kPa °C^{-1}), R_n = net radiation at the crop surface (MJ m^{-2} d^{-1}), G = heat flux at the soil surface (MJ m^{-2} d^{-1}), T = mean daily air temperature at 1.5 to 2.5 m height (°C), U_2 = mean daily wind speed at 2 m height (m s^{-1}), es = saturation vapor pressure (kPa), ea = actual vapor pressure (kPa), $e_s - e_a$ = vapor pressure deficit (kPa), γ = psychrometric constant (kPa °C^{-1}), C_n = numerator constant (°C mm s^3 Mg^{-1} d^{-1}), C_d = denominator constant (s m^{-1}), 0.408 = coefficient having units of m^2 mm MJ^{-1}. Daily R_n, es, and ea were calculated using the equations given by Allen et al. (1998) and ASCE-EWRI (2005) using measured RH, T_{max}, and T_{min}, and constant albedo (α = 0.23). Values for the Stefan-Boltzmann constant (σ = 4.901 × 10-9 MJ K^{-4} m^{-2} d^{-1}) (for calculating net outgoing longwave radiation (R_{nl})), specific heat at constant temperature (cp = 1.013 × 10^{-3} MJ kg^{-1} °C^{-1}), and latent heat of vaporization (λ = 2.45 MJ kg^{-1}) followed FAO-56 and ASCE-EWRI (2005). The psychrometric constant (γ) was computed as a function of atmospheric pressure (P), λ, cp, and the ratio of molecular weight of water vapor to dry air (ε = 0.622). P was calculated as a function of station elevation (z) and an assumed value of daily G=0 MJ m^{-2} d^{-1}. Wind speed can be converted to the standard 2-m height using equation 47 in (Allen et al., 1998).

Daily crop evapotranspiration

For irrigation planning purposes for fully-irrigated situations, a common approach is to calculate crop evapotranspiration (ETc) using the single crop coefficient approach as (Allen et al., 1998):

$$ETc = ETo \, x \, Kc \tag{6}$$

Where, Kc = crop coefficient (unitless). This approach, however, is not adequate for dealing with crops stress and for irrigation scheduling. Therefore, for this study a computer model was developed based on dual crop coefficient approach (Allen et al., 1998) to estimate daily crop water use for each irrigation treatment. The model calculated ETc for non-stressed and stressed crops as:

$$ETc = (K_s K_{cb} + K_e) ETo \tag{7}$$

Where, K_s = factor describing the effect of water stress on crop transpiration (unitless), K_{cb} = basal crop coefficient (unitless), which is ETc/Eto when the soil surface is dry but transpiration is occurring at a potential rate such as water stress is not limiting transpiration, K_e = soil evaporation coefficient (unitless). Application of Eq. 7 requires conducting a daily soil water balance to determine if the crop is under stress and apply the necessary adjustments to ETc. The performance of the model was evaluated against the seasonal ETc estimated from the seasonal soil water balance (Eq.1).

Crop development

Crop development was characterized by measuring a series of variables, including leaf area index (LAI), dry matter production (DM), DM partitioning (DMP), plant density (PD), plant components (PC), canopy height (H) and canopy width (W). Also, the architecture of the plant was characterized by measuring the distance to each node (DN), the inter-node length (IL), and counting and measuring the leaves on each node.

LAI, DM, DMP, PD, and PC were determined from destructive plant samples taken approximately every two weeks. All plants on a 1-m length from each plot were cut at ground level. The plants were counted to determine plant density. A sub-sample was taken to determine LAI and PC and the rest of the plants were used to determine DM and DMP. Early in the season, the sub-sample for LAI consisted of four plants, but it was reduced to two plants later in the season.

For each plant in the sub-sample, the distance to every node in the main stem was measured. The different plant components in each node were separated and counted. The plant components included: leaves, squares, flowers (white and purple), green bolls, and open bolls. The area of the green leaf laminaes from each node of each plant, needed to calculate LAI, was measured using an Area Measurement System with Conveyor Belt Unit (Delta-T Devices, Cambridge, England). Calibration was checked each time, and adjusted if needed, using a simulated leaf of known area. The DM of the plant components for each plant in the LAI sub-sample was measured. DM was determined by drying the plant samples with a forced draught oven at 80°C until a constant weight was achieved (for at least 48 hours). The DM of the samples was then measured with an electronic laboratory scale to the nearest 0.01 g. Plant canopy height (h) and width (W) were determined throughout the season, from soon after emergence to defoliation. The h and W of four representative plants from each plot were measured with a ruler. The h was measured from the soil surface to the top leaf, and W was taken as the maximum width of the canopy.

Yield and lint quality

A 5 m length of one row was hand-harvested to determine lint yield. For the T85% treatment (solid and skip), a 2.5 m lengths of two rows were hand-harvested. The seed cotton (lint + seeds) from the open bolls and the green bolls were collected separately. The number of open and green bolls in each plant of a 1-m length was determined. The seed cotton and green boll samples were oven-dried at 40^{o}C for about a week. The green bolls opened after drying and the seed cotton was collected and kept separate from that harvested in the field. Seed cotton samples from the green bolls and those harvested in the field were weighted separately. A 350 g subsample from the seed cotton was used to separate the lint from the seeds using a laboratory gin that was built in-house (Figure 10). The mass of the lint and seeds in the subsample was measured. The lint was sent to the lab to determine fibre quality. Fibre quality analyses were conducted at a commercial laboratory, where industry standard quality tests were performed. Another set of samples was sent to the CSIRO fibre quality laboratory where more detailed analyses were performed. Seed samples were also sent to a commercial laboratory for to be analysed for nutrient content.

Figure 10. Ginning cotton using a laboratory ginning machine.

Results and discussion

Following is a summary of results, not all measurements described in the methods section are presented in this paper.

Weather conditions

Weather conditions during the 2007-08 cotton season at Kingsthorpe are shown in Figure 11 and Figure 12. A monthly summary is shown in Table 4. Total rainfall during the growing season was 271 mm, representing only 34% of the 804 mm of seasonal Eto. February was the wettest month with 126 m of rain, representing almost half (46%) of the seasonal rainfall. The minimum temperature (Figure 11.B) shows that there was a frost on 29 April 2008, which visually stunted the crop but did not kill it.

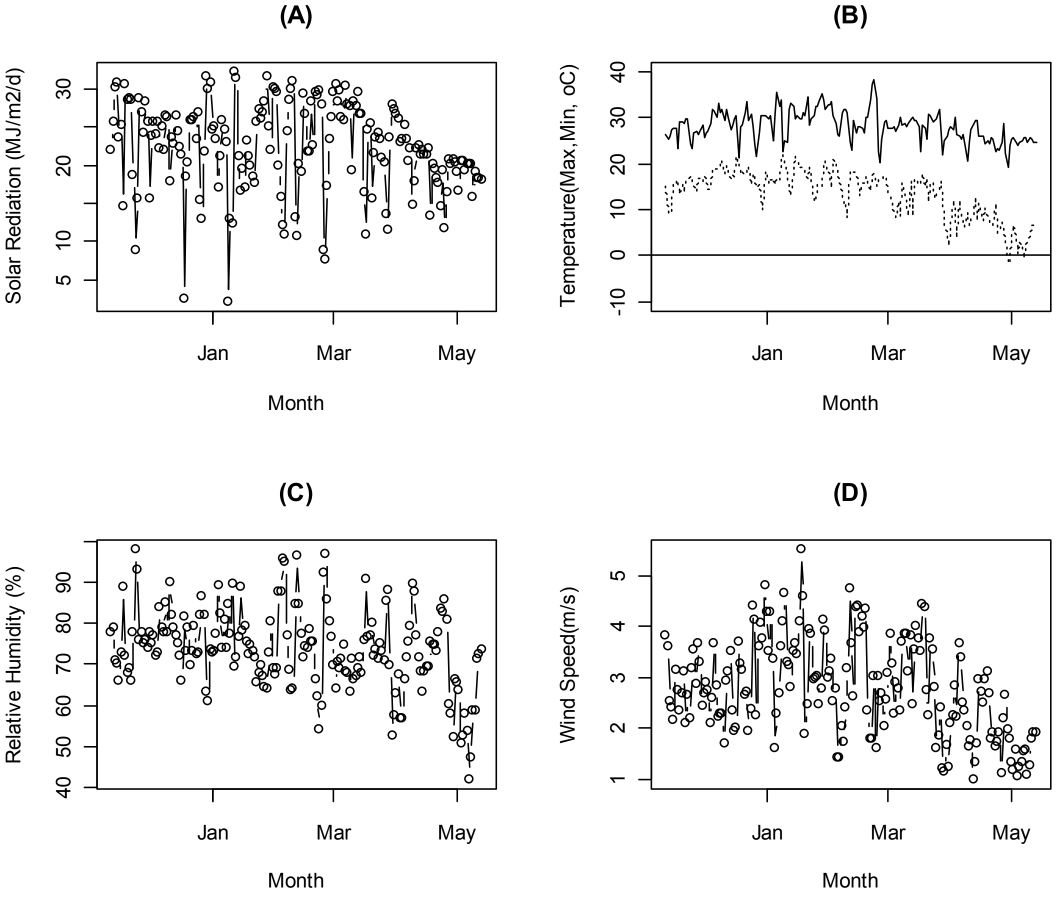


Figure 11. Averages of daily weather variables measured at Kingsthorpe during the 2007-2008 cotton growing season.

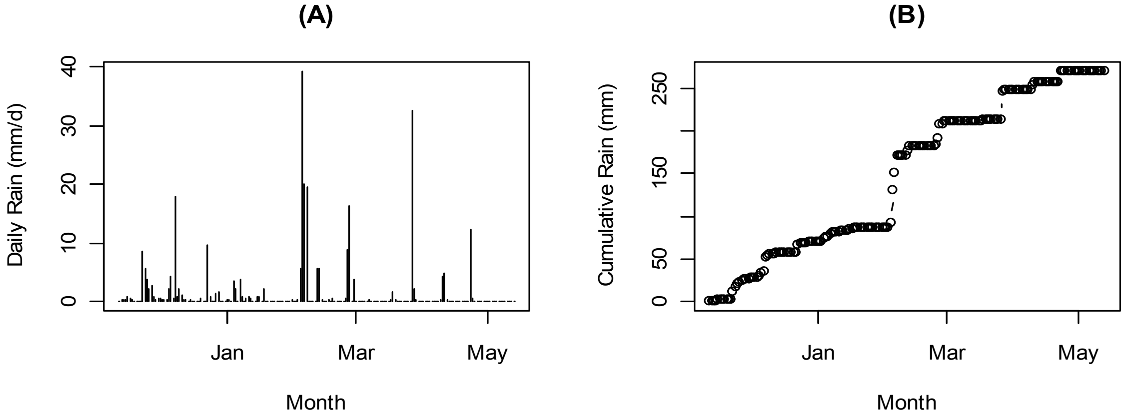


Figure 12. Daily and cumulative rain during the 2007-2008 cotton growing season at Kingsthorpe.

Table 4. Summary weather conditions during the 2007-08 cotton season at Kingsthorpe.

	Month							Season
Variable [a]	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Avg/total**
Tmax (oC)	27.0	29.0	30.7	29.2	28.0	25.4	25.0	*27.8*
Tmin (oC)	14.7	17.5	17.5	16.1	12.6	7.3	3.7	*12.8*
Rs (MJ/m2/d)	24.6	22.9	22.4	22.3	24.1	20.3	19.0	*22.2*
RH (%)	76.3	76.5	75.2	77.4	71.7	71.6	59.1	*72.5*
u (m/s)	2.9	2.9	3.4	2.9	3.0	2.2	1.5	*2.7*
Daily Eto (mm)	4.7	4.8	5.0	4.6	4.5	3.3	2.8	*4.3*
Monthly Eto (mm)	88.5[b]	149.6	156.1	132.5	140.5	100.1	36.7	*804.0*
Monthly Rain (mm)	26.0	44.0	16.0	126.0	37.0	22.0	0.0	*271.0*

[a]Tmax, Tmin = Maximum and minimum air temperatures, Rs = Solar radiation
RH= Relative humidity, u = Wind speed, Eto = Grass-reference evapotranspiration
[b] For Nov and May, only data within the cotton growing season was included.

Irrigation

Irrigation timing and amounts applied to each treatment are shown in Table 5. Six irrigations were applied to the wettest treatment (T50%), ranging from 5 to 76 mm per irrigation event. The amount of each irrigation event was adjusted to avoid water loss by deep drainage. The T60% and T70% treatments received practically the same amount of seasonal irrigation, although the T70% received the first irrigation much later in the growing season. The T85% treatment was not irrigated.

Table 5. Irrigation applied to each treatment in 2007-08 (mm)

	Irrigation Treatment			
Date	**T50%**	**T60%**	**T70%**	**T85%**
26/01/2008	5			
27/01/2008	45			
28/01/2008	20			
1/02/2008		10		
29/02/2008	76	45		
4/03/2008			54	
27/03/2008	58			
21/04/2008	24			
22/04/2008		28	28	
Total	**228.0**	**83**	**82**	**0**

Soil water and seasonal ETc from neutron probe

Total profile soil water, measured with neutron probe, as a function of days after sowing for the four treatments are shown in Figure 13. Figure 14 shows the means separation of profile soil water at start (Figure 14 A) and end of season (Figure 14 B), seasonal change in profile soil water (Figure 14 C) and the seasonal crop ETc (Figure 14 D) estimated using a soil water balance approach (Eq.1).

There were no significant differences in profile soil water content at the start and end of season, and therefore, there were no significant differences in seasonal change in profile soil water among treatments. These results suggest that all treatments used practically all the water that was available to the crop. There were, however, significant differences in seasonal ETc among the treatments (Figure 14 D). As expected, irrigation increased ETc.

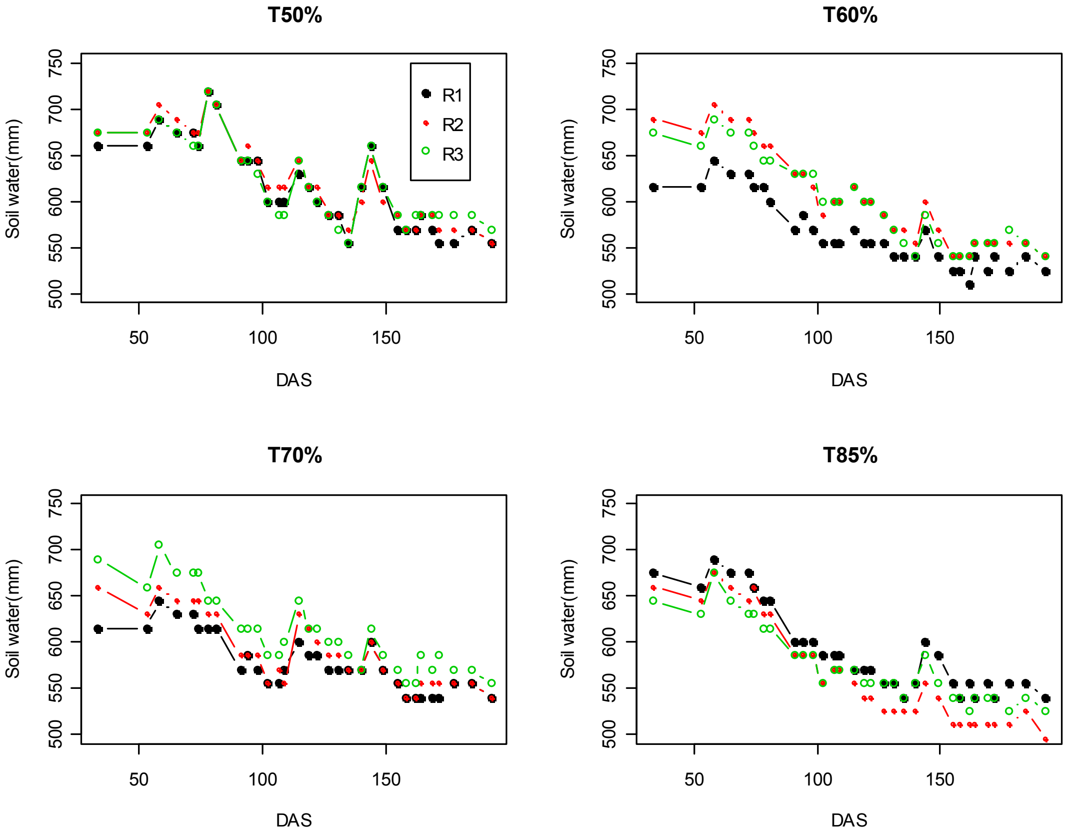


Figure 13. Profile soil water for each treatment and replication (R1, R2, R3) as a function of days after sowing (DAS) for cotton measured with neutron probe at Kingsthorpe during 2007-08.

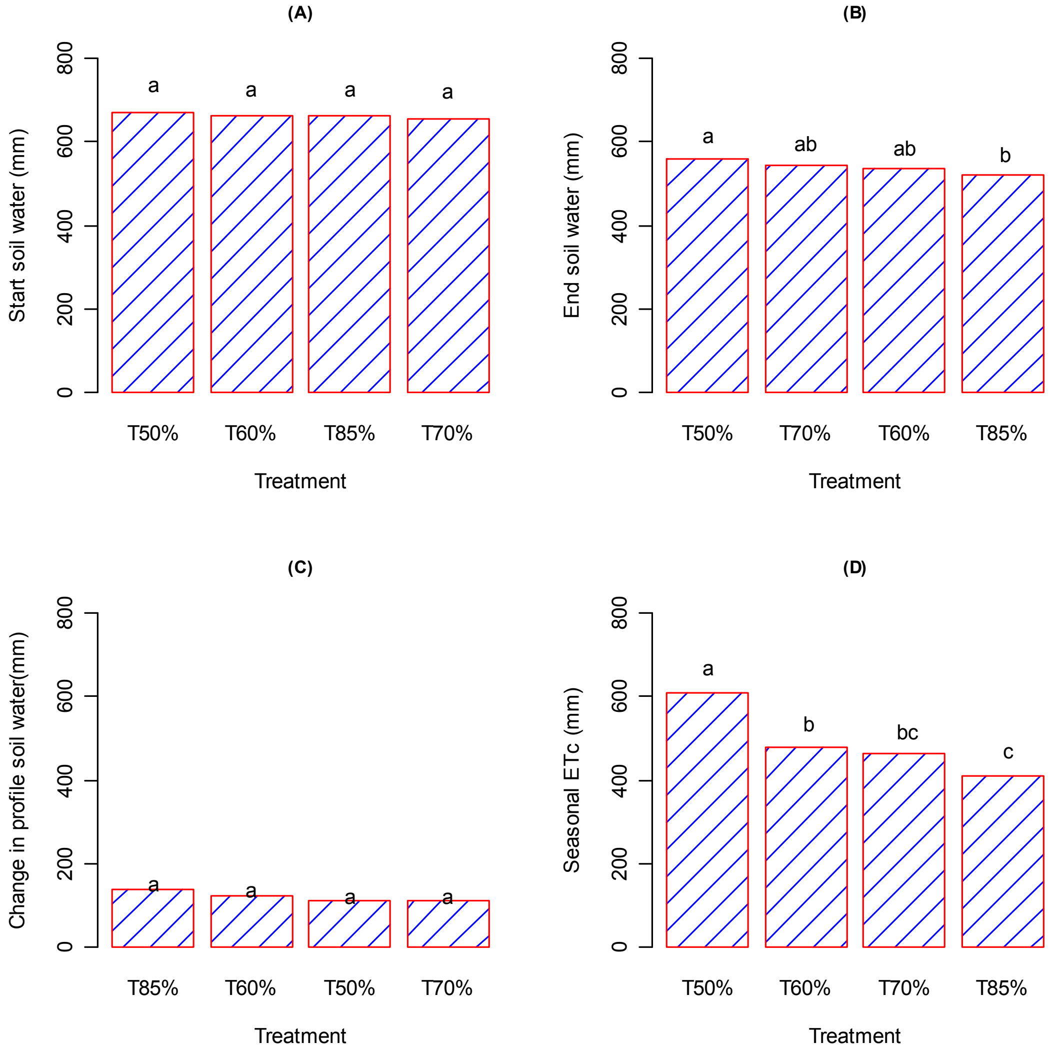


Figure 14. Treatment comparison of (A) profile soil water at start of season, (B) profile soil water at end of season, (C) Change in profile soil water (start-end), and (D) seasonal crop evapotranspiration (ETc) measured for cotton at Kingsthorpe during 2007-08. ETc was determines as: ETc = Rain + Irrigation + change in soil water. Treatments with the same letters were not significantly different.

Daily crop ETc and soil water balance

Daily crop ETc and soil water balance was calculated with a computer model that was developed based on Eq. 7. Figure 15 shows values for daily ETc under water stress (Etcd) and under non-stress conditions (Etcw). It shows the high variability in daily values of both Etcw and Etcd, which respond to daily changes in weather conditions, as well as soil water content (both amount and location within the soil profile), soil surface wetness, and stage of crop development. Etcw during this season ranged from about 0 to 10 mm/d, peaking at about 100 days after sowing (DAS). The difference between Etcw and Etcd indicates the impact of crop water stress. Figure 15 shows that all treatments were stressed at some point during the season (when Etcw > Etcd). It also shows high values of Etcd and Etcw during some periods early in the season when the crop was small and there was incomplete soil cover.

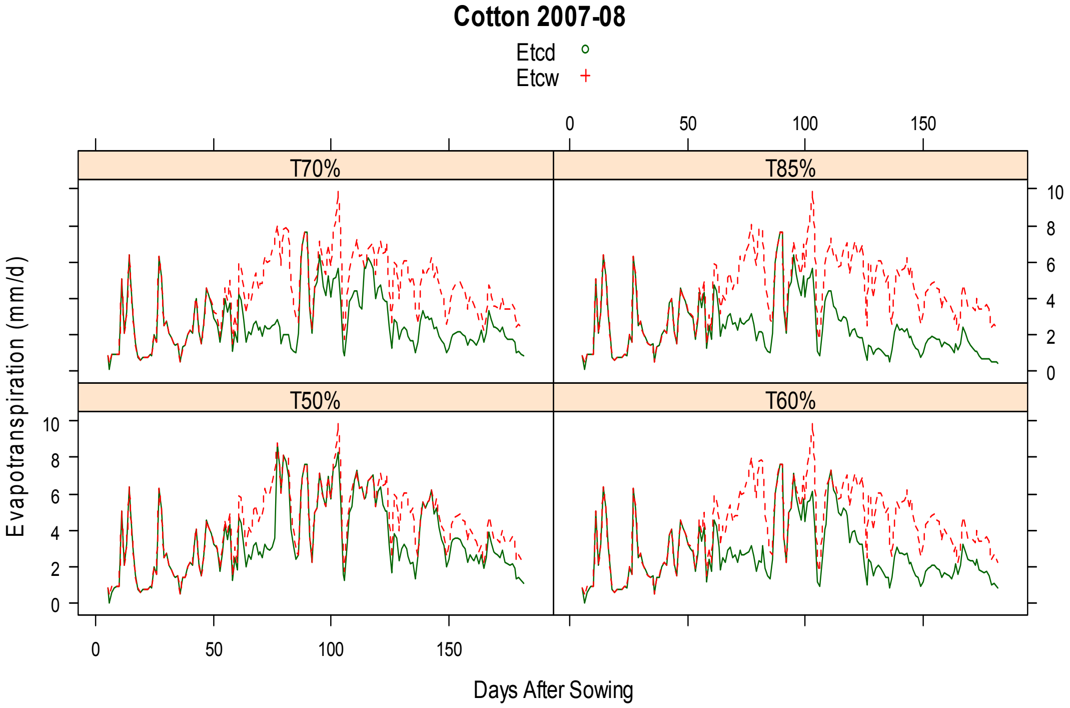


Figure 15. Daily values of actual crop evapotranspiration (Etcd) and potential crop evapotranspiration with no water stress (Etcw) as a function of days after sowing for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%) at Kingsthorpe during 2007-08.

Figure 16 shows a separation of Etcd into its transpiration (Td) and Evaporation (E) components, which indicates that the high Etcd values early in the season were due to soil evaporation resulting from rainfall events rather than from irrigation, since no irrigation was applied until the end of January. Negligible E occurred between about 50 to 150 DAS. Some E occurred after 150 DAS due to crop senescence and defoliation. The E component of Etcd can be considered as water loss since it does not increase yields and should, therefore, be minimised whenever possible. Options to minimise E are: using residue cover or mulching, avoiding irrigation early in the season if possible, irrigating every other furrow rather than every furrow, or using subsurface drip irrigation where applicable.

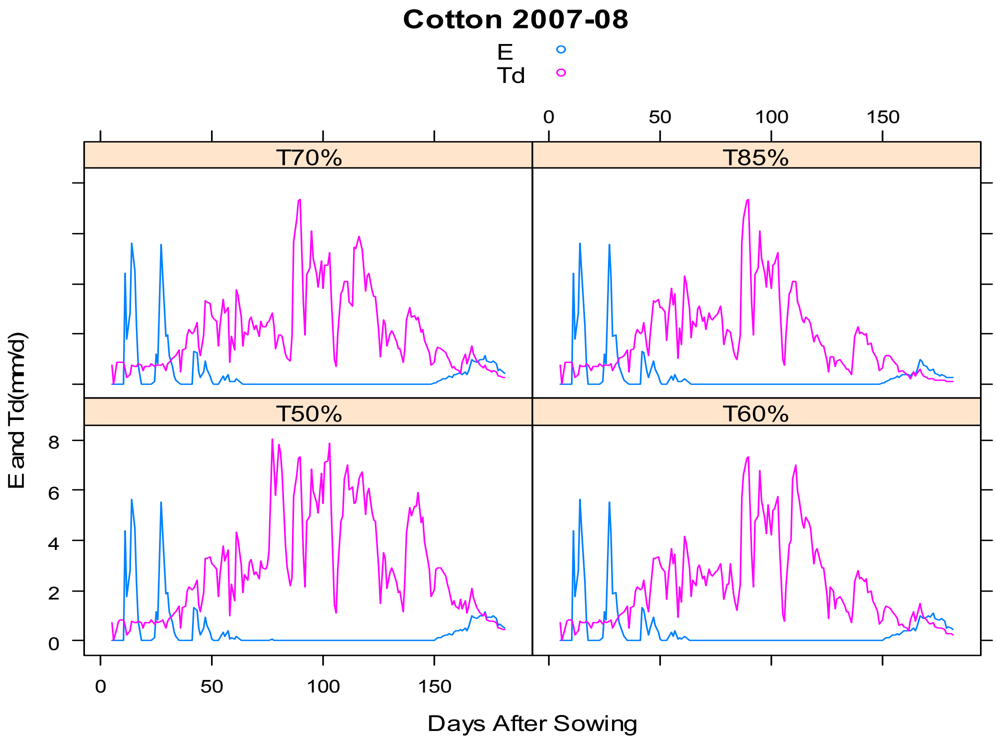


Figure 16. Daily values of crop transpiration (Td) and evaporation (E) as a function of days after sowing for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%) at Kingsthorpe during 2007-08.

Figure 17 shows cumulative values of Etcd (Cum.Etd), Etcw (Cum_Etw) and total water inputs (Cum.W.all) as a function of DAS for each treatment. It shows that Cum_Etw had a change in slope at about 60 DAS, when the crop started using water at a considerably higher rate. Prior to 60 DAS, Cum_Etw increased almost linearly (r^2=0.99) at an average rate of **2.4 mm/d**. After 60 DAS, there was also an almost linear increase (r^2=0.99) in Cum_Etw at an average rate of **5.29 mm/d.**

Figure 17 also shows that all treatments started to experiment stress starting at about 60 DAS. It should be noticed that the T50% treatment experimented some stress at that time regardless of the fact that Cum.W.all > Cum._Etw. It also shows that once the crop has been stressed, Cum.Etd is permanently reduced in relation to Cum_Etw. This reduction cannot be reversed by irrigating after the crop has been stressed. Additional irrigation just prevents further future reduction in Cum.Etd. Because of the irreversible nature of crop stress, if water is limited there is value in considering trying to avoid crop stress early in the season. In other words, stressing the crop early while waiting for rain may be counterproductive, because it permanently reduces the yield potential. This decision, however, depends on many factors, especially on the level of risk that the grower is willing or able to take.

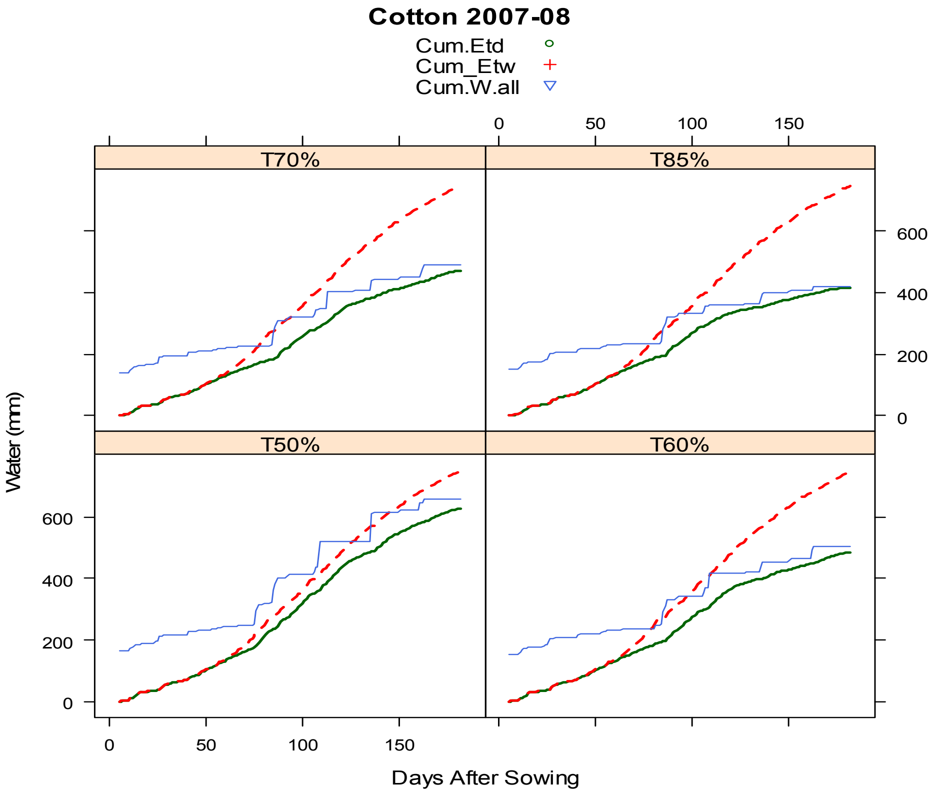


Figure 17. Cumulative values of actual crop evapotranspiration (Cum.Etd), potential crop evapotranspiration with no water stress (Cum_Etw), and total water inputs (Cum.W.all = soil water at start of season + rain + irrigation) as a function of days after sowing for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%) at Kingsthorpe during 2007-08.

Figure 18 shows the results to the daily soil water balance in the crop root zone, including the daily soil water depletion (sum_Rz_depl) compared with the calculated maximum total available water (TAW_Rz) and maximum readily available water (RAW_Rz). When sum_Rz_depl> RAW_Rz the crop is under water stress. Figure 18 shows that all treatments started experimenting stress at about 60 DAS. At this time the soil water deficit was only about 50 mm. This was because at that time the roots had not yet reached their full length and even though there was water stored in the soil profile, it was stored at a depth that the roots were not able to reach. This illustrates the danger of scheduling irrigation based on a fixed deficit as is common in the cotton industry.

The soil water deficit to trigger irrigation should be changed dynamically depending on root development and soil water holding capacity. The appropriate deficit to trigger irrigation changes daily as crop roots grow. Crop water use also changes daily, responding to changes in weather conditions, crop development, and available soil water. **Therefore, irrigation scheduling softwares that integrate all these variables could be very useful in aiding growers make irrigation scheduling decisions.**

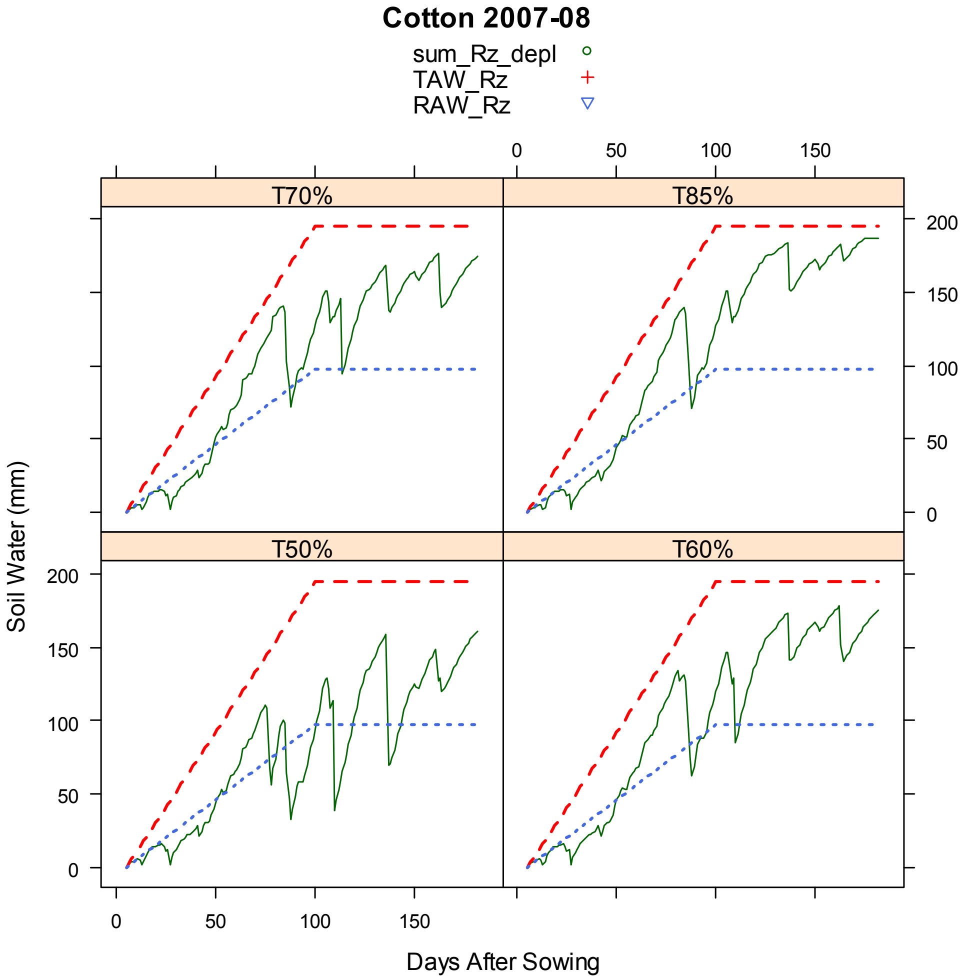


Figure 18. Values of soil water depletion in the crop root zone (sum_Rz_depl), Maximum available water in the crop root zone (TAW_Rz) and readily available water in the crop root zone (RAW_Rz) as a function of days after sowing for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%) at Kingsthorpe during 2007-08.

Seasonal crop ETc and model performance

Table 6 shows seasonal summaries for water variables calculated with the computer model and measured with the neutron probe method. Figure 19 shows excellent agreement between the modelled and measured seasonal crop Etd (Figure 19 A). The modelled values were within 20 mm for the T50% treatment and within 10 mm for the other treatments (Figure 19 B), which was within 3% on a seasonal basis (Figure 19 C).

Table 6 shows that the crop evapotranspiration with no stress (Etp) was around 750 mm during the 2007-08 season at Kingsthorpe. However, because the crop was stressed for all treatment, actual evapotranspiration (Etd) ranged from 417 to 628 mm, which represented between 56% and 84% (Etd/Etp) of Etp. Evaporation (E) ranged from 62 to 69 mm, representing between 11 and 15% of Etd.

Table 6. Treatment averages of seasonal water variables obtained with the model and measured with neutron probe for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%) at Kingsthorpe during 2007-08.

	Calculated by model						Measured with neutron probe				
Treat	Etd (mm)	Etp (mm)	TW (mm)	Td (mm)	E (mm)	Etd/Etp	n.SW.Start (mm)	n.SW.End (mm)	n.SWD (mm)	n.ET (mm)	n.TW (mm)
T50%	628	750	660	525	69	0.84	670	560	110	609	607
T60%	486	747	505	388	67	0.65	660	535	125	479	477
T70%	472	747	491	373	68	0.63	655	545	110	463	462
T85%	417	747	420	326	62	0.56	660	520	140	411	409

Etd= evapotranspiration, Etp =potential evapotranspiration, TW=total water (soil water+rain+irrigation), Td = transpiration, E= evaporation, n.SW.Start=soil water at start of season, n.SW.End= soil water at the end of season, n.ET = evapotranspiration, n.TW = total water.

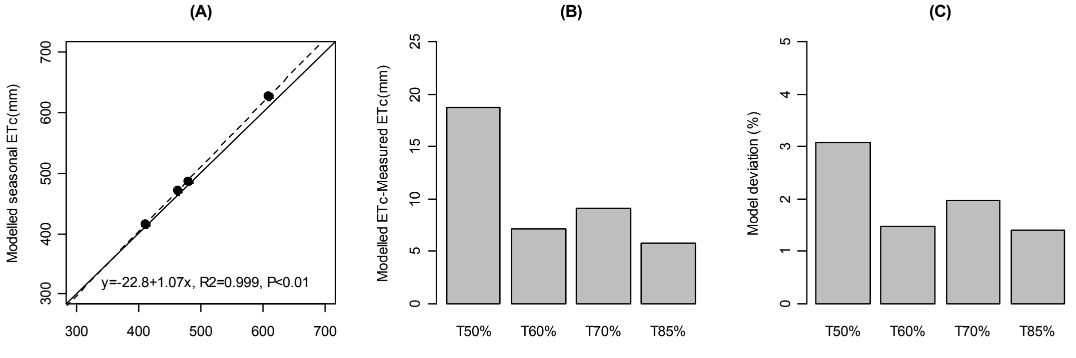


Figure 19. Comparison of measured (using neutron probe) and modeled (using FAO-56) seasonal crop evapotranspiration for cotton at Kingsthorpe during 2007-08.

Distribution of soil water extraction

The distribution of soil water extraction in terms of timing, soil depth and magnitude was evaluated using the EnvironScan data. The EnvironScan data was used rather than the neutron probe data because it provides a continuous record of soil water content in the different soil depths. Figure 20 shows the soil water content as a function of DAS for each soil depth and treatment. It shows that there was soil water extraction from all depths down to 150 cm. It also shows when water started to be extracted from each depth and the relative magnitude of the water extraction. Changes in soil water content became less pronounce as soil depth increased.

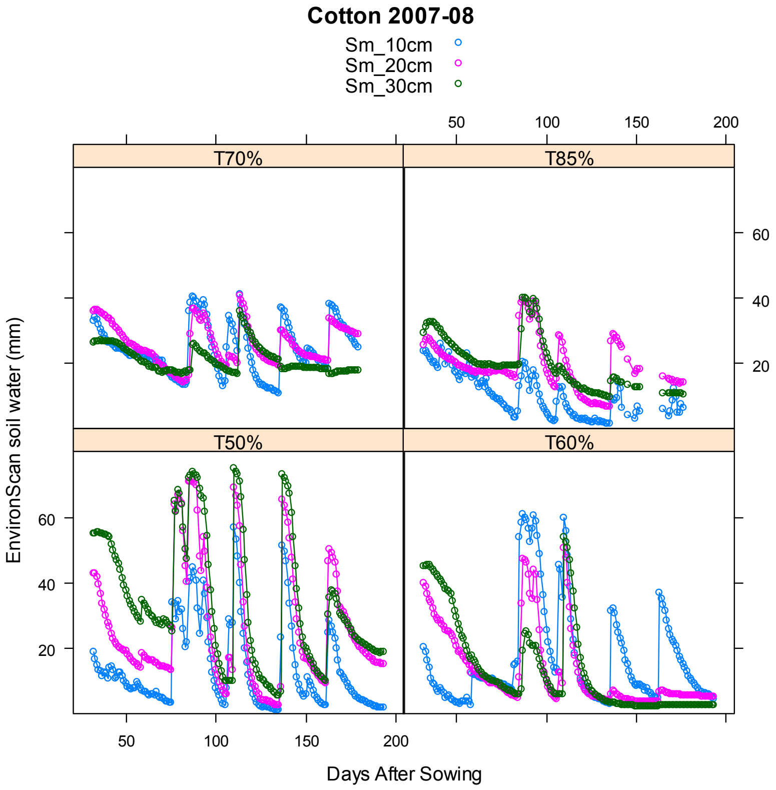


Figure 20. Daily values of soil water for different soil depths measured with EnvironScan as a function of days after sowing for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%) at Kingsthorpe during 2007-08. Sm_10cm, Sm_20cm, Sm_30cm are soil moisture measured at 10, 20, and 30 cm depth, respectively.

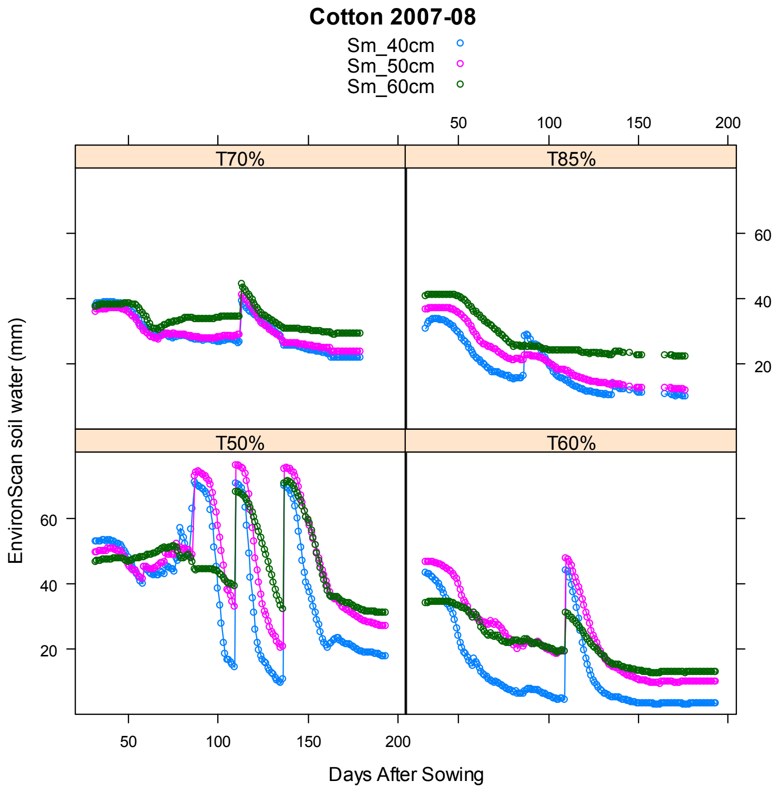


Figure 20. Continuation.

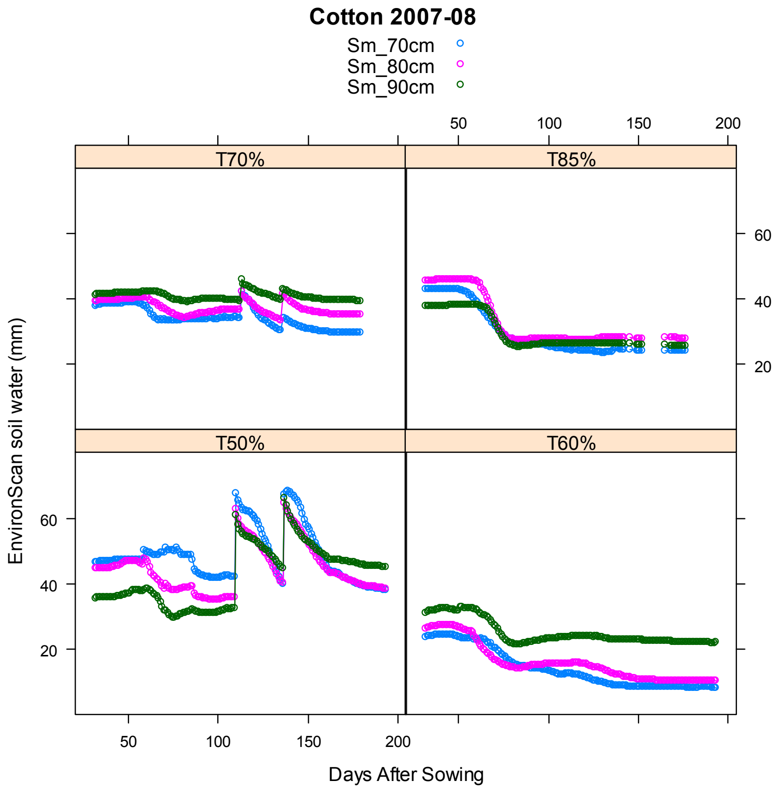


Figure 20. Continuation.

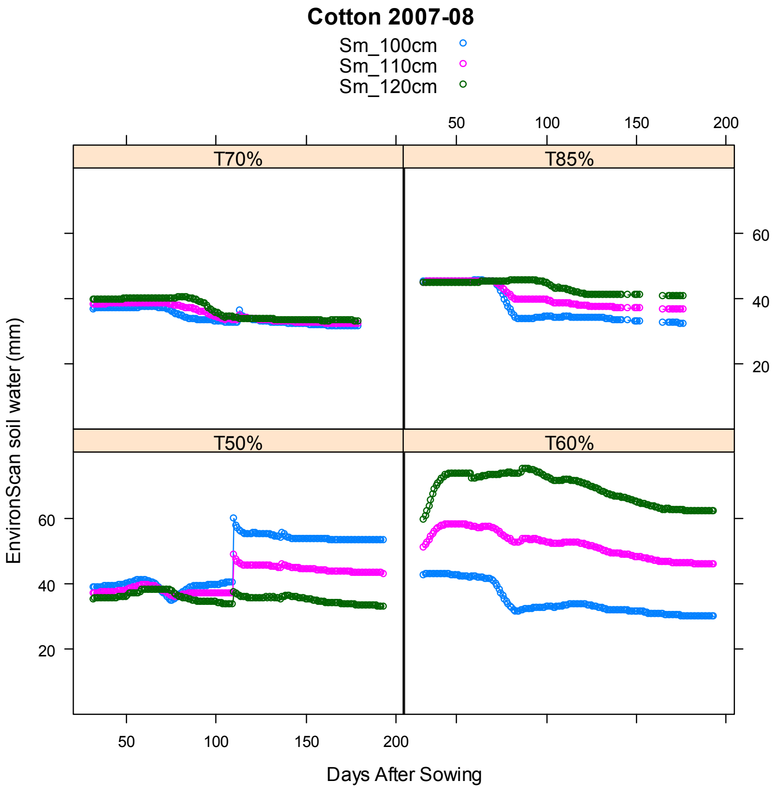


Figure 20. Continuation.

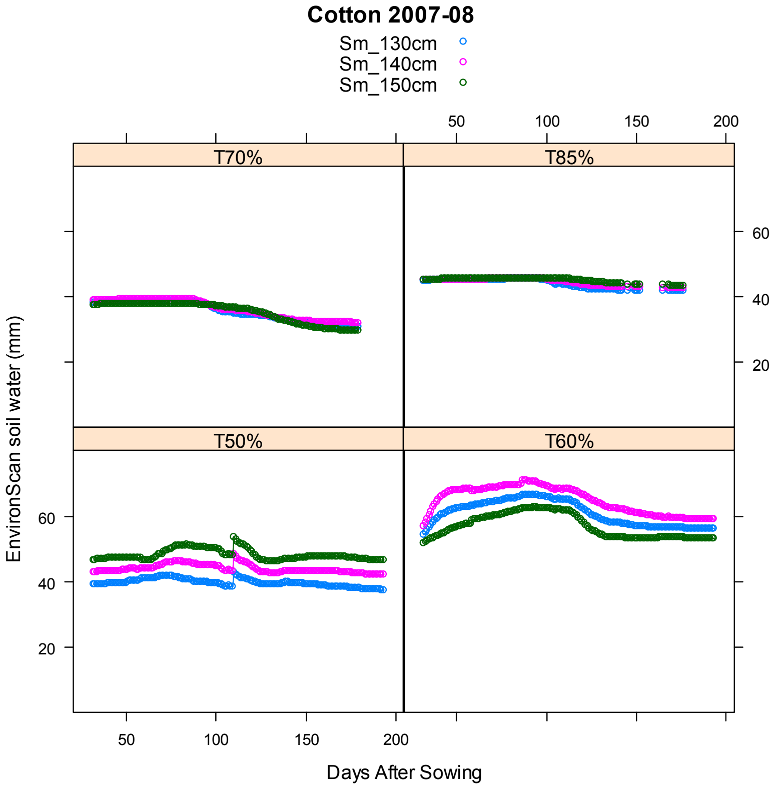


Figure 20. Continuation.

The soil water content information was used to calculate the daily cumulative water use from the whole profile (cumulative profile ET) and from each depth (cumulative depth ET) as a function of DAS. Then the relative cumulative EnvironScan ET were calculated for each depth (cumulative depth ET/cumulative profile ET). These results are shown in Figure 21 for each depth and treatment.

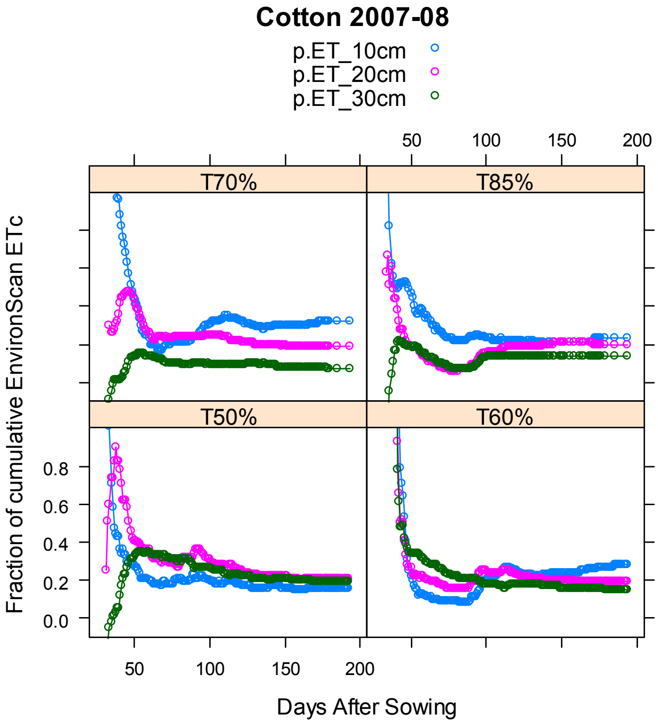


Figure 21. Daily fraction of cumulative ETc by soil depth measured with EnvironScan as a function of days after sowing for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%) at Kingsthorpe during 2007-08. p.ET_10cm, p.ET_20cm, p.ET_20cm are the fraction of cumulative ETc measured at 10, 20, and 30 cm depth, respectively.

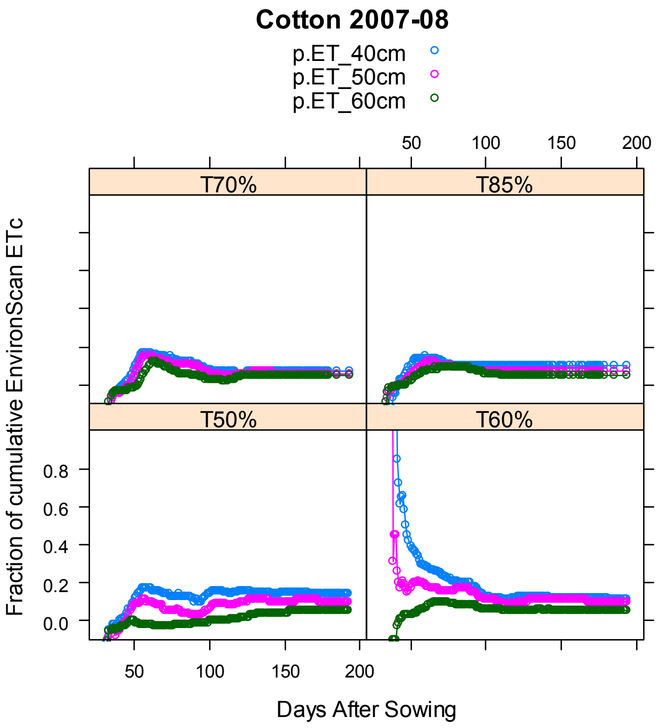


Figure 21. Continuation.

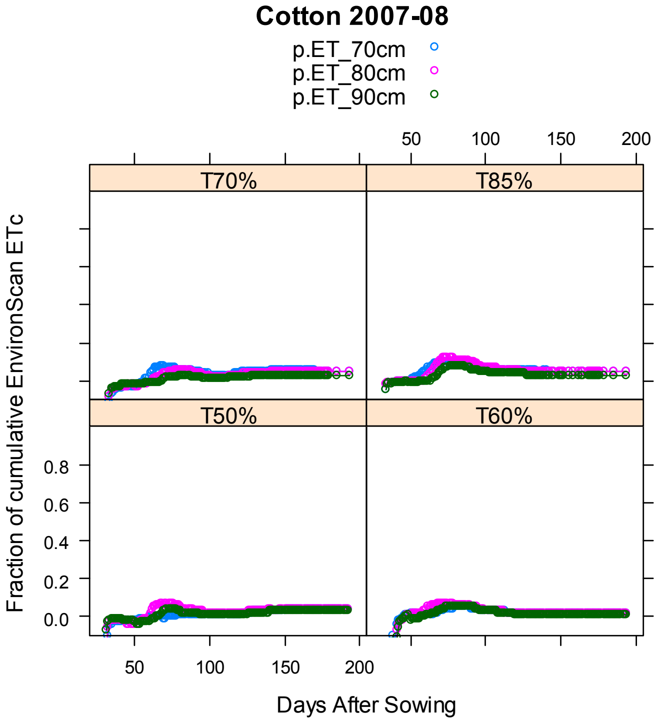


Figure 21. Continuation.

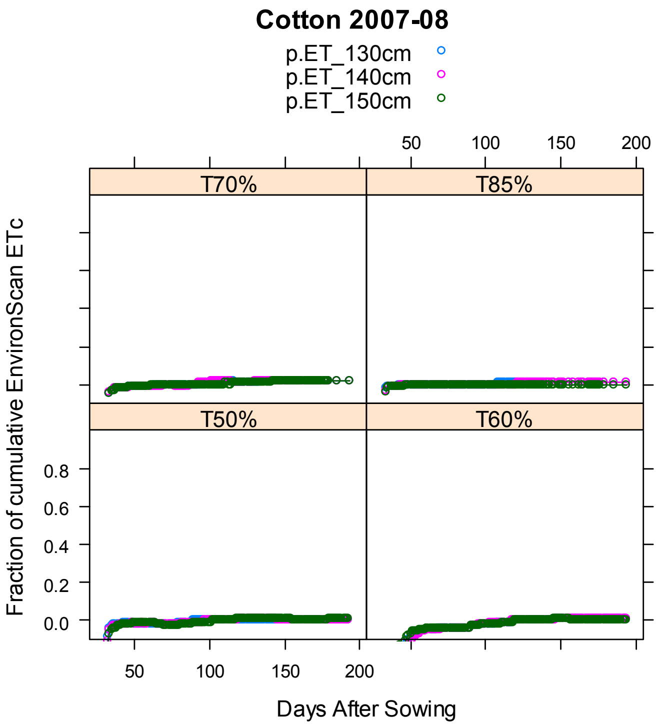


Figure 21. Continuation.

The fraction of seasonal soil water extraction and the cumulative fraction of seasonal soil water extraction as a function of depth of extraction (soil depth) for each treatment are summarised in Figure 22 and Figure 23. Figure 22 shows that the fraction of seasonal soil water extraction tended to decrease with depth from a treatment average of about 0.25 (25%) from the top 10 cm to less than 0.05 (5%) for depths deeper than 60 cm.

Figure 23 shows that under the conditions of this study, even though water was extracted from as deep as 150 cm, about 80% of the seasonal water extraction took place from the top 60 cm and 90% from the top 80 cm soil depth. These results then suggest that irrigation should be targeted at wetting only the top 80 cm of the soil profile.

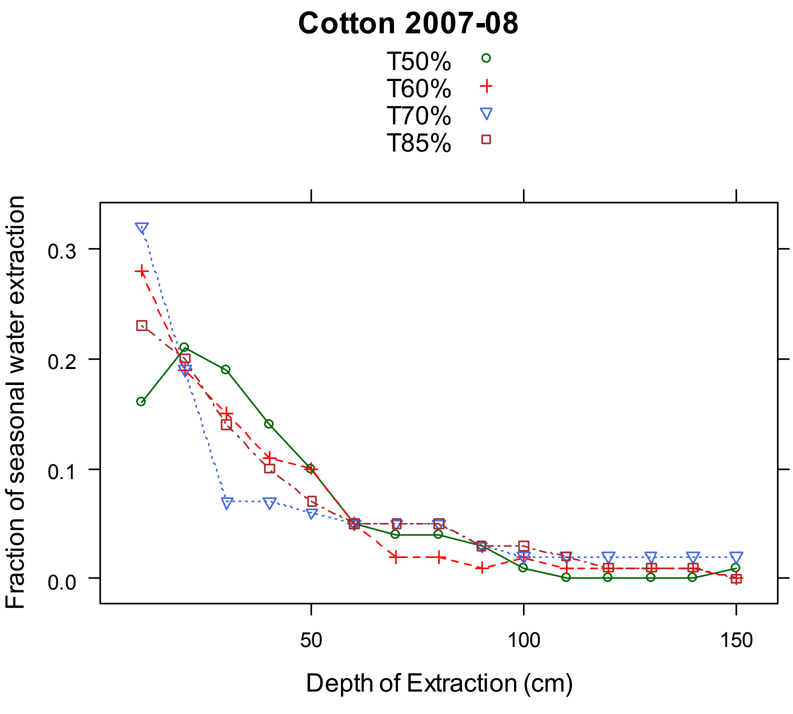


Figure 22. Fraction of seasonal soil water extraction as a function of depth of extraction measured with EnvironScan for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%) at Kingsthorpe during 2007-08.

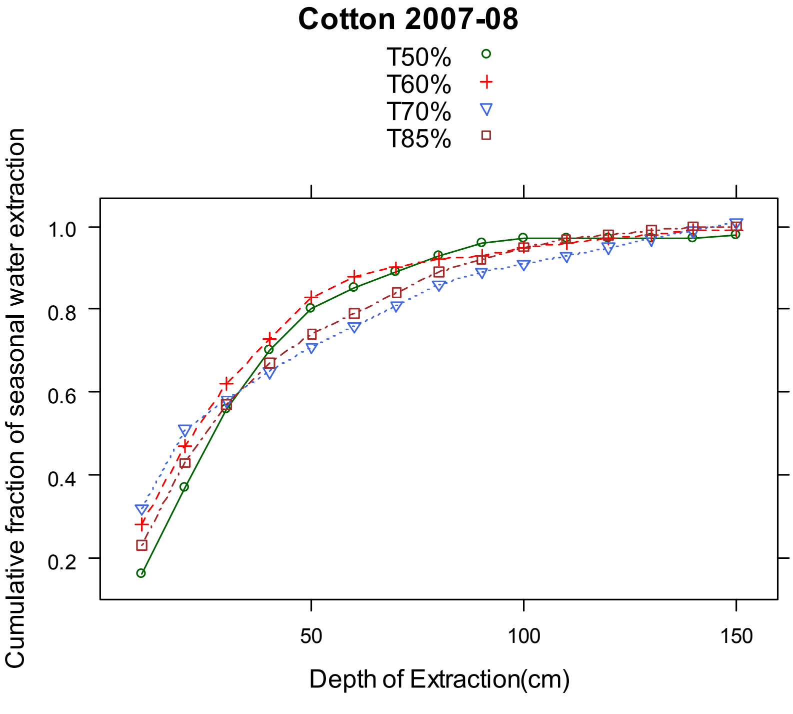


Figure 23. Cumulative fraction of seasonal soil water extraction as a function of depth of extraction measured with EnvironScan for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%) at Kingsthorpe during 2007-08.

Figure 24 shows the relationship between the depth of extraction and the DAS extraction started from a given depth, which was visually determined for each depth and treatment from the soil water content information in Figure 20. Since depth of extraction or rooting depth cannot normally be seen in the field, it is difficult to take this variable into account with precision when scheduling irrigation. Therefore, the depth of extraction was also related to the plant canopy height (Figure 25), which can easily be measured in the field. Even though there were slight variations in these relationships with treatment, the depth of extraction tended to increase nearly linearly with both DAS extraction started from a given depth and with plant canopy height.

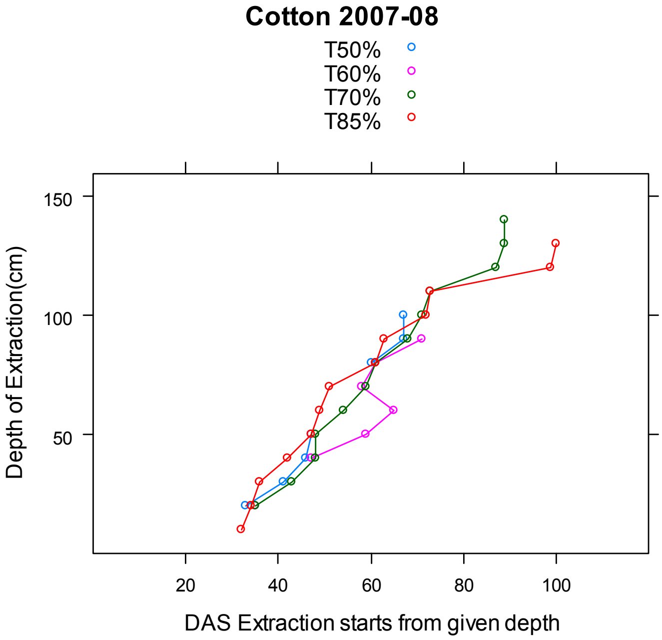


Figure 24. Depth of soil water extraction as a function of days after sowing (DAS) extraction starts from a given depth measured for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%) at Kingsthorpe during 2007-08.

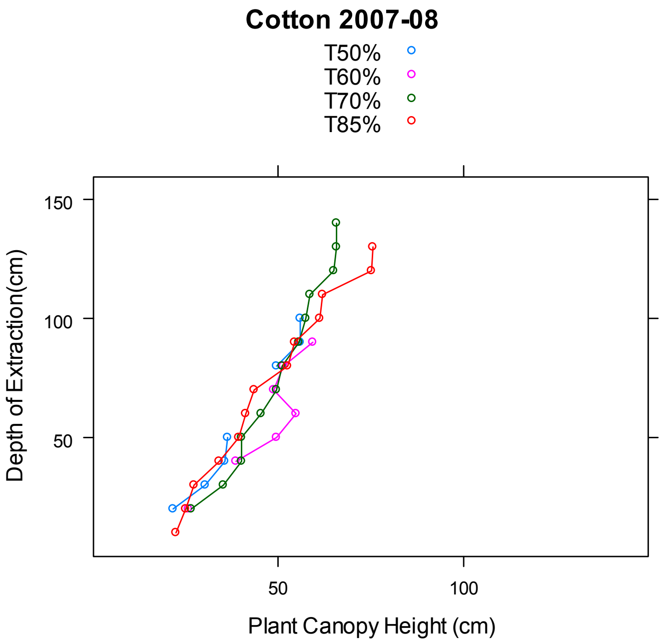


Figure 25. Depth of soil water extraction as a function of plant canopy height measured for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%) at Kingsthorpe during 2007-08.

Figure 26 (A and B) shows linear regression analyses for the relationships between depth of soil water extraction as functions of DAS extraction starts from a given depth and plant canopy height, pooling together data from all treatments. The linear relationships, however, only apply within the range of available data points, including the depth of extraction between 10 and 140 cm. Because EnvironScan data was only available after 32 DAS, there was no data to characterise the relationships earlier in the season. However, it is not expected that the linear relationships will apply earlier in the season. Figure 26 (A) shows that on average for all treatments the depth of extraction increased at a rate of about **1.89 cm/day** from 32 DAS to about 100 DAS with no noticeable increase is depth of extraction after that time. Figure 26 (B) shows that the depth of extraction increased at a rate of **2.36 times the crop canopy height.**

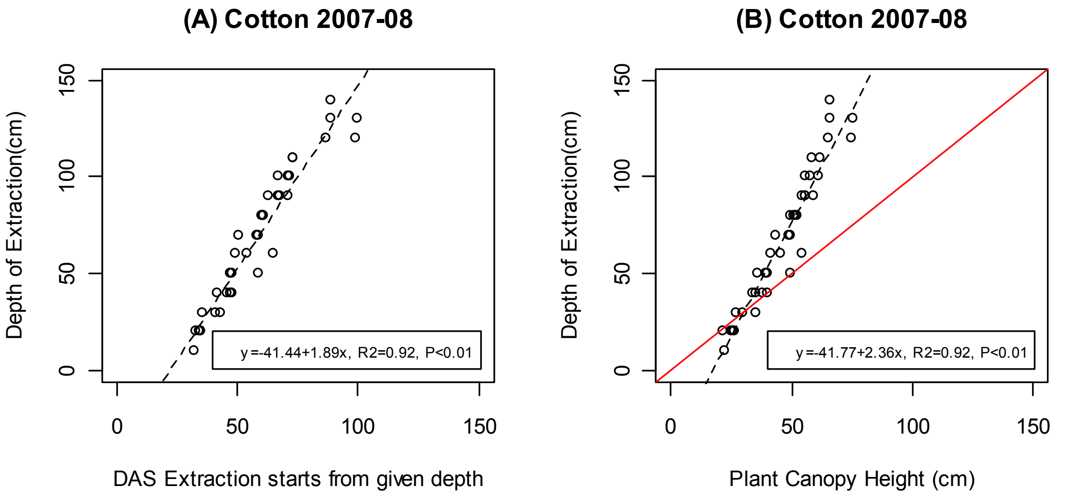


Figure 26. Depth of soil water extraction as a function of days after sowing (DAS) extraction starts from a given depth and plant canopy height measured for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%) at Kingsthorpe during 2007-08. Shown are the regression (dashed) and 1:1 line (solid). Points include data from all four treatments.

Crop growth stages

Some observations about crop development stage are shown in Table 7. Noticeable is that stressed treatment started to mature (as indicated by open bolls) sooner than the fully-irrigated treatments.

Table 7. Crop physiological stages observed for cotton at Kingsthorpe during the 2007-08 season.

Date	DAS	Crop Stage
12/Nov/2007	0	Sowing
20 /Nov/2007	8	Emergence
3/Dec/07	21	4 leaves
10/Dec/07	28	6 leaves
19 Dec 2007	37	8 Leaves
2 Jan 2008	51	Fist Square (9 nodes)
25 Jan 2008	74	50% Flowering
29 Jan 2008	78	100% Flowering
1 Feb 2008	81	Crop was fully flowered and some green bolls had developed
13 Mar 2008	122	A few open bolls in plants with severe water stress
4 April 2008	144	A few open bolls in the fully-irrigated treatment (T50%)
29-30 April 2008	169-170	Defoliation of the T60%, T70% and T85% treatments
7 May 2008	177	Defoliations of the T50% treatment
12-14 May, 2008	182-184	harvest

Crop canopy height

The measured canopy height as a function of DAS for each treatment is shown in Figure 27. Although there were not significant differences in crop canopy height early in the season, it was significantly affected by irrigation later in the season, after about 96 DAS. Plants reached maximum height at about 100 DAS. In general, treatments with more water resulted in taller plants. Plant height ranking was as follows: T50%>T60%=T85%-Skip>T70%=T85%. Figure 28 shows that canopy height measured at 168 DAS was linearly related to seasonal crop evapotranspiration.

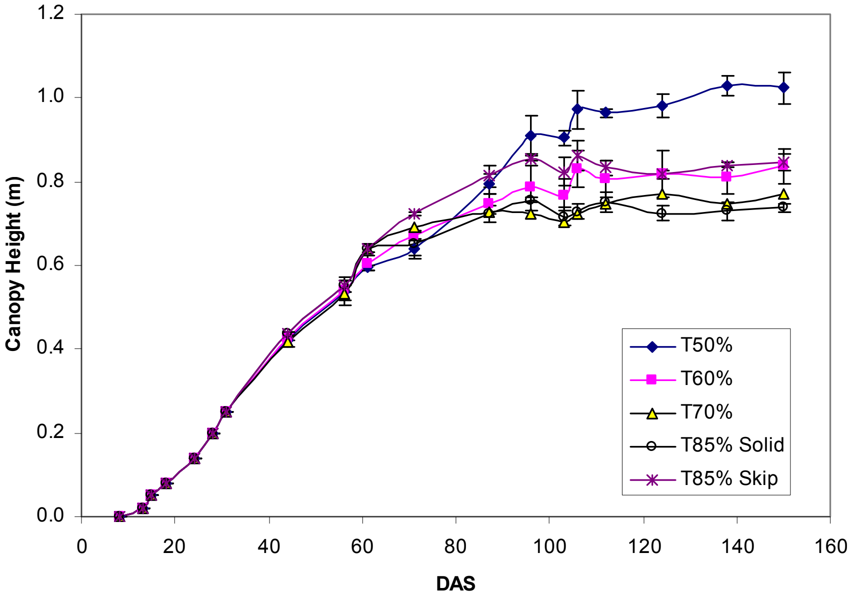


Figure 27. Plant canopy height as a function of days after sowing for cotton grown under five irrigation treatments (T50%, T60%, T70%, T85%-Solid and T85%-Skip) at Kingsthorpe during 2007-08. Each line within each treatment represents a replication.

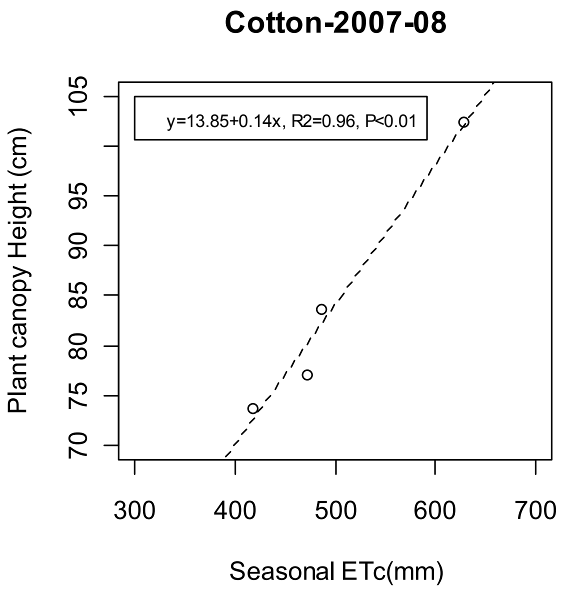


Figure 28. Plant canopy height, measured at 168 days after sowing, as a function of seasonal crop evapotranspiration for cotton grown under four irrigation treatments at Kingsthorpe during 2007-08.

Dry above-ground biomass

Figure 29 shows the dry above-ground biomass as a function of DAS for each irrigation treatment. Figure 30 shows mean separation at 168 DAS, which indicates that although dry biomass tended to increase from the driest to the wettest treatment, there was no significant difference among treatments, which could be due to high variability among replications, given that the T50% treatment resulted in significantly taller plants. Figure 31, however, shows that dry biomass at 168 DAS increased linearly with seasonal crop evapotranspiration. The slope of the line indicates that dry biomass increased at a rate of about 6.86 g/m^2 per additional mm of seasonal ETc.

Also, Figure 32 shows that above-ground biomass production measured at different times throughout the season was linearly correlated to both the daily cumulative crop evapotranspiration and daily cumulative crop transpiration. The average rate of increase in daily dry biomass, pooling data from all treatments, was **11.2 g/m^2** and **12.08 g/m^2 per mm** of evapotranspiration and transpiration, respectively. These values are close the 13-18 g/m^2 per mm of transpiration used by the model AquaCrop (Raes et al., 2009) for C3 crops like cotton.

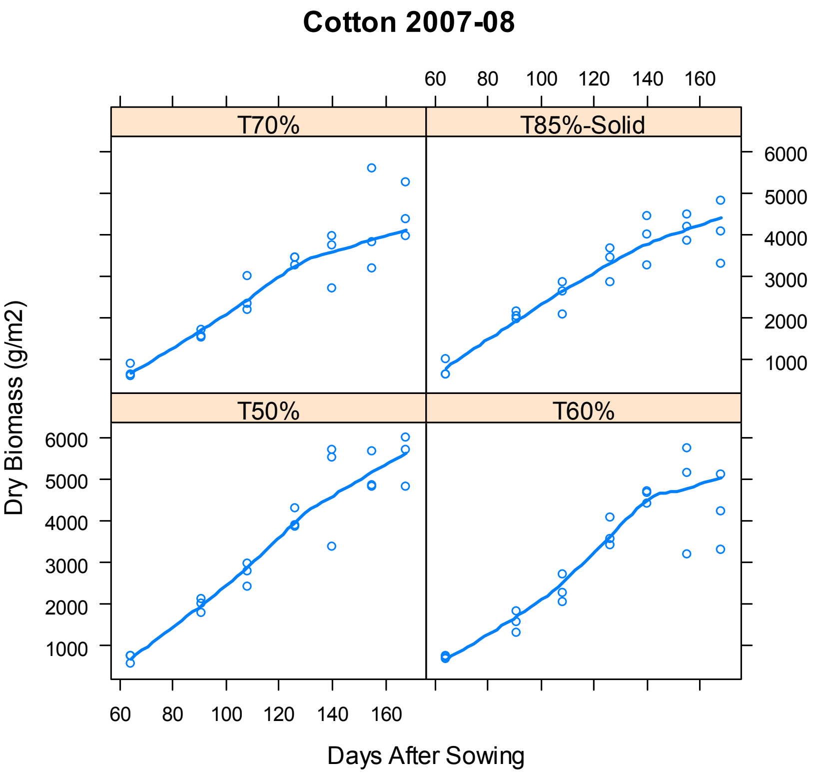


Figure 29. Dry biomass as a function of days after sowing for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%-Solid) at Kingsthorpe during 2007-08.

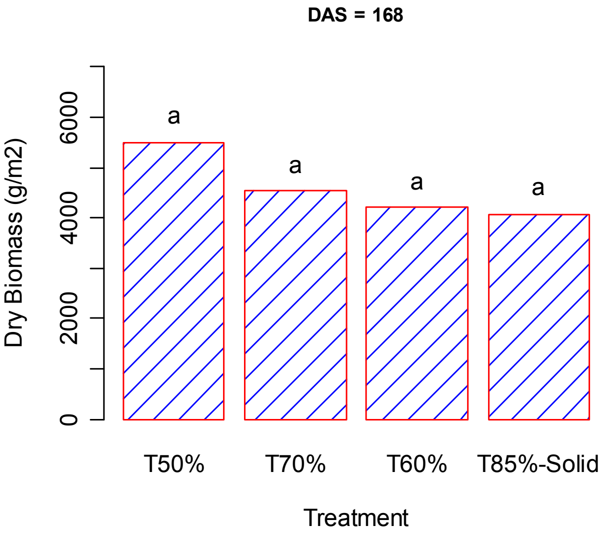


Figure 30. Dry biomass near the end of season [days after sowing (DAS)=168] for cotton grown under four irrigation treatments (T50%, T60%, T70% and T85%-Solid) at Kingsthorpe during 2007-08.

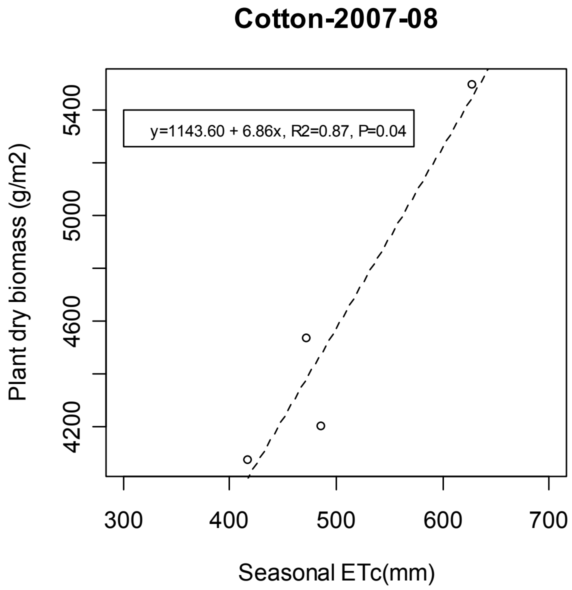


Figure 31. Plant above-ground dry biomass, measured at 168 days after sowing, as a function of seasonal crop evapotranspiration for cotton grown under four irrigation treatments at Kingsthorpe during 2007-08.

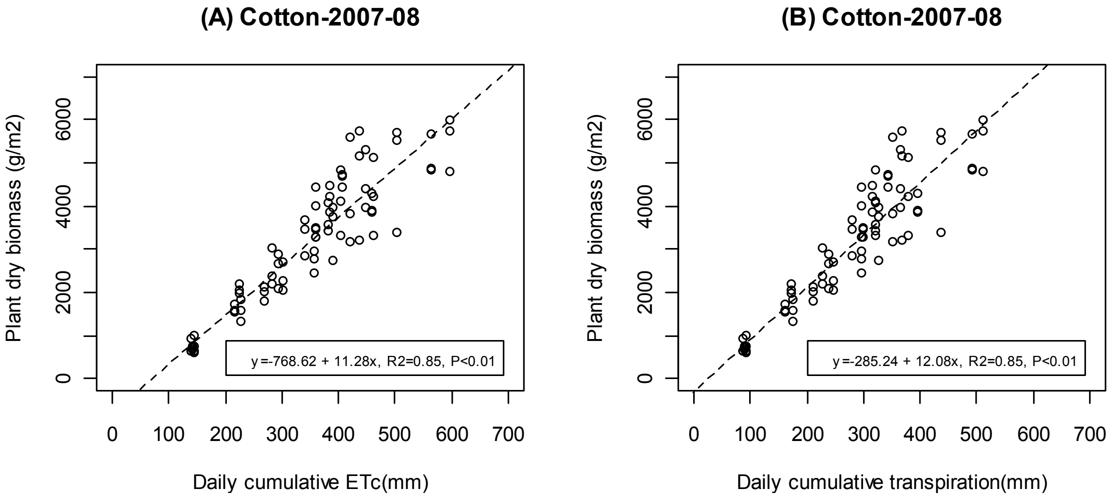


Figure 32. Plant above-ground dry biomass measured at different times during the season as a function of daily cumulative ETc and transpiration for cotton grown under four irrigation treatments at Kingsthorpe during 2007-08. Each point represents data from one replication. Data for all treatments are included.

Reproductive development

Figure 33 to Figure 36 show the reproductive development of the different treatments in terms of total bolls, green bolls, open bolls and the open boll fraction (open bolls/total bolls). Means and mean separation of reproductive variables per meter square for different sampling dates throughout the season are shown in Table 8.

Crop stress significantly affected the production of total bolls. While the total number of bolls continued to increase throughout the whole season for the T50% treatment, the stressed treatments tended to stop producing additional bolls after 91 DAS. The rate of maturity was also affected by irrigation, as indicated by the fraction of open bolls (open bolls/total bolls). By the last sampling date (168 DAS) the T50% treatment had produced almost three times as many bolls as the T85%-Solid treatment. However, only about 15% of the bolls produced by the T50% treatment were open compared to about 81% for the T85%-Solid treatment. That delay in maturity for the T50% treatment could have a big impact on yield and fibre quality, especially since the crop was planted late in the growing season. **Therefore, these results suggest that stressing the crop could be a good strategy for promoting early maturity for late-planted cotton crops in this environment.**

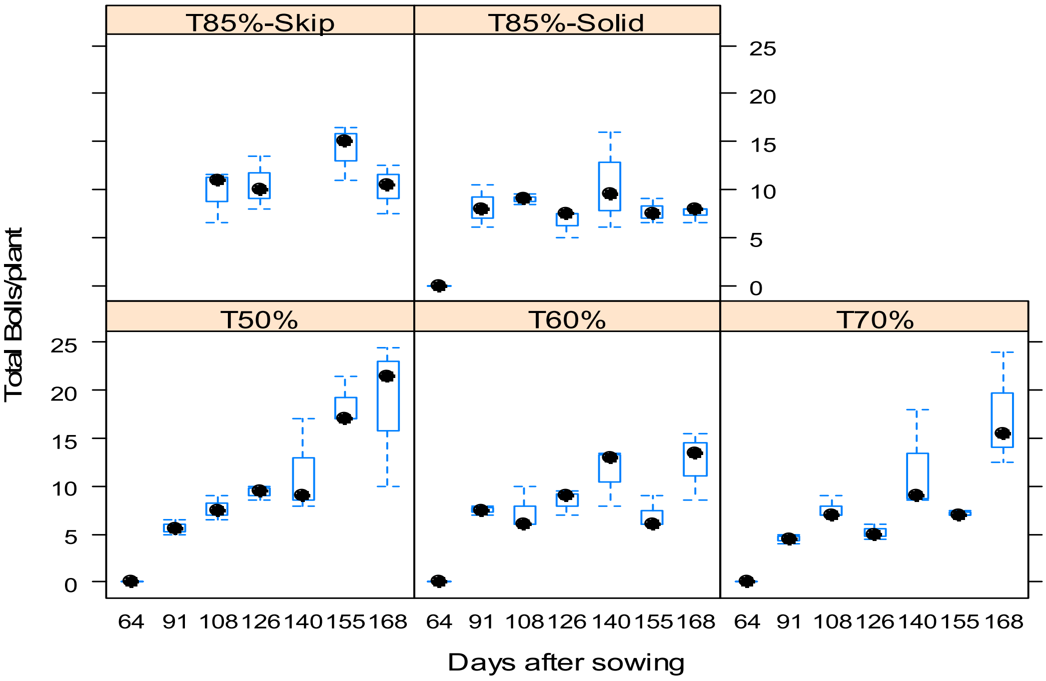


Figure 33. Total bolls per plant measured at different days after sowing for cotton grown under different irrigation treatments at Kingsthorpe during 2007-08.

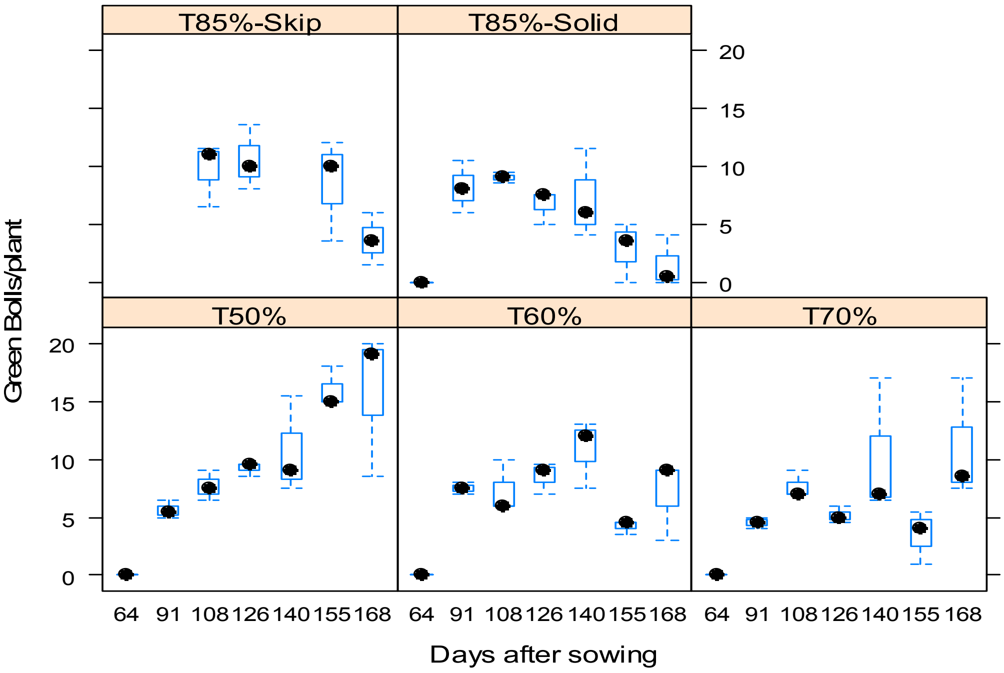


Figure 34. Green bolls per plant measured at different days after sowing for cotton grown under different irrigation treatments at Kingsthorpe during 2007-08.

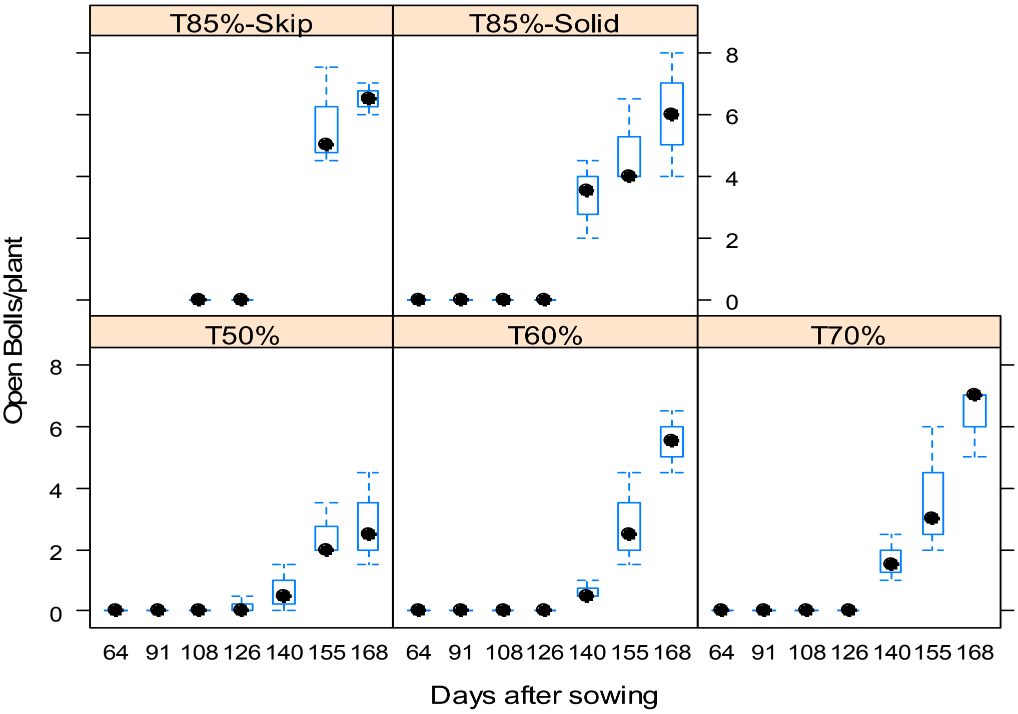


Figure 35. Open bolls per plant measured at different days after sowing for cotton grown under different irrigation treatments at Kingsthorpe during 2007-08.

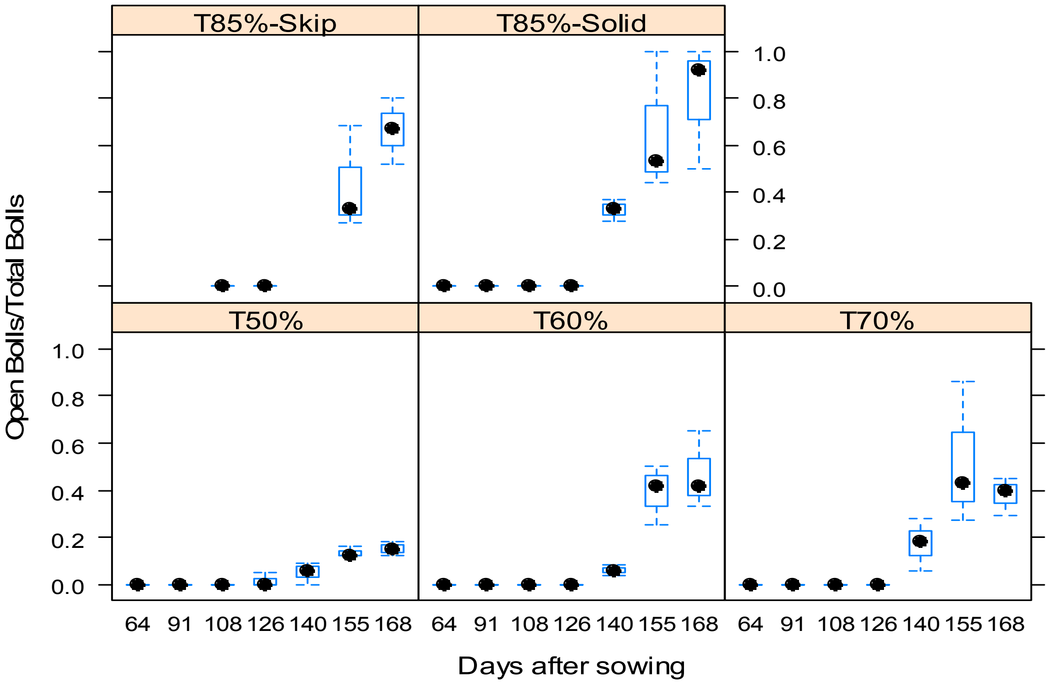


Figure 36. Open bolls fraction (open bolls/total bolls) measured at different days after sowing for cotton grown under different irrigation treatments at Kingsthorpe during 2007-08.

Table 8. Cotton reproductive development variables per m^2 measured at different days after sowing at Kingsthorpe during 2007-08.

		Days after sowing (DAS)						
Variable	**Treatment**	**64**	**91**	**108**	**126**	**140**	**155**	**168**
Flowers/m^2	T50%	0.0	13.8	4.2	36.2 a	1.8	15.5	1.5 ab
	T60%	0.0	18.2	5.2	9.2 ab	0.0	12.0	2.2 ab
	T70%	0.0	20.0	4.0	0.0 b	0.0	10.3	27.2 a
	T85%-Skip			4.0	3.4 ab		2.9	0.0 b
	T85%-Solid	0.0	19.0	0.0	3.3 ab	0.0	0.0	0.0 b
Squares/ m^2	T50%	77.0	89.7	117.0 a	152.5 a	39.2	5.2 b	0.0
	T60%	75.0	62.3	37.3 b	29.5 b	8.7	32.7 b	0.0
	T70%	52.5	78.3	0.0 c	34.5 b	50.0	89.2 a	33.3
	T85%-Skip			25.3 bc	9.3 b		0.0 b	0.0
	T85%-Solid	70.1	60.7	1.5 bc	20.2 b	0.0	14.3 b	18.0
Green bolls/ m^2	T50%	0.0	67.5 bc	95.0	112.8 a	133.7	160.0 a	158.0 a
	T60%	0.0	77.0 b	103.3	112.8 a	103.5	56.8 b	89.0 ab
	T70%	0.0	53.7 c	101.3	66.7 b	116.3	50.8 b	106.5 ab
	T85%-Skip			72.6	75.1 b		63.1 b	20.7 b
	T85%-Solid	0.0	95.0 a	107.2	81.7 b	72.3	30.0 b	14.8 b
Open bolls/ m^2	T50%	0.0	0.0	0.0	2.2	8.3 b	25.0	27.7 b
	T60%	0.0	0.0	0.0	0.0	6.3 b	37.2	67.8 a
	T70%	0.0	0.0	0.0	0.0	19.7 ab	45.7	64.3 a
	T85%-Skip			0.0	0.0		37.4	37.6 ab
	T85%-Solid	0.0	0.0	0.0	0.0	33.5 a	49.7	58.0 ab
Total bolls/ m^2	T50%	0.0	67.5 bc	95.0	115.0 a	142.0	185.0 a	185.7 a
	T60%	0.0	77.0 b	103.3	112.8 a	109.8	94.0 b	156.8 ab
	T70%	0.0	53.7 c	101.3	66.7 b	136.0	96.5 b	170.8 ab
	T85%-Skip			72.6	75.1 b		100.6 b	58.2 b
	T85%-Solid	0.0	95.0 a	107.2	81.7 b	105.8	79.7 b	72.8 ab
Open bolls/Total bolls	T50%	0.0	0.0	0.0	0.0	0.05 b	0.13	0.15 b
	T60%	0.0	0.0	0.0	0.0	0.06 b	0.39	0.47 ab
	T70%	0.0	0.0	0.0	0.0	0.17 ab	0.52	0.38 ab
	T85%-Skip			0.0	0.0		0.43	0.66 a
	T85%-Solid	0.0	0.0	0.0	0.0	0.33 a	0.66	0.81 a
			ANOVA (P>F)					
Flowers/m^2			0.724(ns)	0.765(ns)	0.045	0.441(ns)	0.426(ns)	0.024
Squares/m^2			0.301(ns)	<0.001	0.003	0.421(ns)	<0.001	0.184(ns)
Green bolls/m^2			<0.001	0.304(ns)	0.048	0.486(ns)	0.006	0.006
Open bolls/ m^2			(ns)	(ns)	0.452(ns)	0.019	0.349(ns)	0.018
Total bolls/m^2			(ns)	0.304(ns)	0.046	0.761(ns)	0.014	0.013
Open bolls/Total bolls			(ns)	(ns)	(ns)	0.002	0.137(ns)	0.004

ns = not significant; letters compare treatment means within each DAS.
Treatments with the same letter within each DAS were not significantly different at the P = 0.05 level.

Crop yield

Cotton lint yield in Table 9 shows that yields were low for all treatments and there were no significant differences in crop yield due to the irrigation treatments. Also, there were no significant differences in yield between the two row configuration treatments. The low yields were due to a combination of crop stress for the deficit-irrigated and dryland treatments, and to delay in maturity for the fully-irrigated treatment (T50%). Although the T50% produced enough bolls to produce a much higher yield, the fact that it was planted late, although still within the recommended sowing window for the area, there was not enough degree days accumulated during the season to allow the bolls to fully develop and mature. These results indicate that selecting a medium maturity variety was adequate for the stressed treatments, but an early maturing variety would have been preferable for the T50% treatment.

These results suggest that the industry should consider establishing different sowing windows for dryland and irrigated crops and for different variety maturity classes.

Table 9. Treatment means and Analysis of Variance (ANOVA) of Cotton lint yields obtained at Kingsthorpe during the 2007-08 season.

			Lint from open bolls				Total lint (open + green bolls)			
Treatment	LF[a]	FLGB[b]	(g m^{-1})[c]	(g m^{-2}) [c]	(kg ha^{-1})	(bales ha^{-1})	(g m^{-1}) [c]	(g m^{-2}) [c]	(kg ha^{-1})	(bales ha^{-1})
T50%	0.40 (0.012) [d]	0.209 (0.06)	106.76 (0.95)	106.76 (0.95)	1067.59 (9.49)	4.70 (0.04)	135.57 (10.83)	135.57 (10.83)	1355.69 (108.26)	5.97 (0.48)
T60%	0.41 (0.010)	0.022 (0.02)	123.21 (22.03)	123.21 (22.03)	1232.13 (220.30)	5.43 (0.97)	125.89 (21.54)	125.89 (21.54)	1258.90 (215.39)	5.55 (0.95)
T70%	0.42 (0.004)	0.010 (0.00)	120.52 (4.92)	120.52 (4.92)	1205.17 (49.23)	5.31 (0.22)	121.75 (5.26)	121.75 (5.26)	1217.46 (52.59)	5.36 (0.23)
T85% Solid	0.42 (0.007)	0.014 (0.01)	138.17 (21.29)	138.17 (21.29)	1381.75 (212.91)	6.09 (0.94)	140.07 (20.37)	140.07 (20.37)	1400.70 (203.71)	6.17 (0.90)
T85% Skip	0.42 (0.005)	0.040 (0.02)	170.70 (31.74)	113.80 (21.16)	1137.97 (211.59)	5.01 (0.93)	177.56 (30.62)	118.37 (20.41)	1183.74 (204.13)	5.21 (0.90)
	ANOVA (Including all treatments)									
Pr > F [Treatment (d.f.[e] = 4)]	0.084 (ns)	**<.001 ***	**0.016 ***	0.203 (ns)	0.203 (ns)	0.203 (ns)	**0.043 ***	0.495 (ns)	0.495 (ns)	0.495 (ns)
LSD $_{(0.05)}$	0.016	0.055	32.48	27.78	277.80	1.224	35.68	31.19	311.9	1.374
SEM [f]	0.005	0.017	9.96	8.52	85.2	0.375	10.94	9.56	95.6	0.421
	ANOVA (Excluding the T85% Skip treatment)									
Pr > F [Treatment (d.f.[e] = 4)]	0.126 (ns)	**<.001***	0.205 (ns)	0.205 (ns)	0.205 (ns)	0.205 (ns)	0.576 (ns)	0.576 (ns)	0.576 (ns)	0.576 (ns)
LSD $_{(0.05)}$	0.018	0.066	30.94	30.94	309.4	1.363	34.50	34.50	345.0	1.52
SEM [f]	0.005	0.020	8.94	8.94	89.4	0.39	9.97	9.97	99.7	0.44
	ANOVA (Only treatments T85% Solid and T85% Skip)									
Pr > F [Treatment (d.f.[e] = 4)]	0.979 (ns)	0.097 (ns)	0.141 (ns)	0.136 (ns)	0.136 (ns)	0.136 (ns)	0.109 (ns)	0.160 (ns)	0.160 (ns)	0.160 (ns)
LSD $_{(0.05)}$	0.028	0.038	58.90	43.17	431.7	1.90	58.18	42.71	427.1	1.88
SEM [f]	0.005	0.006	9.68	7.10	71.0	0.313	9.56	9.93	70.2	0.31

[a] LF = Lint fraction = (lint mass)/(seed cotton mass)

[b] FLGB = Fraction of lint from green bolls = (lint yield from green bolls)/(Total lint yield)

[c] Lint yields per unit area (g m^{-2}, kg ha^{-1}, bales ha^{-1}) took into account that plants in the T85% Skip treatment had access to an area 1.5 times larger than plants in the other treatments, while yields per unit length (g m^{-1}) did not take this into account.

[d] Numbers in parenthesis are standard deviations of treatment means

[e] d.f. = Degrees of freedom.

[f] SEM = Standard errors of means

* Significantly different at the 0.05 level, and ns = not significant

Fibre quality results from commercial laboratory

Fibre quality results from the commercial laboratory are shown in Table 10. Of the variables analysed, only micronaire was significantly affected by the irrigation treatments. Figure 37 shows that the wettest treatment tended to have a lower micronaire, that is, stress increased micronaire. Figure 37 (B) shows a good negative correlation between micronaire and seasonal crop evapotranspiration. As more water was available, more bolls were produced that did not have the opportunity to properly develop and mature, especially in a climate where the length of the growing season was limited.

Discount prices are shown in Figure 38, adapted from data supplied by Mike Bange in 2009, assuming a cotton price of AUS$420/bale and AUS$=0.74 US$. Price discounts apply to cotton with micronaire outside the range of 3.5-4.9. In this study, only the T50% treatment had micronaire that would attract a discounted price. From Figure 38, the low micronaire value of 2.9 for the T50% treatment would represent a significant price discount of about AUS$98/bale, which is equivalent to about 23% of the assumed cotton price.

Table 10. Cotton fibre quality for different irrigation treatments obtained at Kingsthorpe during 2007-08.

Treat	L	% area	cnt	Length	Uniformity	SFI	Strength	Elong	Micronaire
T50%	1.3	0.1	4.0	1.22	84.2	7.9	32.1	6.6	2.9d
T60%	1.0	0.0	4.0	1.22	84.6	7.9	33.0	6.6	3.8 c
T70%	2.0	0.2	3.7	1.18	83.9	8.2	32.6	6.6	4.4 a
T85% Skip	1.7	0.1	7.7	1.21	85.4	7.6	33.4	6.6	3.9 bc
T85% Solid	1.7	0.1	3.7	1.18	84.2	8.1	31.7	6.7	4.2 ab
Average	1.5	0.1	4.6	1.2	84.5	7.9	32.6	6.6	3.8
ANOVA including all treatments									
P>F	ns	ns	ns	ns	ns	ns	ns	ns	<0.001
ANOVA for T85% Skip and T85% Solid									
P>F	ns	ns	ns	ns	ns	ns	0.023	ns	ns

ANOVA= Analysis of variance
ns = no significant
Treatment means with the same letter were not significantly different at the P = 0.05 level.
SFI = short fibre index

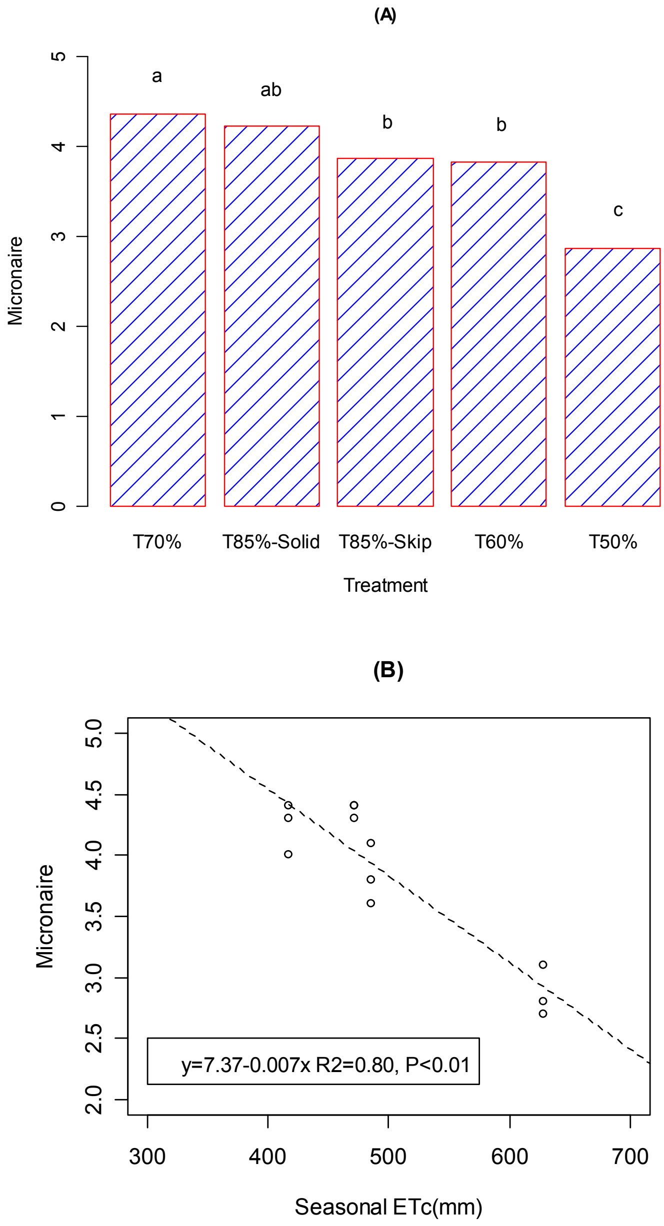


Figure 37. (A) Cotton fibre micronaire by irrigation treatment, and (B) relationship between fibre micronaire and seasonal crop evapotranspiration (ETc) for cotton grown under four irrigation treatments and two row configurations obtained at Kingsthorpe during 2007-08.

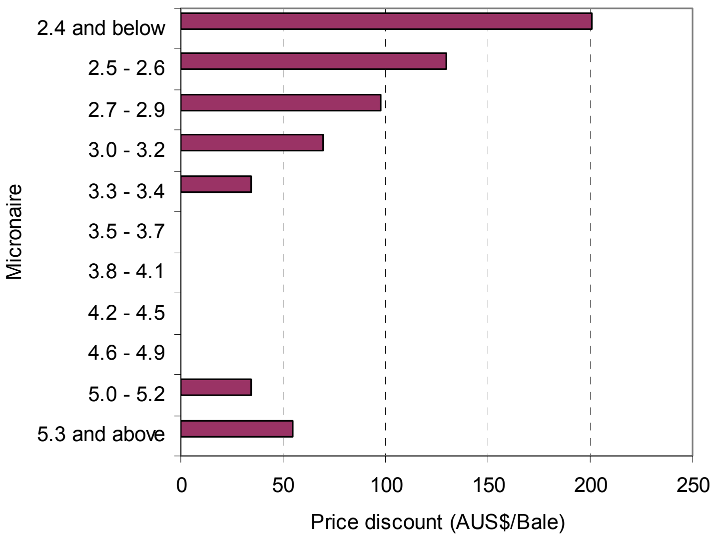


Figure 38. Price discount for cotton fibre with different micronaire (adapted from data supplied by Bange, 2009. Assuming a cotton price of AUS$420/bale and AUS$=0.74 US$)

Fibre quality results from CSIRO laboratory

A total of twenty one fibre quality variables were measured at the CSIRO fibre quality laboratory. Analysis for micronaire was not performed by CSIRO. Results are shown in Figure 39 and are also summarized in Table 11. Significant differences among treatments were found for nep count, length (W and n), short fibre count (W, and n), upper quartile length (UQL), 5.0% span length, fineness, immature fibre content and maturity ratio.

The measured fibre quality variables were correlated with seasonal crop evapotranspiration (ETc) using linear regression analysis. Significant linear relationships with seasonal ETc were found for seven of the fibre quality variables (Figure 40). These variables included length (W), nep count, upper quartile length (W), fineness, fineness measured by cottonscan, immature fibre content and maturity ratio. Fineness and maturity ratio decrease with ETc while the other variables increased with ETc.

In this study, crop stress decreased fibre length, nep count, and immature fibre content, but increased fibre micronaire, fineness and maturity ratio. No information, however, could be found about price discount for fibre quality variables other than micronaire, therefore, their economic impact could not be evaluated.

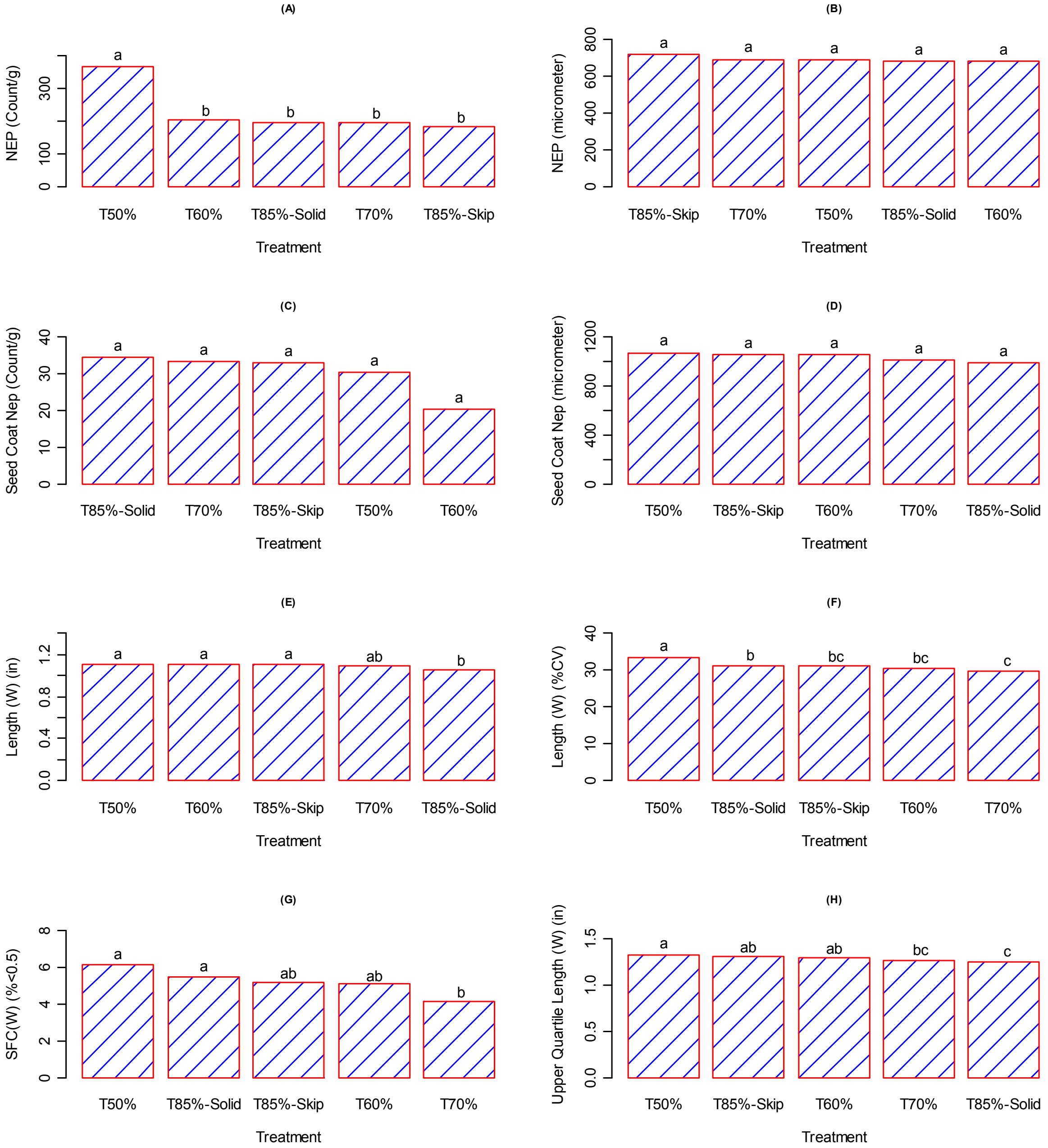


Figure 39. Results of cotton fibre quality analysis for cotton grown under four irrigation treatments and two row configurations (T50%, T60%, T70% and T85%-Solid and T85%-Skip) at Kingsthorpe during 2007-08. Treatments with the same letters are not significantly different.

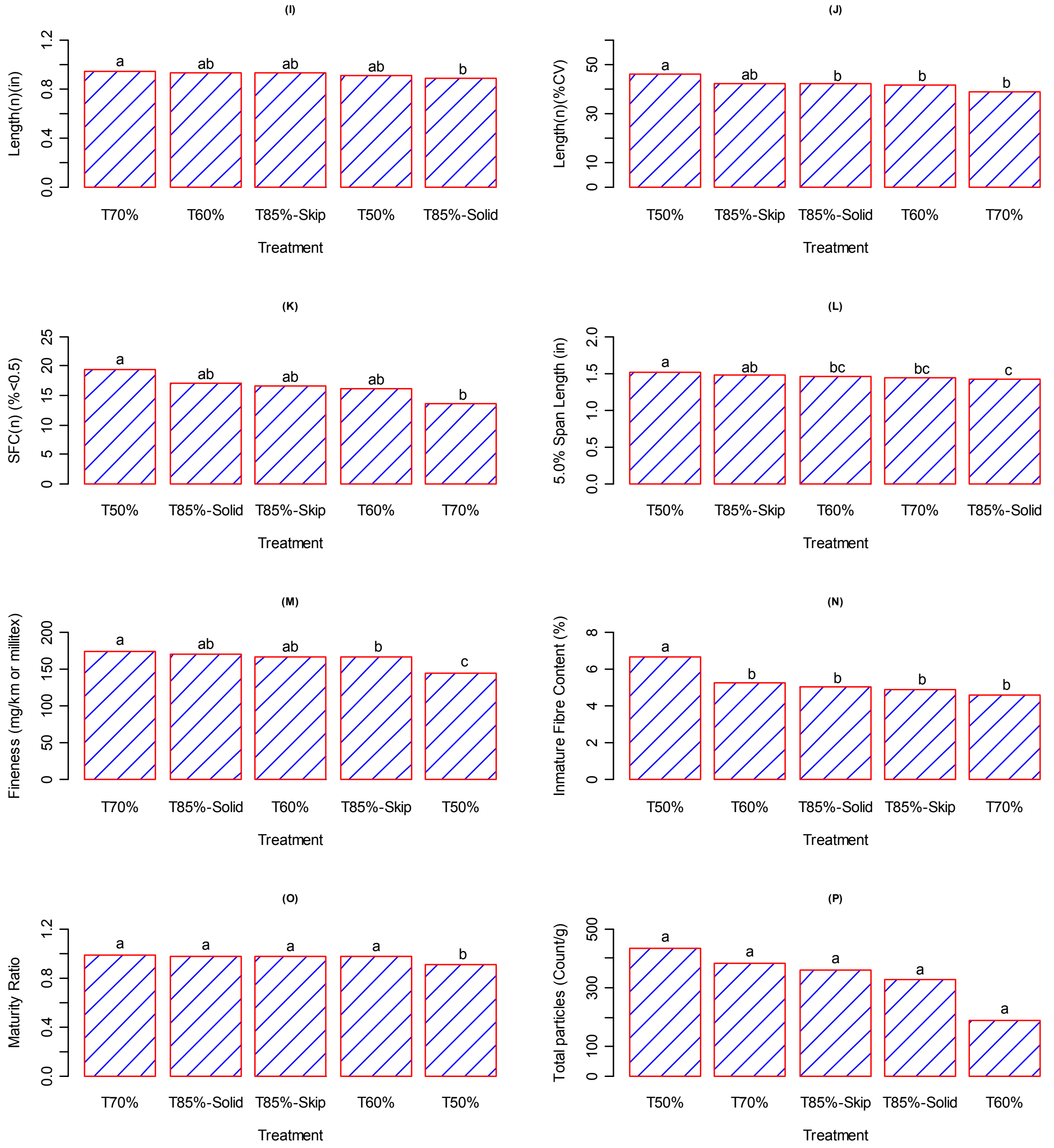


Figure 39. Continuation.

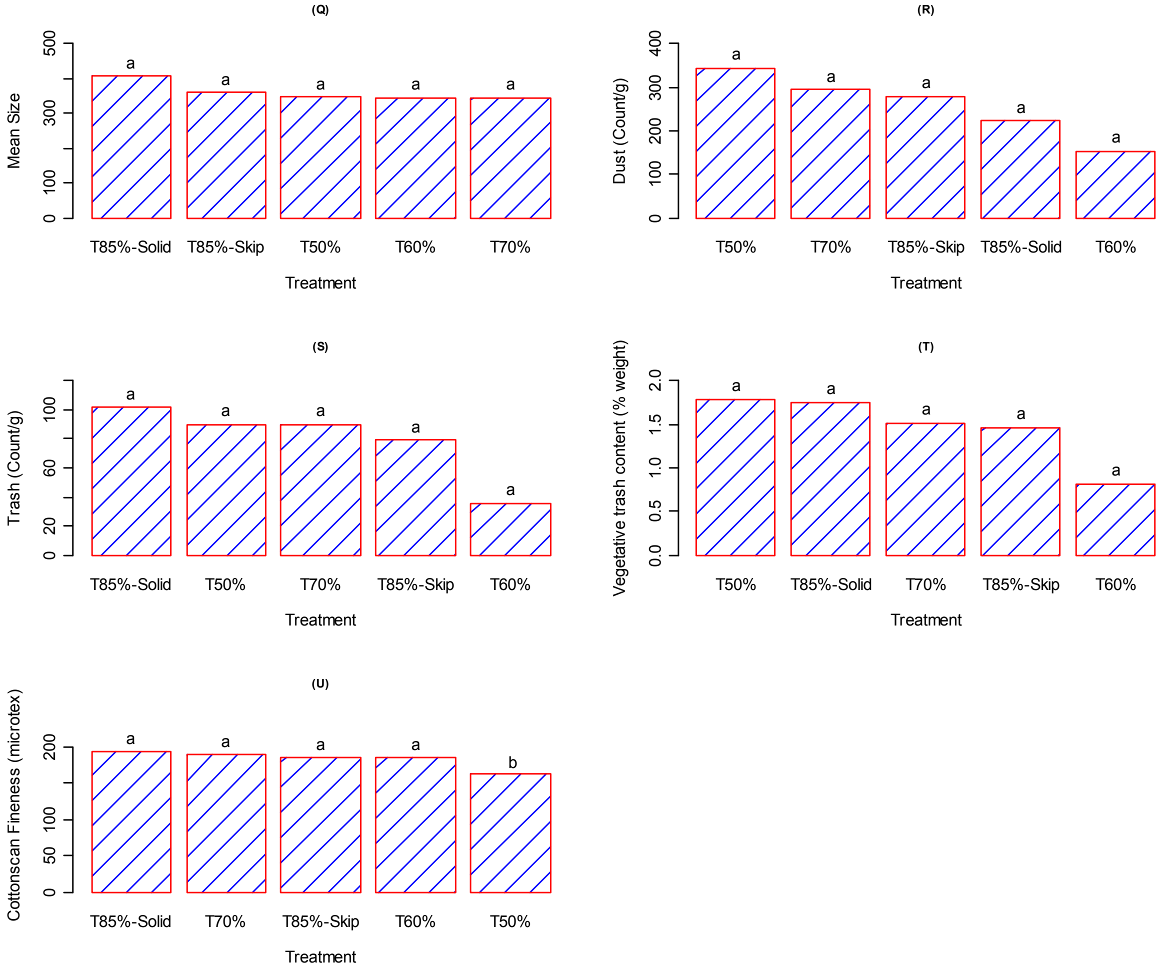


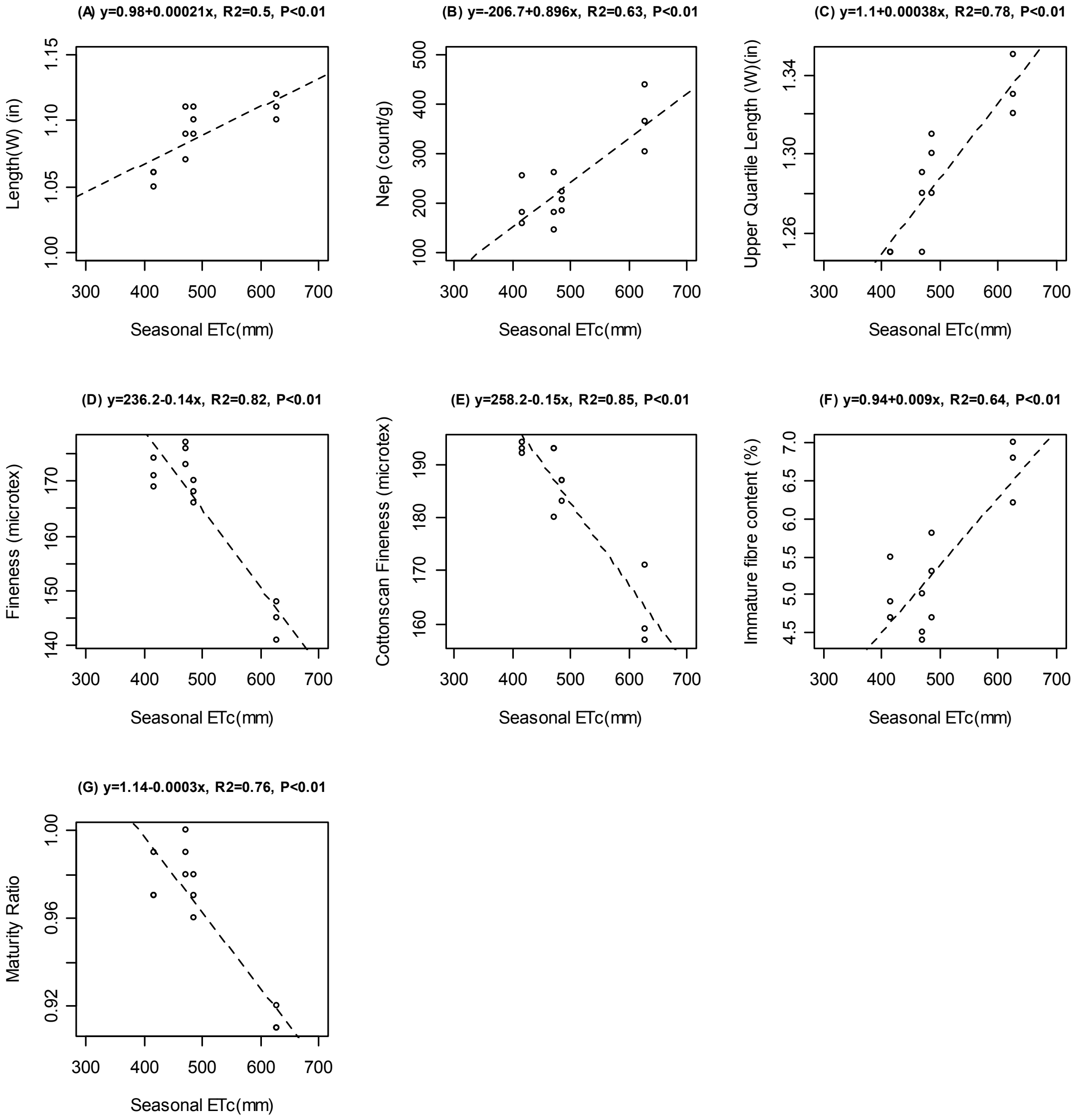
Figure 39. Continuation.

Table 11. Cotton fibre quality by irrigation treatment obtained at Kingsthorpe in 2007-08.

Treat	NEP Cnt/g	NEP [um]	SCN Cnt/g	SCN [um]	L(w)_ [in]	L(w)_%CV	SFC(w) %<0.5	UQL(w) [in]	L(n)_[in]	L(n)_%CV
T50%	369.67 a	690.33	30.33	1068.00	1.11 a	33.53 a	6.17 a	1.33 a	0.92	46.07 a
T60%	204.67 b	682.67	20.33	1051.33	1.10 a	30.50 bc	5.07 ab	1.30 ab	0.93	41.67 a
T70%	195.33 b	694.00	33.33	1008.67	1.09 ab	29.63 c	4.17 b	1.27 bc	0.94	39.10 a
T85%-Solid	199.00 b	684.67	34.33	983.00	1.06 b	31.20 b	5.50 ab	1.25 c	0.90	42.10 a
T85%-Skip	184.67 b	720.67	33.00	1055.33	1.10 a	31.13 bc	5.17 ab	1.31 ab	0.93	42.43 ab
Average	**230.67**	**694.47**	**30.27**	**1033.27**	**1.09**	**31.20**	**5.21**	**1.29**	**0.92**	**42.27**
ANOVA										
Pr(>F)	**0.003**	**0.14 (ns)**	**0.78 (ns)**	**0.64 (ns)**	**0.009**	**<0.001**	**0.008**	**<0.001**	**0.51(ns)**	**0.0018**

Treat	SFC(n) %<0.5	5.0% [in]	FINE mTex	IFC [%]	MAT RATIO	Total Cnt/g	Mean SIZE	DUST Cnt/g	TRASH Cnt/g	VFM%	Fineness (mTex)
T50%	19.40 a	1.51 a	144.67 c	6.67 a	0.91 b	435.00	346.67	344.33	90.00	1.78	162.36 b
T60%	16.17 ab	1.46 bc	168.00 ab	5.27 b	0.97 a	189.00	345.67	153.33	35.67	0.81	185.64 a
T70%	13.57 b	1.44 bc	175.33 a	4.63 b	0.99 a	384.33	345.67	294.00	90.00	1.51	188.51 a
T85%Solid	17.03 ab	1.42 c	171.33 ab	5.03 b	0.98 a	325.67	408.00	223.33	101.67	1.76	193.28 a
T85%Skip	16.60 ab	1.47 ab	167.00 b	4.93 b	0.97 a	359.33	361.00	279.00	79.33	1.47	186.00 a
Average	**16.55**	**1.46**	**165.27**	**5.31**	**0.96 a**	**338.67**	**361.40**	**258.80**	**79.33**	**1.46**	**183.16**
ANOVA											
Pr(>F)	**0.008**	**0.0013**	**<0.001**	**<0.001**	**<0.001**	**0.28 (ns)**	**0.67 (ns)**	**0.20 (ns)**	**0.57 (ns)**	**0.56 (ns)**	**<0.001**

Results are mean values of three replicates/sample.
SCN = seed coat nep
L = length
UQL = upper quartile length
5.0% = 5% span length
FINE = fineness (linear density) in mg/km or millitex. Fineness and maturity are not directly measured in the AFIS. The AFIS signal is related to maturity/fineness reference data
IFC = immature fibre content (proportion of fibres with maturity (theta) value less than 0.25 (0 – 1.0 scale)
MAT RATIO = maturity ratio (scale according to BS and ASTM Standard Methods)
Total cnt = Total particle count inc. dust and trash
VFM% = vegetative trash content as percent weight of sample
Fineness-Cottonscan provides direct measurement of fineness (linear density). Can be considered as reference method.
Ns = not significant; letters compare treatment means. Treatments with the same letter were not significantly different at the P = 0.05 level.



(A) y=0.98+0.00021x, R2=0.5, P<0.01

(B) y=-206.7+0.896x, R2=0.63, P<0.01

(C) y=1.1+0.00038x, R2=0.78, P<0.01

(D) y=236.2-0.14x, R2=0.82, P<0.01

(E) y=258.2-0.15x, R2=0.85, P<0.01

(F) y=0.94+0.009x, R2=0.64, P<0.01

(G) y=1.14-0.0003x, R2=0.76, P<0.01

Figure 40. Relationships between seasonal crop evapotranspiration (ETc) and several cotton fibre quality variables for cotton grown under four irrigation treatments and two row configurations at Kingsthorpe during 2007-08. Each point represents one replication. The linear regression line is shown.

Conclusions

In this study it was estimated that the seasonal ETc for fully-irrigated cotton (ETp) was about 750 mm during 2007-08 at Kingsthorpe. Cumulative daily ETp increased linearly from sowing to 60 DAS at an average rate of 2.4 mm/d. After 60 DAS it increased linearly at an average rate of 5.29 mm/d. Evaporation accounted for about 11-15% of the actual crop evapotranspiration or about 62-69 mm. Crop stress affected crop water use considerably. Treatments resulted in seasonal crop evapotranspiration ranging from 417 to 628 mm, representing from 56 to 84% of potential evapotranspiration (ETp). For all treatments, stress started at about 60 DAS. At this time the soil water deficit was only about 50 mm. This suggests that the common practice of triggering irrigation at a fixed (and higher) deficit should be replaced for dynamic deficits. Irrigation scheduling softwares could be a good aid for growers in determining when and how much to irrigate. In this study, computer model based on the FAO-56 procedure estimated the seasonal crop evapotranspiration for stressed cotton to within 3% compared with a water balance method based on soil moisture measurements with neutron probe. When evaluating the soil water extraction distribution, it was found that the crop extracted water from as deep as 150 cm in the soil profile. However, about 80% of the seasonal water extraction took place from the top 60 cm and 90% from the top 80 cm soil depth. These results then suggest that irrigation should be targeted at wetting only the top 80 cm of the soil profile. Also, from about 32 DAS to 100 DAS, the depth of soil water extraction increased almost linearly at a rate of 1.89 cm/day. The depth of soil water extraction also increased almost linearly at a rate of 2.36 times the crop canopy height during the same period.

When evaluating the impact of irrigation treatments on crop development, reproductive development, yield and lint quality, it was found that crop stress affected crop development. For example, comparing irrigation treatments, plant height measured close to the end of the season (168 DAS) increased almost linearly with seasonal ETc at a rate of 0.14 cm per additional mm of seasonal ETc. Similarly, dry biomass measured at the same time was linearly related to seasonal ETc, increasing at a rate of 6.86 g/m^2 per additional mm of seasonal ETc. On a daily basis, pooling data from all treatments, daily accumulation in above-ground biomass was linearly related to daily cumulative ETc and to cumulative transpiration, at rates of 11.28 and 12.08 g/m^2 per mm of cumulative ETc and T, respectively.

Crop stress affected reproductive development and lint quality, but did not affect lint yield. For example, stress caused the crop to stop producing additional bolls, while the non-stressed plants kept producing additional bolls until the end of the season. Boll produced late in the season, however, did not have the chance to properly develop and mature. Despite irrigation promoting bigger plants, no significant lint yield differences were observed in this study. Therefore, lint yield was not related to seasonal crop evapotranspiration and transpiration, as is commonly the case in this type of studies (Payero et al., 2008; Payero et al., 2009). This was mainly due to late planting and subsequent delay in maturity for the less stressed treatments. Crop stress and delay in crop maturity significantly affected lint quality. Some of the indicators of lint quality were linearly related to seasonal crop evapotranspiration. Crop stress decreased fibre length, nep count, and immature fibre content, but increased fibre micronaire, fineness and maturity ratio. Micronaire decreased almost linearly with seasonal crop evapotranspiration. These finding suggest that it is important to avoid late planting. If it is not possible, early maturing varieties should be selected. Stressing the crop could be a good management option for promoting early maturity of late-planted cotton crops.

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References

Ali, M.H. and Talukder, M.S.U., 2008. Increasing water productivity in crop production-A synthesis. Agricultural Water Management, 95: 1201-1213.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome.

Bange, M. and Constable, G.A., 2006. Crop Physiology - Producing a Better fibre, Australian Cotton Conference. Australian Cotton Growers Research Association, Gold Coast.

Cotton Seed Distributors, 2007. 2007 Variety Guide. Cotton Seed Distributors, Toowoomba, Australia, pp. 1-18.

Payero, J.O., Tarkalson, D.D., Irmak, S., Davison, D. and Petersen, J.L., 2008. Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate. Agricultural Water Management, 95: 895-908.

Payero, J.O., Tarkalson, D.D., Irmak, S., Davison, D. and Petersen, J.L., 2009. Effect of timing of a deficit-irrigation allocation on corn evapotranspiration, yield, water use efficiency and dry mass. Agricultural Water Management, 96(10): 1387-1397.

Raes, D., Steduto, P., Hsiao, T.C. and Fereres, E., 2009. Chapter 1. AquaCrop-The FAO crop model to simulate yield response to water, Food and Agriculture Orgamnization of the United Nations, Rome, Italy.

Sentek Sensor Technologies, 2001. Calibration of Sentek Pty Ltd soil moisture sensors, Srepney, South Australia.

Yeates, S., Roberts, J., Neilsen, J. and Richards, D., 2009. Toward better water management of Bollgard II cotton, The Australian Cotton Grower, pp. 22-27.

Appendix VII

Comparison of water extraction of cotton planted on single-skip and solid row configurations

Jose O. Payero[1]*, G. Robinson*[1]*, D. Singh*[1]

[1] **Agri-Science Queensland, Department of Employment, Economic Development & Innovation,** www.deedi.qld.gov.au **; Email** jose.payero@deedi.qld.gov.au

Abstract

Skip row configuration is one of the strategies used by Australian cotton (*Gossypium hirsutum L.*) growers to minimise production risk in water-limiting environments. Although there have been considerable research comparing yields between different row configurations, detailed information comparing water extraction is still lacking. The objectives of this study were to compare the water use, soil water extraction pattern, crop development and yield of solid and single-skip row configuration of dryland cotton. A field experiment comparing two row configuration treatments (solid and skip) was conducted in a sub-tropical climatic zone and a heavy clay soil located at Kingsthorpe, Australia, during 2007-08. Soil water was measured from each configuration about weekly at 10 cm depth increments using the neutron probe method. Measurements were made at three positions (P1, P2, and P3) with respect to the crop row. We found that in general, the skip configuration tended to have more soil water available in the top 105 cm soil profile between 58 and 98 days after sowing, during the vegetative development stage. The time when the additional water was available for the skip configuration varied with measuring position (P1, P2, and P3). The additional water was available earlier in the season at position P3, which was available during 58 and 65 DAS, compared with positions P1 and P2 where the additional water was available later in the season (72 to 98 DAS). For the entire season, however, both configurations extracted about the same amount of soil water, which was about 128 mm, suggesting that both configurations were water limited and extracted all the water that was available. The 128 mm added to the seasonal rainfall of 271 mm allowed us to estimate the seasonal water use at about 399 mm, which was about half of the seasonal grass-reference evapotranspiration (ETo = 804 mm) for the site. Because of the additional water available between 58 and 98 DAS, the crop under the skip configuration grew about 10 cm taller. The additional water, however, was not enough to produce significant differences in crop yield between the skip and solid configurations.

***Keywords**: skip-row, cotton, soil water*

1. Introduction

In Australia, cotton producers use different row configurations, including solid, single skip, double skip, wide row, and alternate skip (Bange and Stiller, 2002). Although skip-row configurations, instead of solid configurations, are mainly used in dryland production, they are also being used in irrigated cotton in situations where water is limited. Results of research comparing yields of solid to single skip and double skip cotton in Australia have been reviewed by Bange and Stiller (2002), and Gibb (1995). Gibb (1995) suggested the following equations:

$$Yss = 0.82Ys + 0.36 \qquad (1)$$

$$Yds = 0.58\ Ys + 0.79 \qquad (2)$$

where, Yss = single skip yield, Yds = double skip yield, Ys = solid yield, all in units of bales/ha. The equations were derived from over 30 irrigated and dryland experiments conducted during 1984-1993 in Central Queensland and the Darling Downs. Relationships from other studies were also reported by Bange and Stiller (2002) and Goyne and Hare (1999). A plot of Eqs (1) and (2) would show that Ys>Yss>Yds, except for very low yield levels (ie. Yields < 2.5 bales/ha). Therefore, it is to be expected that the configurations with the higher yields will also tend to have higher water use efficiency (WUE, Yield/Total water).

Although skip row configurations give up yield potential compared with solid planting when water is not severely limited, they reduce risk of crop failure when water is limited. Also, since production costs can be significantly reduced with skip row, especially for Bollgard II varieties with high seed cost, Gibb (1995) suggested that gross margins per unit area ($/ha) could actually increase with skip row compared to solid planting. Goyne and Hare (1999) reported gross margins for single and double skip raingrown crops of $532/ha and $604/ha, respectively, compared with only $398/ha for solid planting. Additional potential income from skip row configurations under water limiting situations can also derive from the premium price due to improved fibre quality compared to solid planting, as reported by (Goyne and Here, 1999). Although in Australia there has been extensive research comparing row configurations, the focus has been on yield and fibre quality. Accurate comparisons of water use, soil water extraction pattern, and crop development among cotton configurations are still lacking. The objectives of this study were to compare the water use, soil water extraction pattern, crop development and yield of solid and single-skip row configuration of dryland cotton. This paper reports on the water use, soil water extraction pattern, and crop yield. Details on crop development and fibre quality are given in a companion paper.

2. Methods

2.1. Site description

The field experiment for this study was conducted at the Queensland Primary Industries & Fisheries Kingsthorpe research station during the 2007-08 cotton season. The station is located within the Darling Downs area, in a sub-tropical climatic zone, about 20 km north-west of the city of Toowoomba, Queensland, Australia (27^{o}30'44.5" Latitude South, 151^{o}46'54.5" Longitude East, 431 m above mean sea level). The soil at the site is a *Haplic, self-mulching, black, Vertosol*. It has a heavy clay texture in the 1.5 m root zone profile, with a distinct change in soil color from brownish black in the top 90 cm to dark brown deeper in the profile. The soil is of alluvial fan and basalt rock origin, slowly permeable, with a surface slope of about 0.5%.

2.2. Experimental design

Two cotton (*Gossypium hirsutum L.*) row configuration treatments (Solid and Single-Skip) were compared as a split plot within a larger irrigation experiment. The larger experiment included four irrigation treatments (including a dryland treatment) and three replications. Each main experimental plot was 13 m wide x 20 m long. A 4-m border was allowed between plots and a 4 m road was located at the centre of the research area. A refuge crop (6 rows) was planted on the east and west side of the plots. The plots were irrigated individually with bore water using a hand-shift sprinkler system. Partial-circle sprinkler heads were used to avoid irrigating adjacent plots. The row configuration comparisons were conducted as a split plot within the dryland treatment. The plots for the dryland treatment were divided into two, with half of the plot kept as a Solid row configuration and in the other half, alternate crop rows were eliminated and a Single-skip row configuration was established (Fig. 1).

2.3. Soil water

For the row configuration comparison, six neutron tubes were installed in each plot, three in the Solid configuration and three in the Single-skip configuration. The three tubes were installed at three positions with respect to the crop row, two in the plant line (positions P1 and P3) and one in the middle of the crop row (position P2) (Fig. 1A). Neutron readings were taken about weekly (often twice a week) at 0.10 m depth increments to a depth of 1.4 m. Measurements were taken with a 503DR Hydroprobe (CPN International, Inc., Martinez, CA, USA), using integration periods of 16 seconds for normal counts and 240 seconds for standard counts. Standard counts were taken on water by lowering the neutron source on an access tube installed in the middle of a water drum (≈200 L). The neutron probe was calibrated to the site against gravimetric measurements of soil samples taken from dry and wet locations within the field, resulting in a good linear relationship between count ratios (CR, unitless) and volumetric soil water content (*swc*, fraction) [*swc* = 0.661CR, R^2=0.996]. Measured soil bulk densities (BD) for the site were used to convert from mass-based to volumetric *swc* (Fig. 2).

The measured *swc* for each depth was converted to mm of water as:

$$TWin = swc_i * d_i \tag{3}$$

$$TWto = swc_a * d_a \tag{4}$$

Where, *TWin* = total soil water in deph $_i$ (mm), swc_i = volumetric soil water content in depth *i* (fraction), d_i= depth increment (mm) for depth $_i$, *TWto* = total soil water above soil deph d_a (mm), d_a = soil depth (mm), swc_a = average volumetric soil water content (fraction) above soil depth d_a.

2.4. Cultural practices

Originally the crop was planted to a solid configuration, and the single-skip treatment was established by trimming the unneeded crop rows on 20/12/07 after the neutron tubes were installed. Cotton was planted on 12 November 2007 after the soil received a few small rainfall events during the previous week, within the Bollgard® II cotton planting window for the Darling Downs. The cotton hybrid Sicala 60 BRF, which is a Bollgard® II Roundup Ready Flex® variety, was planted. The conventional (non-Bollgard) variety Sicot 43 RRF was planted as the refuge crop. Sicala 60 BRF is rated as a medium maturity variety with very good yield potential for late planting, excellent fibre quality characteristics, and with a long and strong fibre with mid range micronaire (Cotton Seed Distributors. 2007, 2007). Bollgard® II cotton varieties have been developed by genetically modifying cotton by adding two genes of the soil bacterium *Bacillus thuringiensis* (Bt). The addition of these genes produces two proteins that are toxic to the *Helicoverpa* caterpillar, the most important insect attacking conventional cotton varieties. Cotton seeds were planted at a density of about 17 seeds/m at a depth of about 3.8 cm (1.5”) and a row spacing of 1 m. The aim was to get an established stand of 11-12 plants/m.

Lint yield was determined by hand harvesting a 2.5-m sample of two rows (14 May, 2008). The seed cotton (lint + seeds) was collected from the open bolls. The green bolls were also collected separately. The number of open and green bolls in each plant of a 1-m length was determined. The seed cotton and green boll samples were oven-dried at 40°C for about a week. The green bolls opened after drying and the seed cotton was collected and kept separate from that harvested in the field. Seed cotton samples from the green balls and those harvested in the field were weighted separately. A 350 g subsample from the seed cotton harvested in the field was used to separate the lint from the seeds using a laboratory gin that was built in-house. The mass of the lint and seeds in the subsample was measured. The lint was send to the lab to determine fibre quality.

2.6. Weather data

An EnviroStation (ICT International Pty Ltd, Armidale, NSW, Australia) weather station was installed next to the research plots. The station measured solar radiation, air temperature (maximum, minimum, and average), relative humidity, wind speed and rainfall. Daily and hourly data summaries were recorded.

2.7. Statistical analysis

Statistical analyses were conducted with GenStat (11th Edition, VSN International, Ltd), using the ANOVA and MANOVA procedures for comparing treatment means for datasets including one or more variables, respectively. Data plotting was conducted with R version 2.6.2 (The R Foundation for Statistical Computing) and Microsoft Excel.

3. Results and Discussion

3.1. Weather conditions

A summary of the weather conditions at Kingsthorpe during the study are shown in Table 1. The growing season extended for about six month, from mid November to mid May. Air temperatures and water requirements peaked in January. For all moths, the grass-reference evapotranspiration (ETo) far exceeded rainfall. February was the wettest month, accounting for almost half of the seasonal rainfall. Rainfall accounted for only about 1/3 of the seasonal ETo, which explains the need for irrigation to be able to maximize crop yield. Sufficient rainfall was especially lacking in January, when ETo was at its peak. Insufficient rain early in the growing season is expected to significantly reduce vegetative growth and, therefore, to have a negative impact on crop yield.

3.2. Comparison of total soil water in each depth increment (TWin)

The total water content (*TWin*) by cotton row configuration (Skip and Solid), measurement position (P1, P2, P3) and days after sowing (DAS) in each of 10-cm soil depths increments at 25, 55, 105 and 135 cm soil depths (TWin25, TWin55, TWin105, and TWin135) obtained at Kingsthorpe during 2007-08 are shown in Fig. 3. Differences in TWin between the two configurations (Skip-Solid) as a function of DAS for four selected depths (25, 55, 105, and 135 cm) are shown in Fig. 4.

Differences in *TWin* between the two configurations for each 10-cm depth increment, sampling position, and DAS are shown in Table 2. Table 2 also shows the results of statistical analysis testing if the observed differences in *TWin* between configurations were statistically significant (shaded cells were statistically significant at α = 0.05). Positive differences in *TWin* in Table 2 and Fig. 4 indicate more water available for the skip compared with the solid configuration.

Figure 3 shows that soil water was extracted from all depths. For each depth, the difference in *TWin* between the initial and end sampling date tended to decrease with depth. This indicates that more soil water was extracted from the shallower depths due to a higher concentration of roots and to more water available near the soil surface. For all depths and positions, *TWin* for the two configurations tended to follow each other very closely throughout the entire season. When there were increases in *TWin*, these increases tended to occur at all depths. This could be explained by preferential water flow through the side of the neutron access tubes and/or the cracking nature of the soil type. These black expanding clay soils tend to form big cracks when dry. Water fills the cracks and the soil starts filling from the bottom up rather than from the top as is typical of most soils.

Figure 4 shows that the Skip configuration tended to have just slightly (a few mm) more water at the shallower depths (25 and 55 cm depths) while the solid tended to have more water deeper in the profile (105 and 135 cm depths). This suggests a shallower rooting depth for the solid compared with the skip. More detailed information on the differences in *TWin* for all depths and results of statistical analyses in Table 2 show that on average for all sampling dates, the skip configuration tended to have slightly more water in approximately the top 100 cm while the solid tended to have more water deeper in the profile. Averaging all depths, at position P2, the tendency was for the skip to have slightly more water for the whole season, except for the first two sampling days (DAS 33 and 58). For positions P1 and P3, the tendency was for the skip to have slightly more water early in the season and less late in the season. The results of analysis of variance for each individual cell in Table 2 showed that significant differences in *TWin* were sporadic for position P1. Most significant differences were detected at position P2, showing more water available for the skip configuration. The significant differences for position P2 concentrated in the top 85 cm of the soil profile, and mainly between 72 and 107 DAS. There were also significant differences at P2 during DAS 140 and 144 for the depth ranges of approximately 75 to 95 cm. At Position P3, there was significantly more water for the skip configuration during 58 and 65 DAS, mainly near the soil surface (top 35 cm). Under water-limiting situation, slightly more water available for the skip row early in the season is expected to have promoted more vegetative growth, biomass and yield (per plant) compared with the solid configuration.

3.3. Comparison of total soil water above a given soil depth (TWto)

Plots of *TWto* by position, configuration, and DAS for four selected depths (25, 55, 105 and 135 cm) are shown in Fig. 5. Differences in *TWto* between configurations by position and DAS are plotted in Fig. 6. Differences in *TWto* between the two configurations above each depth increment, position and DAS are shown in Table 3. Table 3 also shows the results of statistical analysis testing if the observed differences in *TWto* between configurations were statistically significant (shaded cells were statistically significant at $\alpha = 0.05$). Again, positive differences in *TWto* in Table 3 and Fig. 6 indicate more water available for the skip compared with the solid configuration. Figure 5 shows similar *TWto* pattern between configurations for position P1 at each of the four depths shown. At position P2, there was slightly more water available for the skip compared with the solid, especially in the early to mid season. Position P3 shows the largest differences between the skip and solid, especially near the soil surface. However, the *TWto* above 135 cm shows that both configurations seem to have extracted about the same amount of soil water during the season. Since water was limited, it is expected that the crop would have extracted all the water that was available to it. However, Fig. 5 shows that late in the season there was slightly more *TWto* at position P3 for the solid compared to the skip. This could be due to more soil evaporation taking place from the bare soil at position P3 for the skip configuration.

Figure 6 suggests that the skip configuration tended to have more water available during the crop development stages at position P1, but less water late in the season. At position P2, it tended to have more water in the profile for practically the entire season. At position P3, it had more water early in the season and less water after about 100 DAS. Table 3 shows significant differences in *TWto* between configurations at the three positions. Significant differences resulted during 94 and 98 DAS at position P1, during 72, 94 and 98 DAS at position P2, and during 58 and 65 DAS at position P3. Not significant differences were detected below 105 cm depth for any of the positions. These results indicate that overall, the skip configuration had more soil water available to it from about 58 to 98 DAS. Figure 6 shows that a maximum of about 15 mm more water was available to the skip configuration, which was mostly stored in the top 105 cm of soil.

3.4. Changes soil water and estimate of crop water use

Table 4 shows a summary of *TWto* for the entire soil profile (to 135 cm soil depth), the total soil water difference (*TD)* and daily soil water difference (*DD*) between consecutive sampling dates, for each configuration, position and DAS. *TD* and *DD* provide an indication of soil water extraction (positive) or water gain (negative) during consecutive sampling periods. Figure 7 shows the seasonal change in *TWto* for the entire soil profile (to 135 cm soil depth) by configurations and positions. It shows that although there were small differences among positions, when all positions were averaged the seasonal change in *TWto* was the same for both configurations (128 mm). Therefore, since there was 271 mm of seasonal rain and 128 mm of water extracted from the soil, a rough estimate of seasonal water use for the crop was about 399 mm (for both configurations), assuming that all the rain was effective and that there was no deep percolation, which are reasonable assumptions under the conditions of this study. This seasonal water use represents about half of the seasonal ETo for this location, which indicates that the crop was water stressed, and therefore, yield was expected to reduce yield.

3.5. Crop development and yield

Figure 8 shows the maximum canopy height for the solid and skip configurations. Cotton plants in the skip configuration grew more than 10 cm taller than those in the solid. This difference in canopy height was statistically significant ($\alpha = 0.05$). The difference in canopy height could be explained by the skip configuration having slightly more water available during the early and mid season, during the crop vegetative development stages. Figure 9 sows the dry biomass (DB) production per unit area for both treatment measured at four sampling dates (DAS 108, 126, 155, and 168). It shows that, even though the skip configuration produced taller plants, the solid configuration tended to have more DB production per unit area, and significantly higher DB resulted near the end of the season (DAS=168).

Crop lint yields are shown in Table 5. When comparing skip and solid configurations, it is necessary to compare yields both per unit area (g m^{-2}, kg ha^{-1}, bales ha^{-1}) and yield per linear meter (g m^{-1}, which provides and indication of yield per plant). Table 5 shows no significant differences in lint yield, both when expressed per unit area and per linear meter. Significant differences were not detected mainly due to high yield variability among replications. Although differences in yield were not significant, the general tendency was for the skip configuration to produce more yield per linear meter while the opposite occurred for the yield per unit area. Table 5 also shows that the lint fraction (LF=lint mass/seed cotton mass) was 0.42 (42%) for both configurations, with no significant difference between them. Also, there were no significant differences in the fraction of lint from green balls (FLGB) between the two configurations.

4. Conclusions

This study compared single skip and solid cotton configurations under dryland conditions in sub-tropical climatic zone. It was found that in general, the skip configuration tended to have more water available in the top 105 cm soil profile. This additional water was available between 58 and 98 days after sowing, during the vegetative development stage. The measuring position affected when the additional water was available. The additional water was available earlier in the season at position P3, which was available during 58 and 65 DAS, compared with positions P1 and P2 where the additional water was available later in the season (72 to 98 DAS). For the entire season, however, both configurations extracted about the same amount of soil water, which was about 128 mm, which suggest that both configurations were water limited and extracted all the water that they had available. The 128 mm added to the seasonal rainfall of 271 mm allowed us to estimate the seasonal water use at about 399 mm, which was about half of the seasonal ETo (804 mm) for the site. Because of the additional water available between 58 and 98 DAS, the crop under the skip configuration grew about 10 cm taller. The additional water, however, was not enough to produce significant differences in crop yield between the skip and solid configurations.

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References

Bange, M.P. and Stiller, W., 2002. Agronomy, Australian dryland cotton production guide. Australian Cotton Cooperative Research Centre, Narrabri, Australia, pp. 41-52.

Gibb, D., 1995. Cotton production during drought. Cooperatice Research Centre for Sustainable Cotton Production, Moree, Australia.

Goyne, P.J., and J. Hare. 1999. Improved understanding of cotton water use for better management in water limited environments: Annual Progress Report. Report. Queensland Department of Primary Insdustries and Fisheries/Farming Systems Institute, Hermitage.

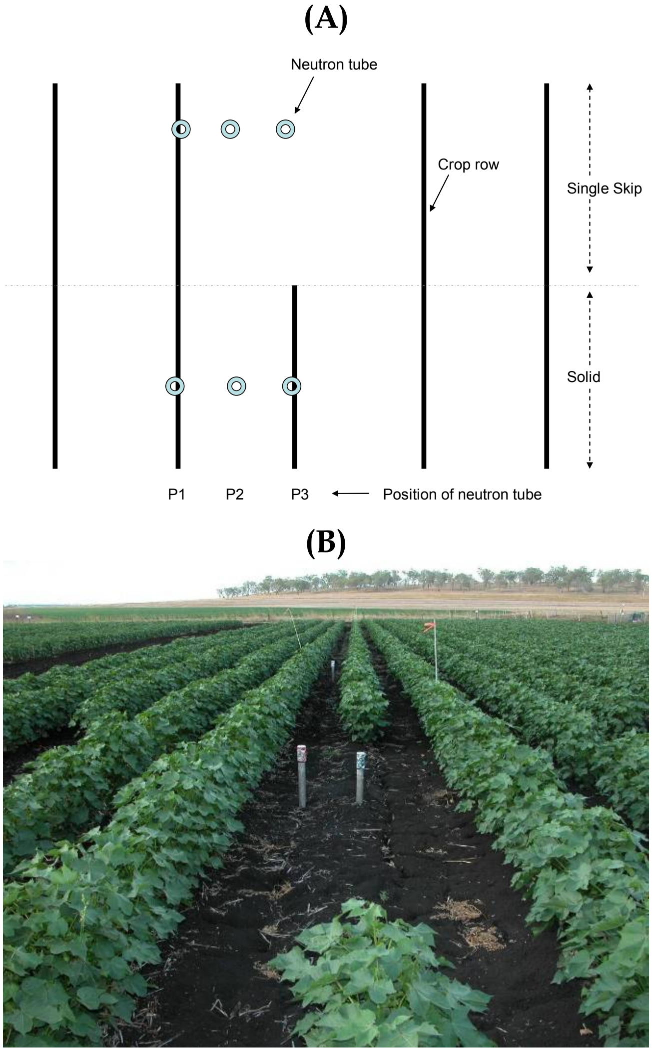


Figure 1. (A) Positions of neutron tubes in the solid and single skip cotton row configurations compared at Kingsthorpe during 2007-08, and (B) picture of the cotton crop showing the two row configurations.

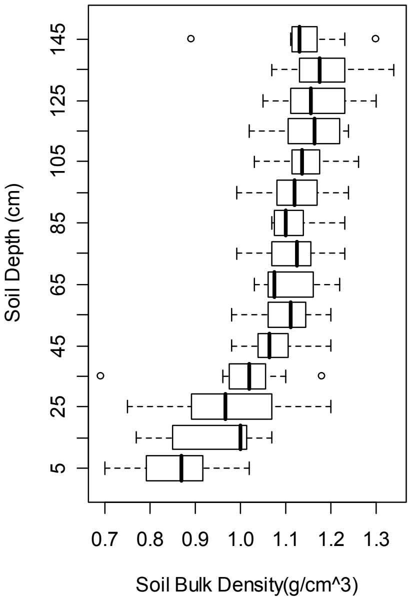


Figure 2. Boxplot of soil bulk density profile measured at Kingsthorpe.

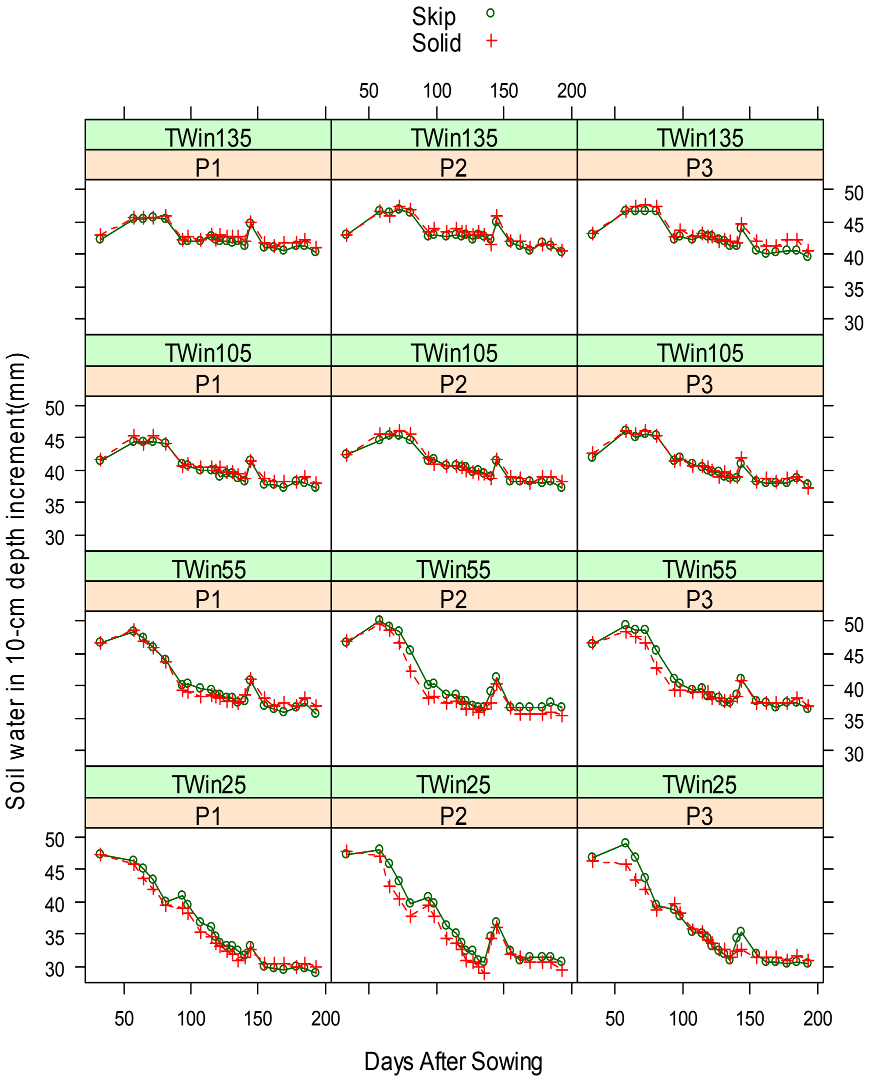


Figure 3. Soil water content by cotton row configuration (Skip and Solid), measurement position (P1, P2, P3) and days after sowing in each of 10-cm soil depths increments at 25, 55, 105 and 135 cm soil depths (TWin25, TWin55, TWin105, and TWin135) obtained at Kingsthorpe during 2007-08.

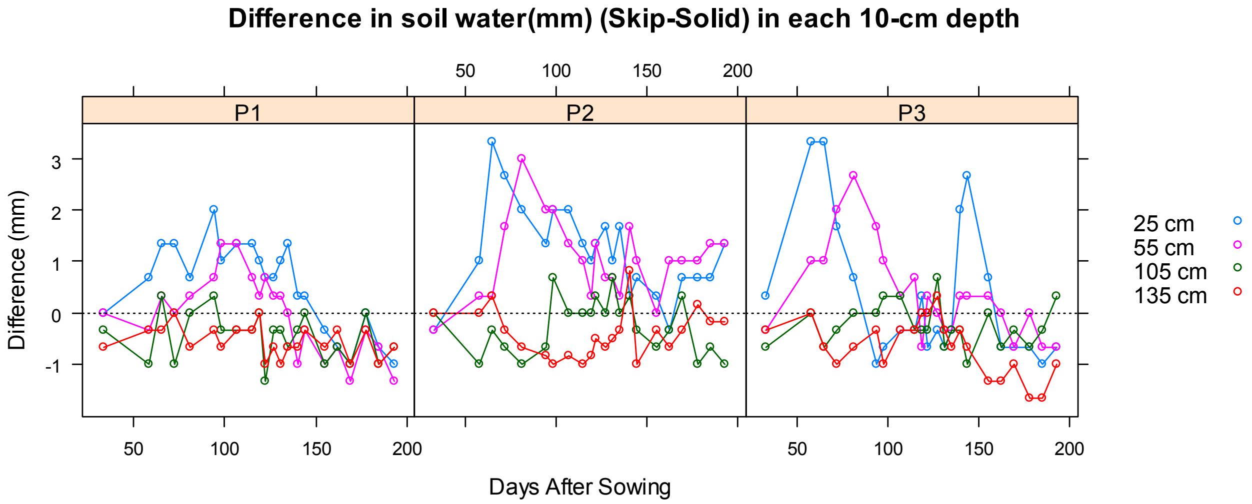


Figure 4. Difference in soil water between Skip and Solid cotton configurations by days after sowing and measurement position (P1, P2, and P3) in each 10-cm depth increment at 25, 55, 105 and 135 cm soil depths obtained at Kingsthorpe during 2007-08.

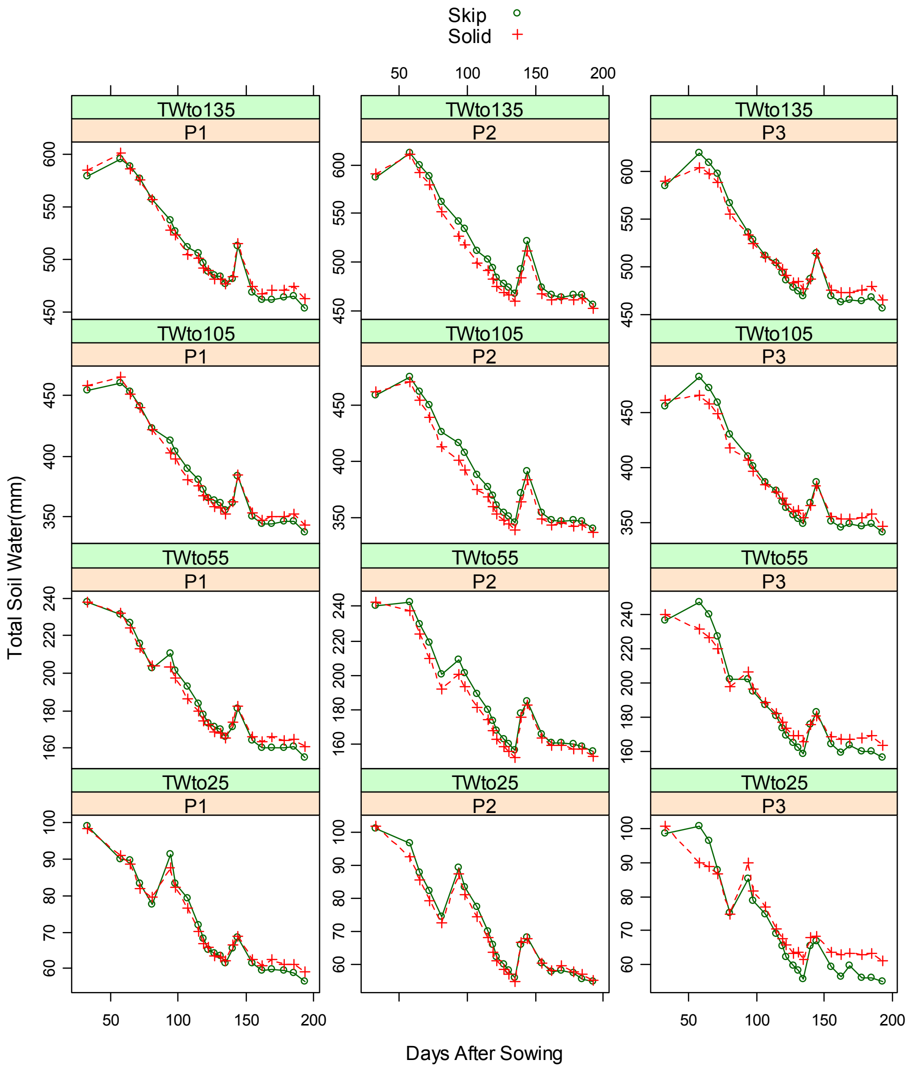


Figure 5. Total soil water content by cotton row configuration (Skip and Solid), measurement positions (P1, P2, P3) and days after sowing in the top 25, 55, 105 and 135 cm soil depths (TWto25, TWto55, TWto105, and TWto135) obtained at Kingsthorpe during 2007-08.

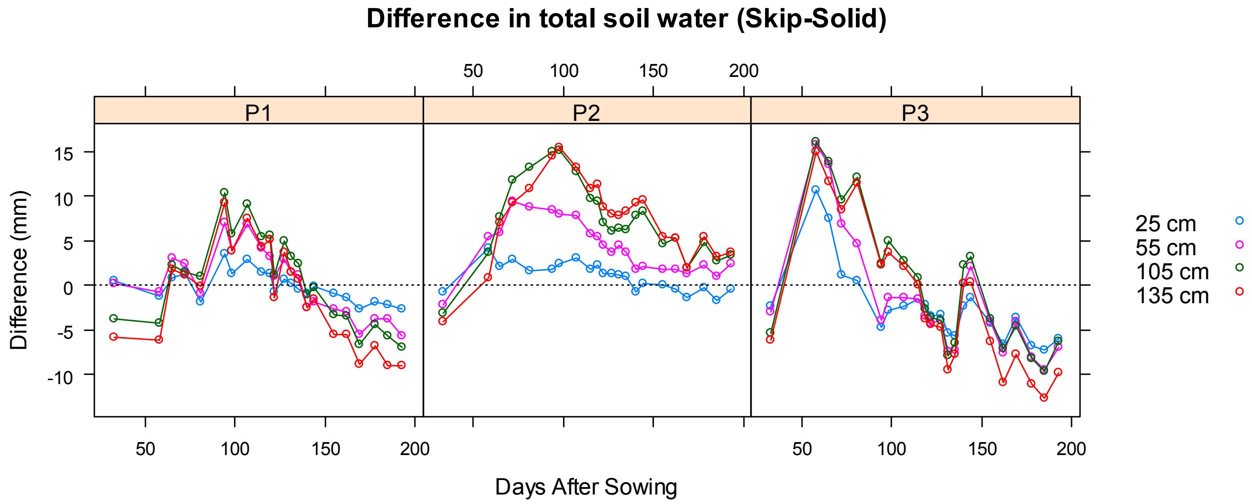


Figure 6. Difference in total soil water content between Skip and Solid cotton configurations by days after sowing and measurement position (P1, P2, and P3) above the top 25, 55, 105 and 135 cm soil depths obtained at Kingsthorpe during 2007-08.

Figure 7. Comparison of seasonal change in soil water in the whole soil profile (to 135 cm) between configurations (skip and solid) and positions (P1, P2, P3) first and last sampling dates (days after sowing 33 to 193).

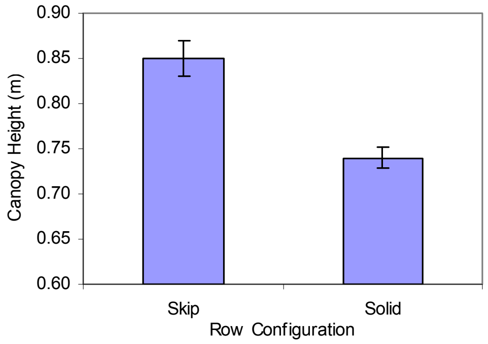


Figure 8. Maximum canopy height for cotton at Kingsthorpe during 2007-08. Error bars are standard error of the means.

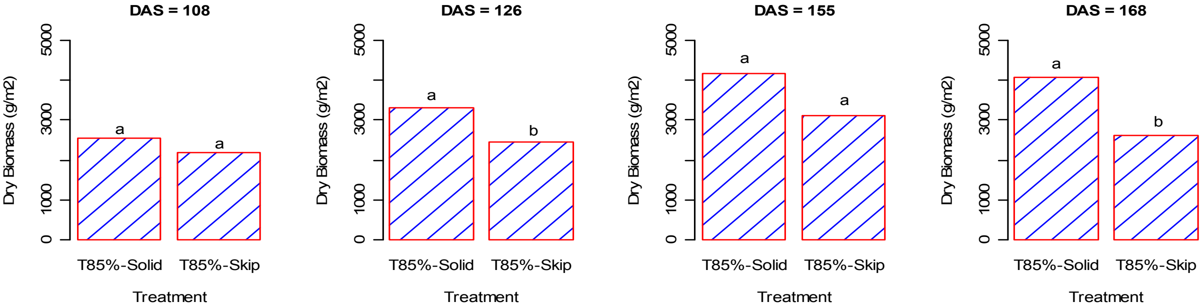


Figure 9. Comparison of dry biomass at four days after sowing (DAS).

Table 1. Summary weather conditions during the 2007-08 cotton season at Kingsthorpe.

	Month							**Season**
Variable [a]	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Avg/total**
Tmax (oC)	27.0	29.0	30.7	29.2	28.0	25.4	25.0	*27.8*
Tmin (oC)	14.7	17.5	17.5	16.1	12.6	7.3	3.7	*12.8*
Rs (MJ/m2/d)	24.6	22.9	22.4	22.3	24.1	20.3	19.0	*22.2*
RH (%)	76.3	76.5	75.2	77.4	71.7	71.6	59.1	*72.5*
u (m/s)	2.9	2.9	3.4	2.9	3.0	2.2	1.5	*2.7*
Daily ETo (mm)	4.7	4.8	5.0	4.6	4.5	3.3	2.8	*4.3*
Monthly ETo (mm)	88.5[b]	149.6	156.1	132.5	140.5	100.1	36.7	*804.0*
Monthly Rain (mm)	26.0	44.0	16.0	126.0	37.0	22.0	0.0	*271.0*

[a] Tmax, Tmin = Maximum and minimum air temperatures, Rs = Solar radiation
RH= Relative humidity, u = Wind speed, ETo = Grass-reference evapotranspiration

[b] For Nov and May, only data within the cotton growing season was included.

Table 2. Difference (Skip-Solid) in **soil water content (mm) in each 10-cm depth increment** between skip and solid cotton configurations by days after sowing (DAS) and sampling positions (P1,P2, P3) obtained at Kingsthorpe during 2007-08. Differences in shaded cells were statistically significant (α = 0.05).

Position	Depth (cm)	DAS																						*Average*
		33	**58**	**65**	**72**	**81**	**94**	**98**	**107**	**115**	**119**	**122**	**127**	**131**	**135**	**140**	**144**	**155**	**162**	**169**	**178**	**185**	**193**	
P1	15	-0.3	-0.3	1.0	0.3	-0.3	2.0	1.3	1.7	1.3	0.3	-1.0	0.0	0.0	-0.3	-0.3	0.0	-0.7	-0.7	-1.7	-1.7	-1.3	-1.3	***-0.1***
	25	0.0	0.7	1.3	1.3	0.7	2.0	1.0	1.3	1.3	1.0	0.7	0.7	1.0	1.3	0.3	0.3	-0.3	-0.7	-1.0	0.0	-0.7	-1.0	***0.5***
	35	-0.7	0.7	0.7	0.3	0.3	0.7	1.0	1.3	1.0	0.7	0.7	0.7	0.3	0.7	-0.3	-0.7	-0.7	-0.3	-1.0	-0.7	-0.7	-1.0	***0.1***
	45	0.3	0.7	1.0	0.3	0.7	1.7	0.7	1.3	1.3	0.7	0.7	1.3	0.3	1.0	-0.7	-0.7	-0.7	-0.3	-1.0	-1.3	-0.3	-0.7	***0.3***
	55	0.0	-0.3	0.3	0.0	0.3	0.7	1.3	1.3	0.7	0.3	0.7	0.3	0.3	0.0	-1.0	-0.3	-1.0	-0.7	-1.3	-0.3	-0.7	-1.3	***0.0***
	65	-2.0	-1.3	-0.3	0.3	0.3	0.7	0.3	0.7	0.3	1.0	0.3	1.0	1.0	1.0	0.3	-0.3	0.0	0.0	0.7	0.3	-0.3	0.0	***0.2***
	75	-1.0	-0.7	0.0	0.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.7	1.0	1.0	0.3	0.3	0.3	0.0	0.0	0.0	0.3	***0.5***
	85	-1.0	-0.7	-0.3	-0.3	0.0	1.0	0.3	0.3	0.3	0.7	0.7	0.3	0.0	0.0	0.0	2.0	0.0	0.0	0.3	0.3	-0.7	-0.3	***0.1***
	95	-0.7	-0.7	-1.0	0.0	-1.0	0.7	0.7	0.0	0.3	-0.3	-1.0	0.7	0.3	-0.7	0.3	0.7	-0.3	-0.3	0.0	0.0	0.3	-0.7	***-0.1***
	105	-0.3	-1.0	0.3	-1.0	0.0	0.3	-0.3	-0.3	-0.3	0.0	-1.3	-0.3	-0.3	-0.7	-0.3	0.0	-1.0	-0.7	-1.0	0.0	-1.0	-0.7	***-0.5***
	115	-0.7	-0.7	0.3	-0.3	-0.3	0.0	-1.0	-0.7	-0.3	-0.3	-1.3	-1.0	-1.3	-1.3	-0.7	-0.7	-0.3	-1.3	-1.3	-0.7	-1.7	-1.0	***-0.8***
	125	-0.7	-1.0	-0.3	0.7	0.0	-0.3	-0.7	-0.3	0.0	0.3	-0.7	0.0	-0.3	-0.7	0.0	0.0	-0.7	-0.7	0.0	-2.0	-0.7	-0.3	***-0.4***
	135	-0.7	-0.3	-0.3	0.0	-0.7	-0.3	-0.7	-0.3	-0.3	0.0	-1.0	-0.7	-1.0	-0.7	-0.7	-0.3	-0.7	-0.3	-1.0	-0.3	-1.0	-0.7	***-0.5***
	Average P1	***-0.6***	***-0.4***	***0.2***	***0.1***	***0.2***	***0.8***	***0.4***	***0.6***	***0.5***	***0.4***	***-0.1***	***0.3***	***0.1***	***0.1***	***-0.2***	***0.0***	***-0.5***	***-0.4***	***-0.6***	***-0.5***	***-0.7***	***-0.7***	***0.0***
P2	15	0.0	2.3	1.7	1.0	1.3	0.7	0.7	1.7	0.7	1.0	1.0	1.0	0.7	1.0	0.0	0.0	0.0	0.3	0.0	0.0	-0.7	-0.3	***0.6***
	25	-0.3	1.0	3.3	2.7	2.0	1.3	2.0	2.0	1.3	1.0	1.3	1.7	1.0	1.7	0.3	0.7	0.3	-0.3	0.7	0.7	0.7	1.3	***1.2***
	35	-0.3	0.7	2.0	3.7	2.3	2.3	2.3	1.7	1.7	1.0	1.0	0.7	1.0	1.3	0.7	0.3	1.0	0.3	1.7	1.0	0.7	1.0	***1.3***
	45	-0.7	0.0	1.0	1.7	2.3	2.7	2.3	1.7	2.0	0.7	1.3	0.7	1.3	1.7	1.0	0.7	1.0	1.3	1.0	0.7	1.3	0.3	***1.2***
	55	-0.3	0.3	0.3	1.7	3.0	2.0	2.0	1.3	1.0	0.3	1.3	0.7	0.7	0.3	1.7	1.0	0.0	1.0	1.0	1.0	1.3	1.3	***1.0***
	65	0.0	-0.3	0.7	1.0	2.3	2.0	2.0	1.0	1.0	1.0	1.0	0.3	0.0	0.0	1.7	1.7	1.3	0.7	0.0	0.7	0.7	1.0	***0.9***
	75	-1.3	-1.0	0.3	1.0	2.3	3.0	2.0	2.3	1.3	1.3	0.7	0.3	0.7	1.0	1.3	2.7	0.3	1.3	0.7	0.7	1.0	1.0	***1.0***
	85	0.0	-0.3	0.3	0.3	0.3	1.7	1.7	1.3	1.7	0.7	0.3	1.0	0.0	0.7	2.0	1.7	1.0	1.3	0.0	1.0	0.7	-0.3	***0.8***
	95	-0.3	0.0	0.3	0.0	-0.3	1.0	0.7	0.7	0.0	0.7	0.3	0.3	0.0	0.7	1.7	1.0	0.7	0.3	-0.3	0.7	0.3	0.0	***0.4***
	105	0.0	-1.0	-0.3	-0.7	-1.0	-0.7	0.7	0.0	0.0	0.0	0.3	0.0	0.7	0.0	0.3	-0.3	-0.7	-0.3	0.3	-1.0	-0.7	-1.0	***-0.2***
	115	-0.3	-1.7	-0.3	-1.0	-1.0	-0.3	-0.3	-0.3	0.0	0.0	0.0	0.0	-0.7	-0.7	0.3	0.3	-0.7	-0.3	-1.3	-1.0	-0.7	-0.3	***-0.5***
	125	0.0	-2.0	-0.3	-1.3	-1.3	-0.7	-1.0	-1.0	-0.7	0.0	-0.7	-0.3	-0.3	0.0	0.0	0.0	-0.7	-0.7	-1.0	-0.7	-0.3	-1.7	***-0.7***
	135	0.0	0.0	0.3	-0.3	-0.7	-0.8	-1.0	-0.8	-1.0	-0.8	-0.5	-0.7	-0.5	-0.3	0.8	-1.0	-0.3	-0.7	-0.3	0.2	-0.2	-0.2	***-0.4***
	Average P2	***-0.3***	***-0.2***	***0.7***	***0.7***	***0.9***	***1.1***	***1.1***	***0.9***	***0.7***	***0.5***	***0.6***	***0.4***	***0.3***	***0.6***	***0.9***	***0.7***	***0.3***	***0.3***	***0.2***	***0.3***	***0.3***	***0.2***	***0.5***
P3	15	-0.7	4.7	3.3	0.3	0.0	-2.0	-0.3	-0.7	-0.3	-0.3	-1.3	-0.7	-1.7	-1.3	1.0	1.7	0.0	-0.7	0.0	-1.0	-1.7	-1.0	***-0.1***
	25	0.3	3.3	3.3	1.7	0.7	-1.0	-0.7	-0.3	-0.3	0.3	-0.7	-0.3	-0.7	-0.3	2.0	2.7	0.7	-0.7	-0.7	-0.7	-1.0	-0.7	***0.3***
	35	-0.7	2.3	2.3	2.0	1.0	0.0	0.0	0.0	-0.3	-0.3	-0.3	-0.3	-0.7	-0.3	2.0	2.0	0.3	-0.7	0.7	0.0	-0.3	0.3	***0.4***
	45	0.3	0.7	2.3	1.7	1.0	0.7	1.0	1.0	0.0	0.3	-0.3	0.3	-0.3	0.3	1.3	1.3	0.0	0.0	0.3	0.0	-0.3	0.0	***0.5***
	55	-0.3	1.0	1.0	2.0	2.7	1.7	1.0	0.3	0.7	-0.7	0.3	0.0	-0.3	-0.3	0.3	0.3	0.3	0.0	-0.7	0.0	-0.7	-0.7	***0.4***
	65	0.0	-0.7	0.7	1.3	3.3	2.0	2.0	1.0	1.0	0.7	0.7	-0.3	-0.3	1.3	1.0	0.7	0.0	0.7	0.0	0.0	-0.3	0.3	***0.7***
	75	-1.0	-0.3	0.3	1.0	2.0	2.7	1.7	0.7	1.0	0.3	0.7	0.3	0.3	1.0	0.7	0.7	0.3	0.7	-0.3	0.0	0.0	0.3	***0.6***
	85	0.0	0.0	0.0	1.0	1.7	2.0	2.0	1.3	0.7	0.3	0.3	0.0	1.0	0.3	0.7	0.3	0.7	1.0	0.0	0.0	0.7	0.7	***0.7***
	95	-1.0	0.0	-1.0	-0.3	0.3	0.7	1.0	0.7	0.3	0.3	0.0	0.0	0.0	0.0	0.3	0.3	0.0	-0.3	-0.3	0.3	0.0	0.3	***0.1***
	105	-0.7	0.0	-0.7	-0.3	0.0	0.0	0.3	0.3	-0.3	-0.3	-0.3	0.7	-0.7	-0.3	-0.3	-1.0	0.0	-0.7	-0.3	-0.7	-0.3	0.3	***-0.2***
	115	0.3	-1.0	-1.0	-0.3	0.0	0.0	0.0	-0.3	-0.3	-0.7	-0.3	-0.7	-0.7	-0.3	-0.7	-1.0	-1.0	-1.0	-1.0	-1.0	-0.3	-1.0	***-0.6***
	125	-0.3	-0.3	-0.7	-0.7	-0.7	0.0	-0.3	-0.3	0.0	-0.7	0.0	-0.3	-0.3	-0.7	-1.0	-1.3	-0.7	-1.3	-1.3	-1.0	-1.3	-1.7	***-0.7***
	135	-0.3	0.0	-0.7	-1.0	-0.7	-0.3	-1.0	-0.3	-0.3	0.0	0.0	0.3	-0.3	-0.7	-0.3	-0.7	-1.3	-1.3	-1.0	-1.7	-1.7	-1.0	***-0.7***
	Average P3	***-0.3***	***0.7***	***0.7***	***0.6***	***0.9***	***0.5***	***0.5***	***0.3***	***0.1***	***-0.1***	***-0.1***	***-0.1***	***-0.4***	***-0.1***	***0.5***	***0.5***	***-0.1***	***-0.3***	***-0.4***	***-0.4***	***-0.6***	***-0.3***	***0.1***

Table 3. Difference (Skip-Solid) in **total soil water content (mm) above each soil depth** between skip and solid cotton configurations by days after sowing (DAS) and sampling positions (P1,P2, P3) obtained at Kingsthorpe during 2007-08. Differences in shaded cells were statistically significant (α = 0.05).

Position	Depth (cm)	DAS																					
		33	***58***	***65***	***72***	***81***	***94***	***98***	***107***	***115***	***119***	***122***	***127***	***131***	***135***	***140***	***144***	***155***	***162***	***169***	***178***	***185***	***193***	*Average*
P1	15	0.6	-1.4	0.1	0.0	-2.2	🟥 2.0	0.4	1.3	0.3	0.1	-1.2	0.0	-0.6	-0.9	-0.7	-0.1	-0.6	-0.7	-1.6	-1.4	-1.4	-1.8	***-0.4***
	25	0.6	-1.3	0.9	1.3	-1.9	🟥 3.6	1.3	2.8	1.5	1.3	-0.7	0.7	0.2	-0.5	-0.9	-0.1	-1.0	-1.4	-2.6	-1.9	-2.1	-2.7	***-0.1***
	35	0.1	-0.9	1.5	1.7	-1.6	🟥 4.8	2.2	4.3	2.5	2.0	0.1	1.6	0.8	0.3	-1.3	-0.6	-1.5	-1.8	-3.5	-2.7	-2.8	-3.7	***0.1***
	45	0.4	-0.6	2.6	2.1	-1.3	🟥 6.1	2.8	5.8	3.6	2.9	0.5	2.5	1.2	1.0	-1.8	-1.1	-2.1	-2.3	-4.3	-3.6	-3.3	-4.7	***0.3***
	55	0.2	-0.7	3.1	2.4	-0.9	🟥 7.0	3.8	6.8	4.2	3.2	1.0	2.9	1.5	1.1	-2.5	-1.8	-2.6	-3.0	-5.6	-3.8	-3.8	-5.7	***0.3***
	65	-1.4	-1.7	2.7	3.1	-0.4	🟥 7.9	🟥 4.1	7.3	4.5	4.2	1.2	3.6	2.4	1.9	-2.3	-2.2	-2.7	-3.0	-5.3	-3.8	-4.2	-6.0	***0.4***
	75	-2.3	-2.3	2.5	3.1	1.3	🟥 8.8	🟥 5.1	8.4	5.2	5.4	2.2	4.5	3.1	3.0	-1.5	-1.8	-2.5	-2.9	-5.4	-3.8	-4.4	-5.5	***0.9***
	85	-2.9	-3.0	2.3	2.9	1.7	🟥 9.7	🟥 5.7	8.8	5.6	5.9	3.0	4.9	3.4	3.3	-1.2	-0.4	-2.2	-2.8	-5.4	-3.5	-4.9	-5.6	***1.2***
	95	-3.4	-3.5	1.9	2.6	1.0	🟥 9.9	🟥 6.1	9.1	5.7	5.8	2.2	5.3	3.5	2.8	-0.7	-0.2	-2.3	-3.0	-5.9	-3.9	-4.9	-6.2	***1.0***
	105	-3.7	-4.3	2.3	1.5	1.0	🟥 10.4	5.8	9.0	5.4	5.5	1.2	4.9	3.3	2.4	-1.1	-0.3	-3.2	-3.4	-6.6	-4.3	-5.7	-6.9	***0.6***
	115	-4.3	-4.9	2.5	0.9	0.8	10.2	5.2	8.4	5.0	5.4	0.0	3.9	2.5	1.5	-1.6	-1.4	-3.9	-4.5	-7.9	-5.0	-7.0	-7.5	***-0.1***
	125	-5.1	-5.8	1.9	1.0	0.3	9.6	4.5	8.1	4.8	5.2	-0.5	3.9	2.0	1.2	-1.8	-1.5	-4.8	-5.0	-8.0	-6.2	-7.7	-8.3	***-0.5***
	135	-5.8	-6.1	1.8	1.1	0.0	9.3	3.9	7.4	4.4	5.1	-1.4	3.6	1.4	0.7	-2.5	-1.6	-5.5	-5.4	-8.9	-6.8	-8.9	-9.0	***-1.1***
	Average P1	***-2.1***	***-2.8***	***2.0***	***1.8***	***-0.2***	***7.6***	***3.9***	***6.7***	***4.1***	***4.0***	***0.6***	***3.3***	***1.9***	***1.4***	***-1.5***	***-1.0***	***-2.7***	***-3.0***	***-5.5***	***-3.9***	***-4.7***	***-5.7***	0.2
P2	15	-0.3	2.7	-0.2	0.8	0.4	0.3	0.7	1.5	0.7	1.2	0.4	0.2	0.1	-0.4	-0.7	-0.3	-0.3	-0.4	-1.4	-0.7	-1.6	-1.0	***0.1***
	25	-0.8	4.2	2.2	2.9	1.7	1.8	2.4	3.0	1.7	2.3	1.3	1.4	1.2	0.9	-0.7	0.1	0.0	-0.4	-1.3	-0.3	-1.7	-0.4	***1.0***
	35	-1.2	4.9	4.2	5.9	3.8	3.9	4.3	4.4	3.1	3.6	2.2	2.2	2.6	2.0	0.0	0.4	0.4	0.2	-0.4	0.7	-1.2	0.6	***2.1***
	45	-1.8	5.2	5.3	7.8	5.9	🟥 6.4	6.3	6.3	4.8	4.7	3.5	3.2	3.9	3.2	0.5	1.1	1.2	1.1	0.4	1.4	-0.2	1.2	***3.3***
	55	-2.1	5.5	6.0	🟥 9.5	8.7	🟥 8.4	8.0	7.8	5.8	5.4	4.5	3.7	4.5	3.8	1.8	2.1	1.7	1.9	1.3	2.2	1.0	2.4	***4.3***
	65	-2.3	5.1	6.8	🟥 10.7	11.1	🟥 10.5	🟥 9.6	8.6	6.7	6.4	5.1	4.2	4.9	4.2	3.0	3.8	2.9	2.5	1.6	3.1	1.5	3.3	***5.2***
	75	-3.0	4.6	7.1	11.7	13.2	🟥 13.0	🟥 11.7	10.2	7.9	7.3	5.8	5.0	5.5	5.0	4.4	5.8	3.4	3.7	2.3	4.2	2.4	4.2	***6.2***
	85	-3.1	4.3	7.5	11.9	13.6	🟥 14.5	🟥 13.4	11.8	9.1	8.4	6.3	5.6	6.0	5.5	6.4	7.3	4.4	5.1	2.1	4.9	3.2	4.3	***6.9***
	95	-3.1	4.3	7.7	11.9	13.8	🟥 15.2	14.6	12.6	9.6	9.0	6.6	5.9	5.9	6.3	7.5	8.5	5.0	5.4	2.0	5.4	3.3	4.5	***7.4***
	105	-3.2	3.7	7.7	11.7	13.3	14.9	15.2	12.7	9.7	9.4	7.0	6.0	6.4	6.2	7.9	8.2	4.7	5.2	1.9	4.9	2.8	3.4	***7.3***
	115	-3.3	2.6	7.3	10.9	12.5	14.5	15.2	12.7	9.5	9.2	6.7	6.3	5.8	6.1	7.9	8.5	4.3	4.7	0.8	4.1	2.2	3.2	***6.9***
	125	-3.6	1.0	6.7	9.9	11.6	13.8	14.6	11.9	9.1	9.5	6.5	5.6	5.7	5.8	7.4	8.1	3.7	3.8	0.4	3.4	1.5	1.9	***6.3***
	135	-4.1	0.9	7.1	9.2	10.8	14.4	15.5	13.2	10.8	11.3	8.8	8.0	7.8	8.3	9.2	9.6	5.4	5.3	1.9	5.4	3.3	3.7	***7.5***
	Average P2	***-2.5***	***3.8***	***5.8***	***8.8***	***9.3***	***10.1***	***10.1***	***9.0***	***6.8***	***6.8***	***5.0***	***4.4***	***4.7***	***4.4***	***4.2***	***4.9***	***2.8***	***2.9***	***0.9***	***3.0***	***1.3***	***2.4***	4.9
P3	15	-2.0	🟥 6.9	4.3	0.1	-0.2	-3.2	-2.0	-1.7	-0.9	-1.8	-2.4	-2.7	-4.0	-4.7	-3.3	-2.8	-4.0	-5.2	-2.6	-5.2	-5.7	-4.7	***-2.2***
	25	-2.3	🟥 10.7	7.5	1.2	0.5	-4.8	-2.8	-2.4	-1.5	-2.2	-3.4	-3.3	-5.3	-5.7	-2.3	-1.4	-4.2	-6.6	-3.7	-6.8	-7.2	-6.0	***-2.4***
	35	-2.9	🟥 13.1	🟥 10.1	2.9	1.5	-5.2	-2.9	-2.3	-1.6	-2.8	-3.9	-3.9	-6.3	-6.6	-0.9	0.3	-4.2	-7.3	-3.6	-7.5	-8.2	-6.1	***-2.2***
	45	-2.9	🟥 14.4	🟥 12.3	4.7	2.5	-5.0	-2.1	-1.8	-1.7	-2.8	-4.4	-3.6	-7.0	-6.8	0.0	1.7	-4.3	-7.4	-3.4	-7.8	-9.0	-6.6	***-1.9***
	55	-3.0	🟥 15.8	🟥 13.5	6.8	4.7	-3.9	-1.4	-1.4	-1.5	-3.4	-4.3	-4.0	-7.4	-7.3	0.2	2.1	-4.0	-7.6	-4.0	-8.1	-9.4	-6.9	***-1.6***
	65	-3.5	🟥 15.5	14.1	8.2	7.8	-2.6	0.1	-0.4	-0.7	-3.0	-4.1	-4.2	-7.8	-6.8	1.0	2.5	-4.3	-7.4	-4.1	-8.0	-9.6	-6.8	***-1.1***
	75	-4.3	15.4	14.5	9.4	10.1	-0.3	1.8	0.4	0.2	-2.5	-4.0	-4.0	-7.6	-6.0	1.8	3.2	-3.8	-6.9	-4.2	-7.9	-9.7	-6.8	***-0.5***
	85	-4.5	15.9	14.6	10.2	11.7	1.6	3.4	1.4	0.7	-2.2	-3.5	-3.8	-7.1	-6.0	2.5	3.7	-3.6	-6.1	-4.0	-7.8	-9.3	-6.4	***0.1***
	95	-5.1	15.9	14.1	9.8	12.2	2.4	4.4	2.3	1.0	-2.1	-3.2	-4.0	-7.2	-6.1	2.7	4.0	-3.9	-6.4	-4.1	-7.5	-9.5	-6.2	***0.2***
	105	-5.4	16.1	13.8	9.5	12.1	2.4	5.0	2.8	0.9	-2.6	-3.6	-3.9	-7.8	-6.4	2.3	3.3	-3.8	-7.1	-4.5	-8.1	-9.6	-6.2	***0.0***
	115	-5.5	15.1	13.0	9.4	12.4	2.6	5.0	2.5	0.4	-3.1	-4.2	-4.5	-8.8	-6.8	1.7	2.4	-4.7	-8.1	-5.5	-9.2	-10.1	-7.0	***-0.6***
	125	-5.8	14.7	12.3	8.9	12.1	2.8	4.5	2.4	0.2	-3.6	-4.3	-4.6	-9.2	-7.2	0.7	1.3	-5.3	-9.5	-7.0	-9.9	-11.4	-8.5	***-1.2***
	135	-6.2	14.9	11.6	8.4	11.5	2.3	3.6	2.1	0.0	-3.7	-4.5	-4.7	-9.4	-7.7	0.1	0.4	-6.3	-10.9	-7.7	-11.1	-12.7	-9.7	***-1.8***
	Average P3	***-4.1***	***14.2***	***12.0***	***6.9***	***7.6***	***-0.8***	***1.3***	***0.3***	***-0.3***	***-2.8***	***-3.8***	***-3.9***	***-7.3***	***-6.5***	***0.5***	***1.6***	***-4.3***	***-7.4***	***-4.5***	***-8.1***	***-9.3***	***-6.8***	***-1.2***

Table 4. Total soil water in the soil profile (*TWto*, mm, for 135 cm soil depth), total soil water difference (*TD*, mm) and daily soil water difference (*DD*, mm/d) between consecutive sampling dates, for each configuration (Skip and Solid), sampling position (P1,P2, P3) and days after sowing (DAS) obtained at Kingsthorpe during 2007-08.

			DAS																					
			33	**58**	**65**	**72**	**81**	**94**	**98**	**107**	**115**	**119**	**122**	**127**	**131**	**135**	**140**	**144**	**155**	**162**	**169**	**178**	**185**	**193**
Skip	P1	*TWto*	578.5	594.6	587.6	576.3	557.0	537.0	527.1	511.7	505.4	496.6	488.3	485.6	483.5	477.4	481.4	513.4	468.9	462.2	462.0	464.2	465.2	453.6
		TD		-16.1	7.0	11.3	19.3	20.0	9.9	15.4	6.3	8.8	8.3	2.7	2.1	6.1	-4.0	-32.0	44.5	6.7	0.2	-2.3	-1.0	11.6
		DD		-0.6	1.0	1.6	2.1	1.5	2.5	1.7	0.8	2.2	2.8	0.5	0.5	1.5	-0.8	-8.0	4.0	1.0	0.0	-0.3	-0.1	1.4
	P2	*TWto*	586.6	612.0	599.2	588.5	562.2	541.6	534.0	512.3	502.9	494.0	484.5	477.5	474.0	468.1	493.2	521.8	473.6	466.3	464.5	466.3	466.0	456.1
		TD		-25.3	12.8	10.7	26.3	20.6	7.6	21.7	9.4	8.9	9.5	7.0	3.5	5.9	-25.1	-28.6	48.2	7.4	1.8	-1.8	0.3	10.0
		DD		-1.0	1.8	1.5	2.9	1.6	1.9	2.4	1.2	2.2	3.2	1.4	0.9	1.5	-5.0	-7.2	4.4	1.1	0.3	-0.2	0.0	1.2
	P3	*TWto*	584.3	619.2	608.7	597.1	567.0	535.9	528.4	512.1	504.2	493.6	486.4	478.6	474.9	469.3	487.1	514.6	469.6	462.8	465.8	464.4	467.7	456.5
		TD		-34.8	10.4	11.6	30.1	31.2	7.5	16.3	7.9	10.6	7.2	7.8	3.7	5.6	-17.8	-27.5	45.0	6.8	-3.0	1.4	-3.3	11.3
		DD		-1.4	1.5	1.7	3.3	2.4	1.9	1.8	1.0	2.6	2.4	1.6	0.9	1.4	-3.6	-6.9	4.1	1.0	-0.4	0.2	-0.5	1.4
Avg Skip		***TWto***	***583.2***	***608.6***	***598.5***	***587.3***	***562.1***	***538.2***	***529.8***	***512.0***	***504.2***	***494.7***	***486.4***	***480.6***	***477.5***	***471.6***	***487.2***	***516.6***	***470.7***	***463.8***	***464.1***	***465.0***	***466.3***	***455.4***
		TD		***-25.4***	***10.1***	***11.2***	***25.2***	***23.9***	***8.3***	***17.8***	***7.9***	***9.4***	***8.3***	***5.8***	***3.1***	***5.9***	***-15.6***	***-29.4***	***45.9***	***7.0***	***-0.3***	***-0.9***	***-1.4***	***10.9***
		DD		***-1.0***	***1.4***	***1.6***	***2.8***	***1.8***	***2.1***	***2.0***	***1.0***	***2.4***	***2.8***	***1.2***	***0.8***	***1.5***	***-3.1***	***-7.3***	***4.2***	***1.0***	***0.0***	***-0.1***	***-0.2***	***1.4***
Solid	P1	*TWto*	584.3	600.7	585.8	575.2	557.1	527.7	523.2	504.3	501.1	491.5	489.7	482.0	482.1	476.7	484.0	515.0	474.5	467.6	470.8	471.0	474.2	462.7
		TD		-16.4	14.9	10.6	18.1	29.3	4.6	18.9	3.2	9.6	1.8	7.7	-0.1	5.4	-7.3	-31.0	40.5	6.8	-3.2	-0.2	-3.1	11.5
		DD		-0.7	2.1	1.5	2.0	2.3	1.1	2.1	0.4	2.4	0.6	1.5	0.0	1.4	-1.5	-7.8	3.7	1.0	-0.5	0.0	-0.4	1.4
	P2	*TWto*	590.7	611.1	592.1	579.3	551.4	527.2	518.5	499.0	492.1	482.7	475.7	469.6	466.2	459.8	484.0	512.2	468.2	461.0	462.6	460.9	462.7	452.4
		TD		-20.4	19.0	12.8	27.8	24.3	8.6	19.5	6.9	9.4	7.0	6.1	3.4	6.3	-24.1	-28.2	43.9	7.2	-1.6	1.7	-1.9	10.4
		DD		-0.8	2.7	1.8	3.1	1.9	2.2	2.2	0.9	2.4	2.3	1.2	0.8	1.6	-4.8	-7.0	4.0	1.0	-0.2	0.2	-0.3	1.3
	P3	*TWto*	590.5	604.3	597.1	588.7	555.5	533.5	524.8	510.0	504.1	497.3	490.9	483.3	484.3	477.0	487.0	514.2	476.0	473.7	473.5	475.5	480.4	466.2
		TD		-13.8	7.1	8.4	33.2	22.0	8.8	14.8	5.8	6.8	6.5	7.6	-1.0	7.3	-10.0	-27.3	38.3	2.2	0.2	-2.0	-4.9	14.2
		DD		-0.6	1.0	1.2	3.7	1.7	2.2	1.6	0.7	1.7	2.2	1.5	-0.3	1.8	-2.0	-6.8	3.5	0.3	0.0	-0.2	-0.7	1.8
Avg Solid		***TWto***	***588.5***	***605.4***	***591.7***	***581.1***	***554.7***	***529.5***	***522.2***	***504.4***	***499.1***	***490.5***	***485.4***	***478.3***	***477.5***	***471.2***	***485.0***	***513.8***	***472.9***	***467.5***	***469.0***	***469.1***	***472.4***	***460.4***
		TD		***-16.8***	***13.7***	***10.6***	***26.4***	***25.2***	***7.3***	***17.7***	***5.3***	***8.6***	***5.1***	***7.1***	***0.8***	***6.3***	***-13.8***	***-28.8***	***40.9***	***5.4***	***-1.5***	***-0.2***	***-3.3***	***12.0***
		DD		***-0.7***	***2.0***	***1.5***	***2.9***	***1.9***	***1.8***	***2.0***	***0.7***	***2.1***	***1.7***	***1.4***	***0.2***	***1.6***	***-2.8***	***-7.2***	***3.7***	***0.8***	***-0.2***	***0.0***	***-0.5***	***1.5***

Table 5. Treatment means and Analysis of Variance (ANOVA) of cotton lint yields obtained at Kingsthorpe during the 2007-08 season.

			Lint from open bolls				Total lint (open + green bolls)			
Treatment	LF[a]	FLGB[b]	(g m^{-1})[c]	(g m^{-2}) [c]	(kg ha^{-1})	(bales ha^{-1})	(g m^{-1}) [c]	(g m^{-2}) [c]	(kg ha^{-1})	(bales ha^{-1})
Solid	0.42 (0.007)	0.014 (0.01)	138.17 (21.29)	138.17 (21.29)	1381.75 (212.91)	6.09 (0.94)	140.07 (20.37)	140.07 (20.37)	1400.70 (203.71)	6.17 (0.90)
Skip	0.42 (0.005)	0.040 (0.02)	170.70 (31.74)	113.80 (21.16)	1137.97 (211.59)	5.01 (0.93)	177.56 (30.62)	118.37 (20.41)	1183.74 (204.13)	5.21 (0.90)
Pr > F [Treatment (d.f.[e] = 4)]	0.979 (ns)	0.097 (ns)	0.141 (ns)	0.136 (ns)	0.136 (ns)	0.136 (ns)	0.109 (ns)	0.160 (ns)	0.160 (ns)	0.160 (ns)
LSD $_{(0.05)}$	0.028	0.038	58.90	43.17	431.7	1.90	58.18	42.71	427.1	1.88
SEM [f]	0.005	0.006	9.68	7.10	71.0	0.313	9.56	9.93	70.2	0.31

[a] LF = Lint fraction = (lint mass)/(seed cotton mass)

[b] FLGB = Fraction of lint from green bolls = (lint yield from green bolls)/(Total lint yield)

[c] Lint yields per unit area (g m^{-2}, kg ha^{-1}, bales ha^{-1}) took into account that plants in the skip treatment had access to an area 1.5 times larger than plants in the other treatments, while yields per unit length (g m^{-1}) did not take this into account.

[d] Numbers in parenthesis are standard deviations of treatment means

[e] d.f. = Degrees of freedom.

[f] SEM = Standard errors of means

* Significantly different at the 0.05 level, and ns = not significant

Appendix VIII

Comparison of irrigation and nitrogen management strategies for wheat

Jose O. Payero, Geoff Robinson and Graham A. Harris

Agri-Science Queensland, Department of Employment, Economic Development and
Innovation (DEEDI), 203 Tor St, PO Box 102, Toowoomba, Qld 4350, Australia

Abstract

Wheat is an important winter crop on the Darling Downs, Australia, which is usually grown under dryland or deficit-irrigation conditions in rotation with summer cereals, cotton and pulse crops. Increases in grain prices, compared to cotton prices, and decreases in available irrigation water, has prompted interest in growing irrigated wheat, trying to increase yields and economic returns. Although there is much local knowledge about growing dryland wheat, experience with irrigated wheat is limited, especially regarding irrigation and nitrogen management. The objective of this study was to evaluate the agronomic and economic response of wheat to the combined effect of irrigation and nitrogen management strategies. A replicated field experiment with four irrigation treatments (initiating irrigation at 50%, 60%, 70% or 85% depletion of available soil water) and three nitrogen treatments (100, 150 or 200 kg N/ha) was conducted in 2008 at Kingsthorpe, Queensland. It was found that increasing irrigation significantly increased crop yield, but decreased grain protein content. Irrigation also increased crop leaf area index and plant height, which resulted in increased crop lodging problems. No response was observed from the nitrogen treatments due to high initial soil nitrogen content. Economic analysis showed that irrigation increased gross margins when calculated in terms of $/ha. However, a slightly deficit-irrigated treatment (initiating irrigation at 60% depletion) resulted in similar or higher gross margins compared with a fully-irrigated treatment (initiating irrigation at 50% depletion) when compared in terms of $/ML of water inputs. Severely stressed treatments (initiating irrigation at 70% and 85% depletion) resulted in the lowest gross margins, both in a $/ha and $/ML basis.

Keywords: Wheat, irrigation, Nitrogen, water use efficiency, economic analysis

1. Introduction

Severe drought over the last decade in Australia has placed water as the main limiting factor affecting crop production. Therefore, maximising the beneficial use of water not only makes good economic sense but has also become a stewardship imperative to protect and conserve water resources. This can be accomplished by increasing crop water productivity (CWP) and profits per unit of water inputs. (Ali and Talukder, 2008) suggested that increasing crop water productivity (CWP) requires increasing transpiration while minimising unwanted water losses, exchanging transpired water for CO_2 more efficiently in producing crop biomass, and converting more of the produced biomass into harvestable yield. They also suggested that to improve CWP, the most promising and efficient proven techniques were limited supplemental irrigation for optimising the use of limited water, and water harvesting to improve farm income in drier environments.

Wheat is an important winter crop on the Darling Downs, Australia, which is usually grown under dryland or deficit-irrigation conditions in rotation with summer cereals, cotton and pulse crops. Increases in grain prices, compared to cotton prices, and decreases in available irrigation water, has prompted interest in growing irrigated wheat, trying to increase yields and economic returns. Farmers on the Darling Down area are usually water-limited rather than land-limited. Therefore, they are faced with the questions of weather to reduce planted land area and fully-irrigate the crop or to increase the planted area and deficit-irrigate. Another option is to weather to grow a winter crop like wheat (under dryland, deficit-irrigation or full irrigation) or to fallow the land during winter and store water (in farm storages and in the soil profile) to growth summer grains or cotton, which are usually more profitable. Another issue, for a given level of irrigation, is how to manage nitrogen inputs to maximize profits.

To answer theses questions, economic analysis needs to be performed which considers both the biophysical response to crop inputs and economic factors such as crop prices and cost of production. Although crop cultivar can affect wheat development and yield ((Karam et al., 2009; Karimi and Siddique, 1991), for a given cultivar, irrigation and nitrogen are usually the main inputs having the biggest impact on crop yield and development. The objective of this study was to evaluate the agronomic and economic response of wheat to the combined effect of irrigation and nitrogen management strategies.

2. Methods

2.1. Site description

The experiment was conducted at the Agri-Science Queensland research station near Kingsthorpe. The station is located in a sub-tropical climatic zone, about 20 km north-west of the city of Toowoomba, Queensland, Australia [27°30'44.5" Latitude South, 151°46'54.5" Longitude East, 431 m above mean sea level]. The soil at the site is a *Haplic, self-mulching, black, Vertosol*. It has a heavy clay texture in the 1.5 m root zone profile, with a distinct change in soil color from brownish black (10YR22) in the top 90 cm to dark brown (7.5YR33) deeper in the profile. The soil is of alluvial fan and basalt rock origin, slowly permeable, with a surface slope of about 0.5%.

2.2. Experimental design

A field experiment with four irrigation treatments, three nitrogen treatments, and three replications was conducted during the 2008 wheat seasons using a split plot design with irrigation as the main plot and nitrogen as the split-plot. Each irrigation main plot was 22 m x 20 m, with the crop planted in the North-South direction. A border (4.0 m) was allowed between main plots and a road (4.3 m) was located at the centre of the research area.

The irrigation treatments were: T50%, T60%, T70%, and T85%, which received irrigation when 50%, 60%, 70%, or 85% of the plant available water capacity (PAWC) was depleted, respectively. The main plots were irrigated individually with bore water using a solid set sprinkler system. Partial-circle sprinkler heads were used to avoid irrigating adjacent plots. Irrigations were scheduled based on neutron probe soil water measurements. Three manual rain gauges were installed in each plot to measured irrigation depths.

The nitrogen treatments were: N100, N150, N200, which received a total of 100, 150 or 200 kg N ha^{-1}, respectively. N100 received all the N at sowing. N150 received 100 kg N ha^{-1} at sowing and 50 kg N ha^{-1} at first node. N200 received 100 kg N ha^{-1} at sowing, 50 kg N ha^{-1} at first node and 50 kg N ha^{-1} at the awn peep growth stage.

2.3. Soil sampling

Prior to sowing (3 June 2008) soil samples were taken to evaluate soil N content. Three soil cores from each plot of the T50% treatment were taken to a depth of 120 cm. The cores were divided into depth increments of 0-15 cm, 15-30 cm, 30-45 cm, 60-90 cm and 90-120 cm. A composite sample for each depth increment was created by mixing the three cores taken from each plot. Samples were oven-dried at 40°C, ground and sent to the lab for analysis. Soil samples from each of the sub-plots were also taken on 8 August.

2.4. Sowing

The variety Lang, a bread wheat variety commonly planted on the Darling Downs, was planted on 6 June 2008 following a cotton crop. The target sowing density was 200 plants/m^2, using a row spacing of 25 cm. Seeds were planted on dry soil at a depth of 50-75 mm followed by an irrigation of 25 mm applied after planting (6-9 June) to promote germination, which started on 16 June.

2.5. Soil water measurements

Soil water from each plot was measured throughout the season using the neutron probe method. This information was used for scheduling irrigations and for estimating seasonal water use and water use efficiency. An access tube was installed on 16 June on each plot of replication 2 to establish the initial soil moisture at crop emergence. Access tubes for the remaining eight plots were installed on 19 June. Neutron probe readings were taken approximately twice a week at 0.10 m depth increments to a depth of 1.5 m. Measurements were taken with a 503DR Hydroprobe (CPN International, Inc., Martinez, CA, USA), using integration periods of 16 seconds for normal counts and 240 seconds for standard counts. The standard counts were taken on water by lowering the neutron source on an access tube installed in the middle of a 200-L water drum. The Hydroprobe had been calibrated against gravimetric soil water content measurements for the soil at the research site during the previous season.

2.6. Weather data

An EnviroStation (ICT International Pty Ltd, Armidale, NSW, Australia) electronic weather station was installed at the research site. The station recorded both daily and hourly values of solar radiation (Rs), air temperature (maximum, minimum, and average), relative humidity (RH), wind speed (u) and rainfall.

2.7. Crop development

A number of measurements and observations were made during the season to evaluate crop development. Crop growth stage was evaluated regularly during the season from five representative plants harvested from each plot. The procedure developed by (Zadocks et al., 1974; Zadoks et al., 1974) and further described by (Stapper, No date) was followed.

Dry matter (DM) was determined from destructive plant samples taken approximately every two weeks. All plants on a 1-m length from each plot were dug out. The plants were counted to determine plant density. A sub-sample of 10 plants was taken to determine LAI (LAI sub-sample). The roots were cut out and the above-ground plant samples were dried to constant weight with a forced draught oven at 80°C for at least 48 hours. The DM of the samples was then measured with an electronic laboratory scale to the nearest 0.01 g. Also, the fresh matter (FM) ad DM of each plant component was determined from the LAI sub-sample. The plant components included: stem, green leaves, dead material, and grain head.

For each of the 10 plants in the LAI sub-sample, the following was determined: Plant height, number of leaves on the main shoot, number of tillers for the whole plant (including the main shoot), total number of leaves in 10 plants (all tillers including the main shoot), number of nodes, distance to each node, number of grain heads, total green leaf area in 10 plants. The total green leaf area, needed to calculate LAI, was measured using a Li-3100C Area Meter (Li-COR Biosciences, Lincoln, Nebraska, USA). Calibration was checked each time, and adjusted if needed, using a simulated leaf of known area. Late in the season, the percent of plants lodging in each plot was estimated by field observation. Not all of this information is presented in this paper.

Figure 1. (A) Counting the number of tillers per wheat plant, (B) Wheat plants separated into leaves, stem, and dead material.

2.8. Harvest

The crop was harvested on 11 November. Grain yield from each irrigation and nitrogen treatment was determined by harvesting the centre 16 rows of each sub-plot using a plot combine. Grain mass and water content were determined in the laboratory and were used to calculate grain yield on a dry mass basis (0% water content) and at a standard water content of 12%. Also, the yield components were determined, including the plants per m^2, heads per plant, seeds per head, seeds per plant, and seed dry mass (g/100 seeds). Grain quality was evaluated by measuring grain protein and screenings.

2.9. Economic analysis

Gross margins were calculated for each irrigation x nitrogen combination, based on variable cost of irrigation and N inputs and the crop revenue considering both crop yield and grain quality (protein content). Typical crop production costs and crop prices for Queensland were assumed in the calculations. Gross margins were calculated in terms of Australian dollars per hectare ($/ha), per ML of irrigation ($/ML Irrigation) and per ML of total water (rain + irrigation+ soil water) ($/Total ML).

3. Results and discussion

3.1. Weather conditions

Daily weather variables measured on site are shown in Fig. 2 (A-D). Average values during the 2008 wheat season for Rs, Ta, RH, and u where 19.36 $MJ/m^2/d$, 14.3 ^oC, 72.7%, and 2.3 m/s, respectively. The average maximum (Tmax) and minimum (Tmin) air temperatures during the season were 22.9 and 5.68 ^oC, with an average daily temperature fluctuation (Tmax-Tmin) of 17.2 ^oC. There were 39 days during the season with Tmin < 0 ^oC. The lowest temperature during the season was -6.1 ^oC, which occurred in early August and produced frost damage on the tips of some leaves (about 2% of leaves), but did not have a significantly effect on crop development.

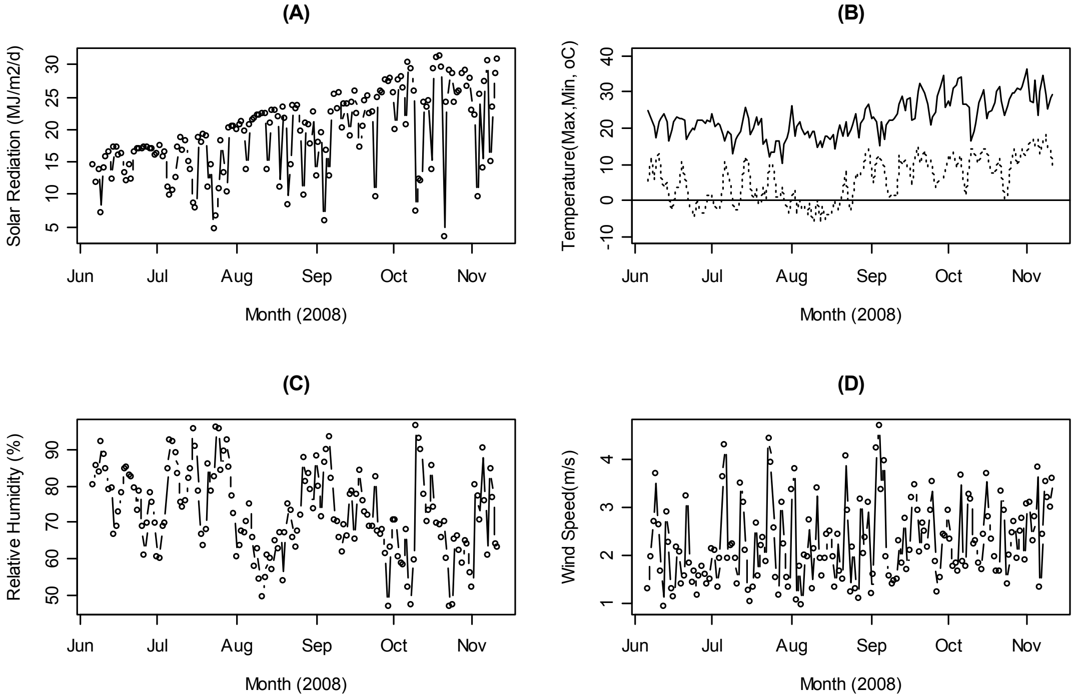
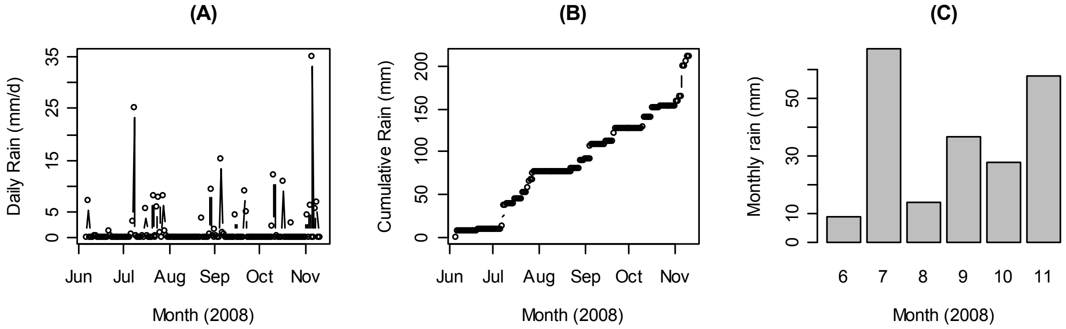


Figure 2. Weather conditions at Kingsthorpe during the 2008 wheat season.

3.2. Rain

Plots of daily, cumulative and monthly rain during the season are shown in Fig. 3 (A-C). There was a total of 212 mm of rain from sowing to harvest. However, 58 mm occurred in November (27% of total rain), which probably had no impact on crop development and yield. Therefore, disregarding the rain in November, the total rain for the season, from sowing until the end of October was 154 mm. Except for the rain event of about 35 mm/d that occurred in November, daily rainfall events were usually small, with intensities of less than 25 mm/d. Although the percent effective rain was not directly measured, the low intensity rain falling on almost level and dry soil was not likely to produce significant runoff and, therefore, practically all the rain was likely to be effective. June and August were the driest months and July was the wettest.



Month	Jun	Jul	Aug	Sep	Oct	Nov
Rain(mm)	9.0	67.2	13.8	36.6	27.6	58.0
Cumulative rain (mm)	9.0	76.2	90	126.6	154.2	212.2

Figure 3. Daily, cumulative and monthly rain during the 2008 wheat season at Kingsthorpe.

3.3. Irrigation

Amounts and timing of irrigations applied to each treatment are shown in Table 1. All treatments were irrigated right after sowing (25 mm) to promote germination. Because of the wet July, no irrigation was needed until early August. Irrigation applications were limited to a maximum of about 50 mm per irrigation event. The number of irrigations per treatment ranged from 3 to 6, and the total application depth for the season ranged from 73 to 197 mm for the driest and wettest treatment, respectively.

Table 1. Irrigation applied to each treatment (mm)

	Irrigation Treatment			
Date	**T50%**	**T60%**	**T70%**	**T85%**
6 Jun	*	*	*	*
9 Aug	22	15		
10 Aug			5	11
19 Aug				49
20 Aug	51	51		
21 Aug			34	
18 Sept	13			
25 Sept	38	15	12	
26 Sept				13
1 Oct	39			
3 Oct	34	28		
8 Oct		16		
13 Oct		29		
14 Oct			28	
Total (mm)	**197**	**154**	**79**	**73**
No. Irrigations	6	6	4	3

*An initial irrigation (25 mm) was applied after planting. Initial soil water was measured after this irrigation and , therefore, was not included in the total.

3.4. Soil water

Figure 4 shows the change in total profile (top 150 cm) soil water as a function of days after sowing for each treatment. It shows that the heavy clay soil at the research site could hold a total of about 700 mm of water in the top 150 cm depth, although not all of it is available to the crop. Wheat was planted following a cotton crop from a deficit-irrigated experiment. Therefore, the soil profile at crop emergence had only from about 540 to 600 mm of water, for the driest and wettest treatments. This represented a soil water depletion of between 100 to 160 mm. However, after the initial irrigation applied after sowing, there was sufficient water in the surface soil layer to supply crop needs during the early growth stage. The treatments that had more water available consumed more soil water during the season. However, the balance between the initial and final profile soil water was very similar for all treatments at about 80 mm.

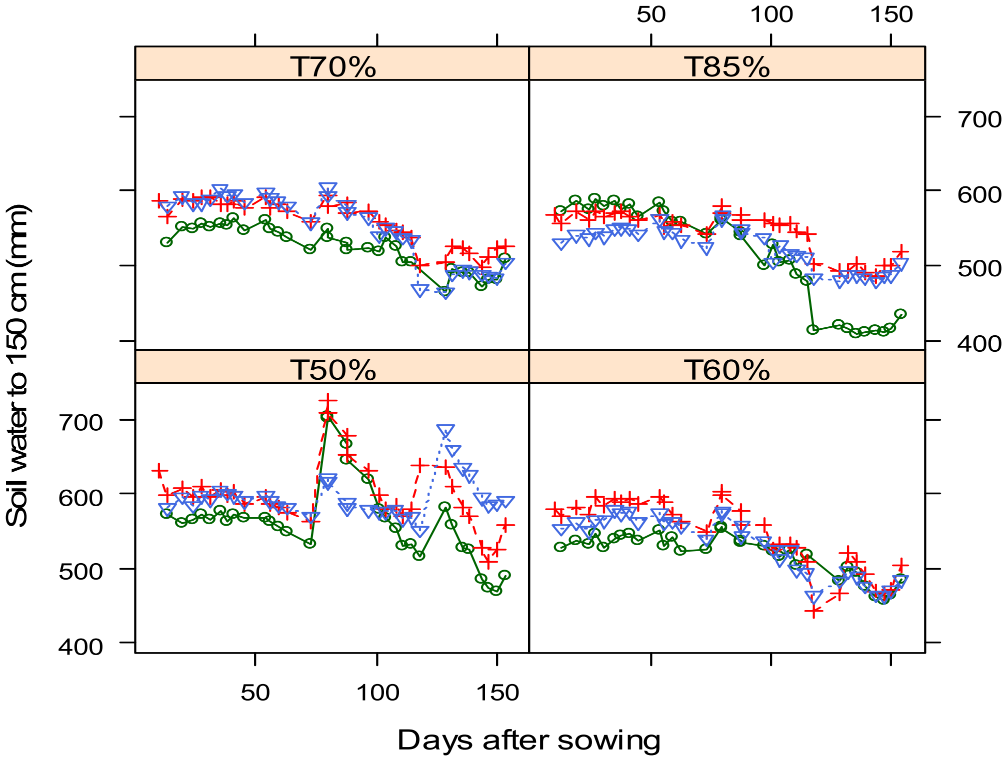


Figure 4. Total soil water in the top 150 cm soil depth as a function of day after sowing for each replication of four irrigation treatments measured for wheat at Kingsthorpe during 2008.

3.5. Soil Nitrogen

Figure 5 shows the cumulative soil nitrogen content in the top 90 cm of soil for each irrigation treatment. The soil N contents among irrigation treatments were quite high and variable, ranging from about 150 to 400 kg N/ha. However, analysis of variance resulted in no significant differences in total N content among treatments. (Lacy and Giblin, 2006) recommended that to obtain high yields, a soil N supply at sowing should be between 100 and120 kg/ha. They suggested that the N demand for a 8-t/ha wheat crop would be about 201 kg N/ha, to be supplied by soil N and fertilizer applications. They warned that a high N content at sowing could result in excessive vegetative growth, crop lodging and potential leaf disease that could cause yield loss. The high soil N content observed in this study could be due to N carried over from a previous low yielding cotton crop.

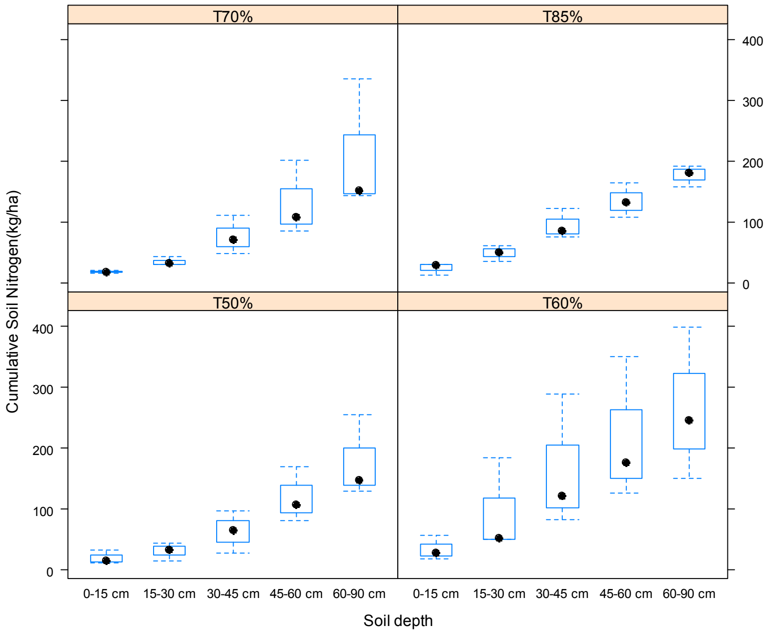


Figure 5. Cumulative soil nitrogen on 8 August 2008 with depth for four irrigation treatments (T50% to T85%) at Kingsthorpe. The box plots represent variability among sub-samples taken for each depth.

3.6. Crop development

Table 2 shows the leaf area index (LAI) and plant height (h) by irrigation treatment measured at different days after showing, as indicators of crop development. Irrigation treatment resulted in significant differences in both LAI and h. There were significant differences in LAI during the second sampling date (DAS 74) and during the last two sampling days (DAS 115 and 131). Significant differences in h resulted during the last 3 sampling dates (DAS 102, 115 and 131). By the last sampling date, the wettest treatment (T50%) was about 10 cm taller compared to the driest (T85%).

Table 2. Treatment averages and analysis of variance (ANOVA) of wheat leaf area index and plant height from four irrigation treatments measured at different days after sowing at Kingsthorpe during 2008.

		Days after sowing (DAS)					
Variable	**Treatment**	**46**	**74**	**88**	**102**	**115**	**131**
Leaf area index	T50%	1.66	4.48 a	7.49	6.14	4.04 ab	2.96 a
	T60%	1.44	4.48 a	5.40	5.93	4.69 a	2.41 a
	T70%	1.32	2.95 b	7.44	3.18	1.84 b	0.20 b
	T85%	1.41	2.89 b	6.96	4.16	2.35 ab	0.09 b
Plant height	T50%	36.8	50.7	66.5	87.0 a	89.7 ab	96.4 a
	T60%	34.8	48.4	66.5	85.4 a	93.5 a	93.1 a
	T70%	34.5	45.7	61.6	71.5 b	80.4 b	81.0 b
	T85%	33.7	46.8	61.0	79.5 ab	82.6 ab	86.6 ab
		ANOVA (P>F)					
Leaf area index		0.530(ns)	0.006	0.55(ns)	0.11(ns)	0.035	<0.001
Plant height		0.44(ns)	0.17(ns)	0.027	0.023	0.021	0.013

ns = not significant; letters compare treatment means within each DAS.
Treatments with the same letter within each DAS were not significantly different at the P = 0.05 level.

3.7. Crop lodging

These differences in crop development, as indicated by the differences in LAI and h, had implication for crop lodging. Figure 6 and Table 3 show the percent crop lodging by irrigation and nitrogen treatment. The driest treatments (T75% and T85%) had not lodging problems, while the wettest treatments (T50% and %T60%) had considerable lodging. ANOVA in Table 3 shows significant differences among irrigation treatments. There were no significant differences among nitrogen treatments or among nitrogen x irrigation interactions (I x N). It is an important dilemma in wheat production that the conditions needed to obtain high yield, such as sufficient nitrogen and water, can also promote excessive vegetative growth, which can make the crop more susceptible to lodging. Therefore, the challenge is to limit water and nitrogen inputs early in the season, just enough to avoid excessive vegetative growth, but without significantly reducing yields. These results suggest a need for plant breeders to develop shorter varieties with high yield potential, less susceptible to lodging under irrigated conditions and nitrogen-rich soils.

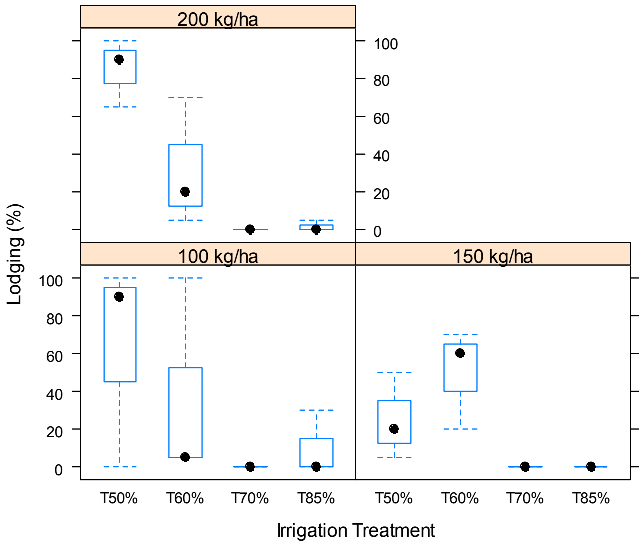


Figure 6. Percent crop lodging by irrigation (T50% to T85%) and nitrogen (100 to 200 kg/ha) treatment obtained at Kingsthorpe during 2008.

Table 3. Percent crop lodging by irrigation and nitrogen treatment obtained at Kingsthorpe during 2008.

	Nitrogen			
Irrigation	**100 kg/ha**	**150 kg/ha**	**200 kg/ha**	Mean
T50%	63.3	25.0	85.0	57.8 a
T60%	36.7	50.0	31.7	39.5 ab
T70%	0.0	0.0	0.0	0.0 b
T85%	10.0	0.0	1.7	3.9 b
Mean	27.5	18.8	29.6	25.3
ANOVA (d.f)		Pr>F		
Irrigation (3)		<0.05		
Nitrogen (2)		0.534 (ns)		
I x N (6)		0.242 (ns)		

Means with the same letter are not significantly different using $LSD_{(0.05)}$.
d.f = degrees of freedom, ns = not significant
N=nitrogen, I= irrigation, LSD = least significant difference

3.8. Crop yield and yield components

Wheat yields on a dry mass basis and at 12% grain water content by irrigation and nitrogen treatments are shown in Table 4. Irrigation significantly affected yields, while nitrogen and irrigation x nitrogen (I x N) interaction did not. As expected, yields increased with irrigation.

The different components determining crop yield are shown in Table 5. Irrigation significantly increased yield by increasing both the number of seeds (seeds/head and seeds/m^2) and the seed mass (g/100 seeds). The findings agree with those of (Karam et al., 2009) who obtained similar results for two durum wheat cultivars. They found that regardless of cultivar, supplemental irrigation significantly increased grain number and grain weight, which resulted in higher yield with respect to a dryland treatment. They also found nitrogen to increase yield by increasing grain number. In this study, no significant effect on yield components was observed from N application. Irrigation did not affect plant density (plants/m^2) or the number of heads (heads/plant or heads/m^2).

Table 4. Wheat grain yields obtained in 2008 at Kingsthorpe

Wheat grain yield ($g\ m^{-2}$) (dry mass basis)

		Nitrogen		
Irrigation	**100 kg/ha**	**150 kg/ha**	**200 kg/ha**	Mean
T50%	412.1	386.4	389.4	**396.0a**
T60%	341.5	339.5	358.2	**346.4b**
T70%	196.5	184.7	201.1	**194.1c**
T85%	203.0	155.6	177.5	**178.7c**
Mean	**288.3**	**266.5**	**281.5**	**278.8**

Wheat grain yield ($g\ m^{-2}$) at 12% grain water content

		Nitrogen		
Irrigation	**100 kg/ha**	**150 kg/ha**	**200 kg/ha**	Mean
T50%	468.3	439.1	442.5	**450.0a**
T60%	388.1	385.8	407.0	**393.6b**
T70%	223.3	209.9	228.5	**220.5c**
T85%	230.7	176.8	201.7	**203.1c**
Mean	**327.6**	**302.9**	**319.9**	**316.8**

ANOVA (d.f)	Pr>F
Irrigation (3)	<0.001
Nitrogen (2)	0.411 (ns)
I x N (6)	0.943(ns)

Means with the same letter are not significantly different using $LSD_{(0.05)}$.
d.f = degrees of freedom, ns = not significant
N=nitrogen, I= irrigation, LSD = least significant difference

Table 5. Irrigation treatment averages (for 200 kg N/ha) and Analysis of Variance of wheat yield components obtained at Kingsthorpe during 2008.

Treatment	Plants/m^2	Heads/plant	Seeds/head	Seeds/plant	heads/m^2	Seeds/m^2	g/100 seeds
T50%	205.3	2.4	36.9 a	92.2	448.4	16621 a	3.52 a
T60%	156.0	2.7	32.0 ab	87.3	412.5	13179 ab	3.57 a
T70%	162.7	2.1	21.6 c	44.5	328.0	7073 c	2.57 b
T85%	185.3	2.1	27.6 bc	59.4	386.7	10423 bc	2.45 b
Average	**177.3**	**2.3**	**29.5**	**70.9**	**393.9**	**11824.0**	**3.03**
ANOVA (d.f)				Pr>F			
Irrigation (3)	0.715 (ns)	0.452(ns)	**<0.01**	0.153(ns)	0.279(ns)	**<0.01**	**<0.001**

Means with the same letter are not significantly different using $LSD_{(0.05)}$.
d.f = degrees of freedom, ns = not significant

3.9. Water use and water use efficiency

Details of water inputs and calculations of water use efficiencies by irrigation treatment are shown in Table 6. Total water (TW) was considered as the total amount of water supplied to the crop during the season, include soil water, irrigation and rain. Because there was considerable rain in November that probably had no impact on crop development, total water was calculated in two ways: (1) considering only rain and soil water until the end of October and, (2) considering rain and soil water until harvest. Two indicators of water use efficiency (WUE) were calculated, including the irrigation water use efficiency (IWUE= yield/irrigation) and the gross production water use efficiency (GPWUE = yield/TW).

Several relevant relationships are plotted in Fig. 7 (A-D). Fig.7 (A) indicates that yield increased almost linearly with irrigation. This linear increase, even for the wettest treatment, suggests that it is unlikely that there was over-irrigation during this study. It is good to point out that the relationship between irrigation and yield varies with season. This relationship depends on the amount and timing of other sources of water available to the crop, such as rainfall (amount, timing and effectiveness) and soil water at crop emergence (amount and location within the soil profile). It also depends on how well water supplies match crop water demands, both in magnitude and timing.

Table 6. Water inputs and wheat water use efficiencies obtained at Kingsthorpe during 2008.

Variable measured	**Irrigation Treatment**			
	T50%	**T60%**	**T70%**	**T85%**
Profile soil water at crop emergence (mm)	602.4	552.9	558.6	540.7
Profile soil water at end of October (mm)	501.94	446.27	472.51	445.31
Profile soil water at harvest (mm)	521.30	468.00	489.20	462.70
Profile soil water used by end of October (mm)	100.46	106.63	86.09	95.39
Profile soil water used by harvest (mm)	81.1	84.9	69.4	78.0
Irrigation (mm)	197.0	154.0	79.0	73.0
Rain by end of October (mm)	154.2	154.2	154.2	154.2
Rain by harvest (mm)	212.2	212.2	212.2	212.2
Total Water by end of October (TWO, mm)	451.66	414.83	319.29	322.59
Total Water by harvest (TWH, mm)	490.3	451.1	360.6	363.2
Dry grain yield (g/m^2)	396.0	346.4	194.1	178.7
GPWUE_o (yield/TWO) (g/m^2/mm)	0.88	0.84	0.61	0.55
GPWUE_h (yield/TWH, g/m^2/mm)	0.81	0.77	0.54	0.49
IWUE (yield/irrigation, g/m^2/mm)	2.01	2.25	2.46	2.45

GPWUE= gross production water use efficiency, IWUE =irrigation water use efficiency

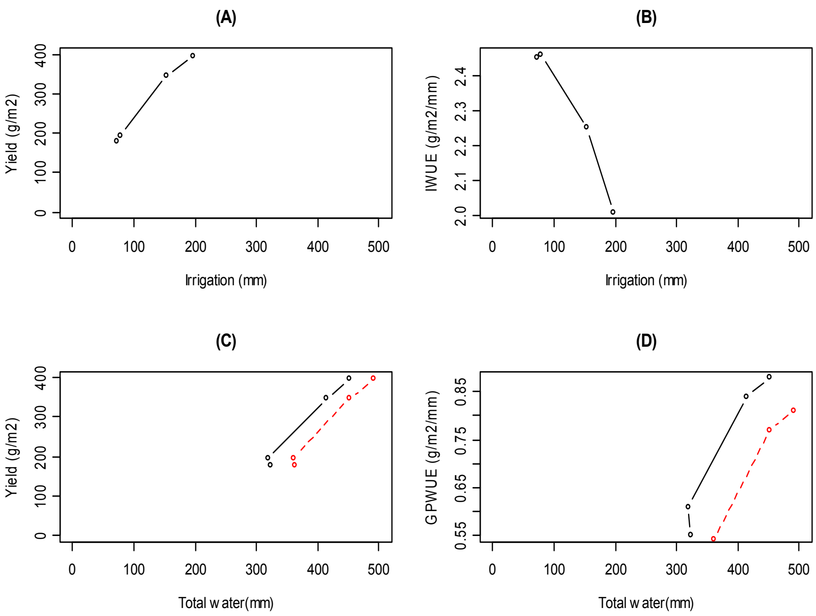


Figure 7. Relationships between irrigation, total water (irrigation + soil water + rain), wheat grain yield (dry mass basis), irrigation water use efficiency (IWUE=yield/irrigation), and gross production water use efficiency (GPWUE=yield/ total water) obtained at Kingsthorpe in 2008. In Figs C and D, the solid and dashed lines are for total water by end of October and harvest respectively.

Figure 7 (C) indicates that yield also increased almost linearly with total water as:

Yield = -334.99 + 1.63(TWoct) (R^2=0.99) ……………..……….. (1)
Yield = -416.46 + 1.67(TWharvest) (R^2=0.99) ……………………… (2)

Where, TWoct and TWharvest are the total water (irrigation + soil water + rain) by the end of October and by harvest, respectively. Yield is grain yield (dry mass basis) (g/m^2). Equations (1) and (2) indicate that each mm of TWoct and TWharvest produced 1.63 and 1.67 g/m^2 of dry grain yield, respectively. From Eqs. (1) and (2) it can also be determined that it took about 206 mm of TWoct (334.99/1.628 = 205.8 mm) and 249 mm of TWharvest (416.46/1.670 = 249.38 mm) to produce the first grain yield increment under this environment. This includes water needed to produce vegetative growth and any water losses. In this study, water losses were mainly from soil evaporation.

IWUE sharply decreased with irrigation (Fig. 7(B)). Depending on the environment, IWUE can increase, decrease, or stay constant with irrigation. This depends on weather the intercept of the yield versus irrigation relationship is positive, zero, or negative. In semi-arid environments, growers can usually produce some crops under dryland conditions. This means that the intercept is positive in this situation and IWUE decreases with irrigation. If the relationship between yield and irrigation extrapolates to and intercept of exactly zero, then IWUE is constant with irrigation. On the other hand, in a very arid environment (or in a very dry season) it could take a significant amount of irrigation to start producing yield. In this case, the relationship will extrapolate to a negative yield intercept (at least in theory), and IWUE will increase with irrigation.

Figure 7(D) shows that the GPWUE increased with total water. The IWUE and GPWUE had opposite behavior under the conditions of this study, but as suggested above, could both increase in a very dry environment. The question then is, which of these two indicators of WUE should farmers aim at maximising, if any, or should they focus on maximising some other indicator of WUE. At the end, agriculture is a business and farmers usually aim to maximize profits, not only yield. Therefore, this question should be explored via economic analysis, which considers not only the biophysical crop response to water (in terms of crop quantity and quality), but also crop prices and cost of production.

3.10. Grain protein

Before performing economic analysis, the effect of irrigation and nitrogen on grain quality, which can affect crop price, was evaluated. In Australia, the main indicator of grain quality is grain protein content. Figure 8 shows that grain protein decreased as irrigation increased for all nitrogen treatments. Statistics in Table 7 shows that irrigation significantly affected grain protein, while nitrogen and irrigation x nitrogen interaction (I x N) did not. Again, N did not have an effect most likely due to the high initial soil N content. The driest treatment resulted in lower yield, but the higher protein contents would attract a price premium, which could compensate for the lower yields. The relevant question is then how to achieve the optimum balance of yield and protein content that would maximize profits.

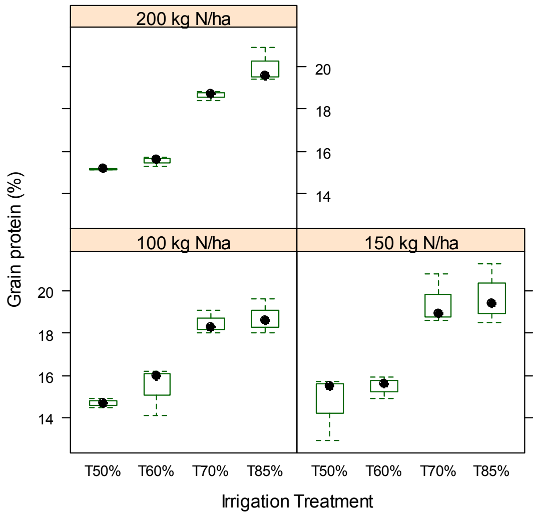


Figure 8. Comparison of wheat grain protein (dry-mass basis) between different irrigation and nitrogen treatments measured at Kingsthorpe during 2008.

Table 7. Wheat grain protein (%) at harvest obtained in 2008 at Kingsthorpe

	Nitrogen			
Irrigation	**100 kg/ha**	**150 kg/ha**	**200 kg/ha**	Mean
T50%	14.71	14.70	15.17	**14.86b**
T60%	15.43	15.47	15.53	**15.48b**
T70%	18.47	19.43	18.63	**18.84a**
T85%	18.73	19.97	19.97	**19.48a**
Mean	**16.84**	**17.33**	**17.33**	**17.17**
ANOVA (d.f)		Pr>F		
Irrigation (3)		<0.001		
Nitrogen (2)		0.22 (ns)		
I x N (6)		0.61 (ns)		

Means with the same letter are not significantly different using $LSD_{(0.05)}$.
d.f = degrees of freedom, ns = not significant
N=nitrogen, I= irrigation, LSD = least significant difference

3.11. Economic analysis

Figure 9 shows the gross margins for the different irrigation and nitrogen treatments, taking into account both grain yield and grain quality. Figure 9 shows the gross margins in terms of Australian dollars per hectare ($/ha), per ML of irrigation ($/ML Irrigation) and per ML of total water (rain + irrigation+ soil water) ($/Total ML). The lower N treatment within each irrigation treatment tended to have the highest gross margins. Since there was not yield or grain protein response to the nitrogen treatments, the gross margins by irrigation treatments, averaging all N treatments within each irrigation treatment, are shown in Fig. 10. Figure 10 shows that the two driest treatments (T70% and T85%) always had the lowest gross margins in terms of $/ha, $/ML irrigation or $/Total ML compared to the two wettest treatments (T50% and T60%).

Figure 10 also shows that in terms of $/ha, the gross margins increased from the driest to the wettest treatment. These results suggest that if water is not limited fully-irrigating the crop rather than dryland or deficit irrigation is the best option from the purely economic point of view. However, in terms of $/ML irrigation slightly higher gross margins were obtained with the slightly deficit-irrigated treatment (T60%) compared to the fully-irrigated treatment (T50%). Very similar gross margins were also obtained from the T50% and T60% treatments in terms of $/Total ML. Also, the T60% treatment saved about 43 mm of water compared to the T50% treatment. These results could be partially due to less water loses, likely from soils evaporation, from the T60% treatment compared with the T50% treatment. Therefore, if water is limited, under the conditions of this study, the T60% treatment seems like a more feasible option compared to the T50% treatment from and economic and environmental stewardship prospective. However, it should be clear that the treatment with the highest gross margins in terms of $/ML (of irrigation or total water) will only be the best option if the water savings can be used to obtain additional income, such as expanding irrigated cropping area, trading the water, or carrying over allocation for later use. This is because farmers are interested in maximising the income of the whole farm and not necessarily in a per hectare or per ML basis.

In a similar analysis in Australia, (Cotton Seed Distributors, 2008) found comparable gross margins for cotton and wheat in terms of $/ML (they did not specify which $/ML irrigation or $/Total ML), although cotton still had a much higher gross margin when compared in a $/ha basis. This shows why cotton is still the preferred crop to allocate water to, but because of the lower water requirements, wheat could be a viable option if water is limited.

It should, however, be taken into account that gross margin comparisons of irrigation strategies are very sensitive to changes in crop prices, cost of production and seasonal rainfall. Therefore, gross margin comparisons of irrigation strategies need to be made on a season by season basis, using tools that incorporate both the dynamics of economical and biophysical variables affecting crop production and marketing. Also, in the analysis it should be considered weather the farmers have the flexibility of using the water savings of deficit-irrigation strategies to generate additional income. For example, it the farmer is using a centre pivot system to irrigate, his irrigated area is fixed and cannot be easily expanded without making significant investment, such as investing in another centre pivot or enlarging the area under the current system by using a corner system or a big gun. Carrying water forward for the next season could be an option (if water regulations allow it), but in surface systems where water is stored in farm storages, as is common in Australia, water left in storage could be lost by evaporation and seepage.

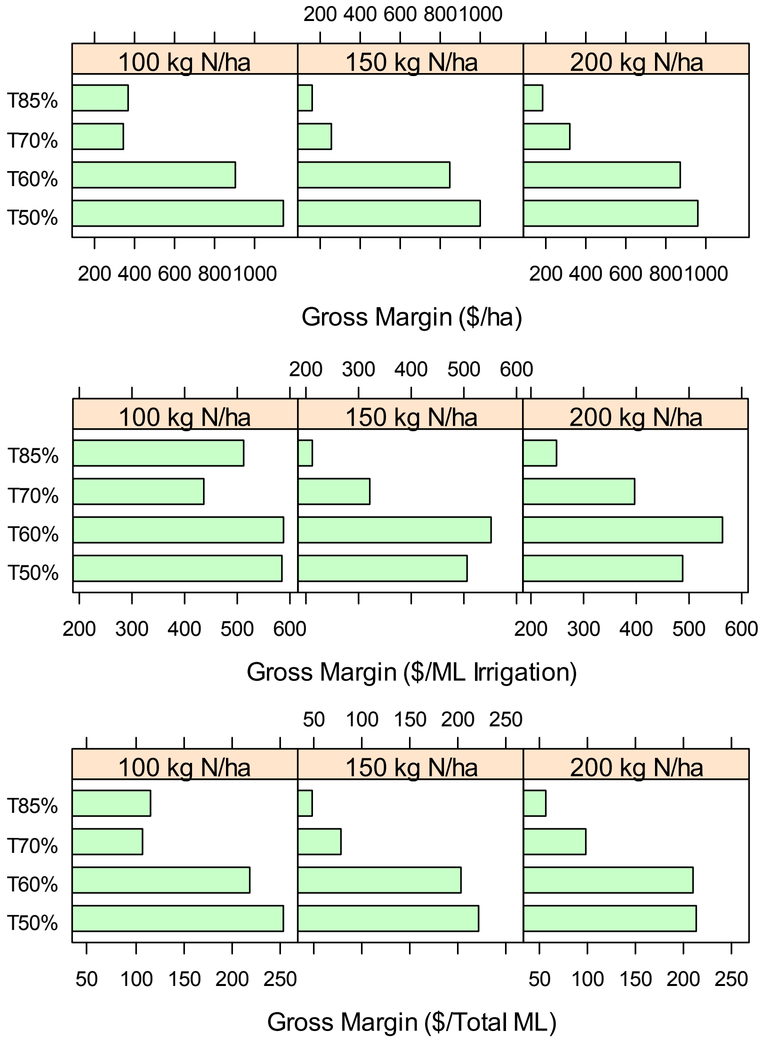


Figure 9. Gross margins by irrigation (T50%-T85%) and nitrogen (100-200 kg N/ha) treatments obtained for wheat at Kingsthorpe during 2008.

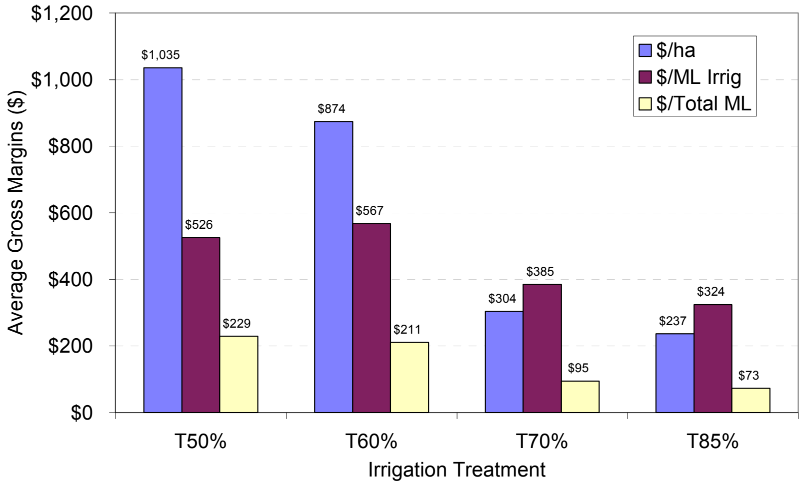


Figure 10. Average gross margins by irrigation treatments obtained for wheat at Kingsthorpe during 2008.

4. Conclusions

It was found that increasing irrigation significantly increased crop yield, but decreased grain protein content. Irrigation also increased crop leaf area index and plant height, which resulted in increased crop lodging problems. No response was observed from the nitrogen treatments due to high initial soil nitrogen content. Results from this study showed that the irrigation water use index (IWUI = yield/irrigation) decreased with irrigation while the gross production water use index (GPWUI = yield/total water) increased with total water (rain + irrigation + soil water). Since these two indicators of water use efficiency (WUE) have opposite behavior under the conditions of this study, it is necessary to be specific when referring to the "need to increase WUE." It was then suggested that economic analysis is needed to be able to decide what WUE indicator farmers should maximize.

Economic analysis of the results of the field experiment showed that irrigation increased gross margins when calculated in terms of $/ha. However, a slightly deficit-irrigated treatment (initiating irrigation at 60% depletion) resulted in similar or higher gross margins compared with a fully-irrigated treatment (initiating irrigation at 50% depletion) when compared in terms of $/ML of water inputs. Severely stressed treatments (initiating irrigation at 70% and 85% depletion) resulted in the lowest gross margins, both in a $/ha and $/ML basis. It is, however, suggested that this type of economic analysis is very sensitive to changes in prices, crop production cost and seasonal rainfall. It is also suggested that producers need to maximized whole-farm income, not just the income per hectare or per ML. Therefore, when water is limited, although some deficit-irrigation strategies could provide higher $/ML compared with full irrigation, to maximize whole-farm income growers will need to be able to generate additional income with the water savings.

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References

Ali, M.H., and M.S.U. Talukder. 2008. Increasing water productivity in crop production-A synthesis. Agricultural Water Management 95:1201-1213.

Cotton Seed Distributors. 2008. Cotton & wheat gross margin analysis [Online] http://www.csd.net.au/fof/show/2508 (verified 10 April).

Karam, F., R. Kabalan, J. Breidi, Y. Rouphael, and T. Oweis. 2009. Yield and water production functions of two durum wheat cultivars grown under different irrigation and nitrogen regimes. Agricultural Water Management 96:603-615.

Karimi, M.M., and H.M. Siddique. 1991. Crop growth and relative growth rates of old and modern wheat cultivars. Australian Journal of Agricultural Research 42:13-20.

Lacy, J., and K. Giblin. 2006. Growing eight tonnes a hectare of irrigated wheat in southern NSW Primefact 197. NSW Department of Primary Industries.

Stapper, M. No date. Crop monitoring and Zadoks growth stages for wheat. CSIRO Plant Industry, Canberra, Australia.

Zadocks, J.C., T.T. Chang, and C.F. Konzak. 1974. A decimal code for the growth stages of cereals. Weed Research 14:415-421.

Zadoks, J.C., T.T. Chang, and C.F. Konzak. 1974. A decimal code for the growth stages of cereals. Weed Research 14:415-421.

Appendix IX

Development of a lysimeter research facility for crop evapotranspiration measurement

Jose Payero, Trevor Harris, Graham Harris and Geoff Robinson

Agri-Science Queensland, Department of Employment, Economic Development and Innovation (DEEDI)

Abstract

In times of decreased water availability in many parts of the world, there is a pressing need to make a more efficient use of limited water resources. This is especially important in agricultural production, which uses a large proportion of the extracted water for irrigation. To use irrigation water more efficiently, it is necessary to irrigate crops according to their water demand, which requires a good understanding of crop evapotranspiration (ETc). Measuring crop ETc at the farm level is difficult, and good procedures to estimate ETc are needed to assist farmers make better irrigation scheduling decisions. To calibrate these procedures, direct ETc measurements, usually done with weighing lysimeters, are needed. This paper describes a lysimeter research facility consisting of twelve large (1m x 1m x 1.5 m) repacked weighing lysimeters that was installed in 2008 near Kingsthorpe, Australia. This paper covers aspects related to the design, construction, installation, cost, and performance of the lysimeter research facility.

Keywords: Lysimeter, Evapotranspiration

Introduction

Limited water supply in many parts of the world is making it imperative to use irrigation water more efficiently. This responds to the need to maintain or even increase agricultural production, with the same or less water, to feed an ever increasing population. Using water more efficiently implies that water is not wasted during storage, conduction, and field application. It also implies that water applications are properly matched to crop water demands, both in amount and timing. Knowing how much water crops need and when they need it, is vital for long-term irrigation planning, irrigation system design, and day-to-day irrigation scheduling.

There has been a long history of development to try and estimate crop water requirements, usually known as crop evapotranspiration (ETc), using weather data and crop coefficients (Allen et al., 1998; Doorenbos and Pruitt, 1977). The crop coefficients (Kc), however, need to be derived empirically, which requires direct and accurate measurements of ETc. Daily ETc can be directly measured using micrometeorological methods, such as eddy covariance (Goltz et al., 1969; Li et al., 2008; Suyker and Verma, 2009), Bowen ratio (Heilman et al., 1989; Moran et al., 1994; Todd et al., 1998; Todd et al., 2000; Tomlinson, 1996; Wolf et al., 2008), and Surface Renewal (Anandakumar, 1999; Castellvi et al., 2008; Paw U et al., 1995; Simmons et al., 2007). Crop ETc can also be measured using a soil water balance approach based on intensive soil moisture measurements (Hunsaker, 1999). However, weighing lysimeters have traditionally been used to measure ETc, and many lysimeters have been designed and installed around the world (Allen and Fisher, 1990; Allen and Fisher, 1991; Howell et al., 1985; Hunsaker et al., 2002; Ko et al., 2009a; Ko et al., 2009b; Marek et al., 1988; Meyer et al., 1987; Payero and Irmak, 2008; Piccinni et al., 2006; Wright, 1982). A discussion of the different types of lysimeters has been provided by (Payero and Irmak, 2008).

Much of the crop coefficient data obtained around the world has been summarized by (Allen et al., 1998). An issue with the crop coefficients provided by (Allen et al., 1998) is that values are given as function of time (days), however, crops develop based on growing degree units rather than calendar days, therefore, extrapolating published Kc values to locations other than where they were originally developed can be challenging. Also, Kc values are empirically derived for specific crop varieties, but different crop varieties can have different development pattern, which makes it desirable to have locally-obtained Kc values, determined for local varieties, if ETc is to be estimated accurately.

Direct ETc measurements in Australia, and especially in Queensland, have been limited. The available work, although recently reported was mostly conducted back in the 1980’s (Meyer, 1999; Meyer and Mateos, 1990; Meyer et al., 1999) when crop varieties were different. Therefore, there is a need to develop appropriate procedures to calculate ETc for local crops based on locally-calibrated Kc values with current crop varieties. This paper discusses the construction, field installation, and performance of twelve repacked weighing lysimeters for measuring ETc of a variety of crops on the Darling Downs, Australia.

Methods

Research facility

The lysimeters research facility consisted of twelve weighing lysimeters. They were installed at the Agri-Science Queensland, Department of Employment, Economic Development & Innovation (DEEDI) Kingsthorpe research station. The station is located in a sub-tropical climatic zone, about 20 km north-west of the city of Toowoomba, Queensland, Australia ($27^{o}30'44.5"$ Latitude South, $151^{o}46'54.5"$ Longitude East, 431 m above mean sea level). The soil at the site is a haplic, self-mulching, black, vertisol. It has a heavy clay texture in the 1.5 m root zone profile, with a distinct change in soil colour from brownish black (10YR22) in the top 90 cm to dark brown (7.5YR33) deeper in the profile. The soil is of alluvial fan and basalt rock origin, slowly permeable, with a surface slope of about 0.5%.

The lysimeters are part of an irrigation research facility that was installed to conduct deficit irrigation research with a variety of crops. The research site consists of twelve experimental units (plots) (Figure 41). Each plot is 13 m x 20 m, with the crop planted in the North-South direction. A border (4 m) is allowed between plots and a road (4 m) is located at the centre of the research area. When growing cotton, a refuge crop can be planted at the East and West sides of the plots. The plots are irrigated individually with bore water using a solid-set sprinkler system. Partial-circle sprinkler heads are used to avoid irrigating adjacent plots. One lysimeter was installed at the center of each plot.

An EnviroStation (ICT International Pty Ltd, Armidale, NSW, Australia) weather station was installed next to the research plots. The station recorded hourly values of solar radiation, air temperature (maximum, minimum, and average), relative humidity, wind speed, and rainfall. From the weather data, daily grass-reference evapotranspiration (ETo) values, needed to calculate Kc from ETc measurements, can be calculated using the standardized FAO-56 Penman-Monteith method (Allen et al., 1998).

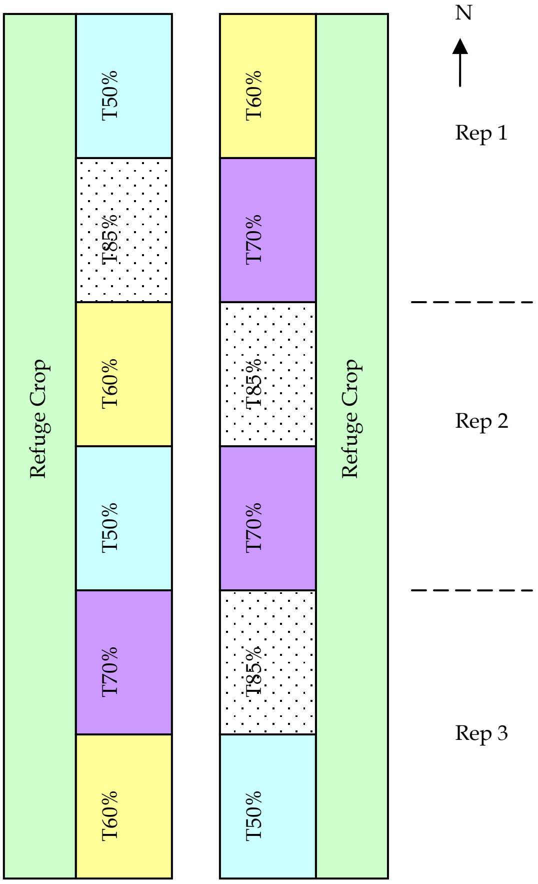


Figure 41. Field experimental layout at Kingsthorpe. T50%, T60%, T70%, and T85% are irrigation treatments. The refugee crop was needed for cotton production.

Design and construction

The lysimeters were constructed by a local engineering shop (T.H. & J.M. Graham Engineering, Toowoomba). Each weighing lysimeter consisted of an inner and an outer box constructed out of stainless steel (Figure 2 and 6). Stainless steel was selected, rather than normal steel, because it less susceptible to corrosion. Consequently, a thinner grade of plated steel could be selected, which made the lysimeter boxes lighter and easier to handle. Also, the stainless steel did not require painting, as normal steel would have. Because of these advantages, in this case it resulted cheaper to use stainless steel.

The inner box had inside dimensions of 1 m x 1 m x 1.5 m, and the outer box had outside dimensions of 1.2 m x 1.2 m x 1.7 m. The inner box was constructed from a 1.6 mm, 304 grade stainless steel sheet, reinforced on the outside by three square frames made out of steel RHS, located at the top, middle, and near the bottom of the box. The top RHS had dimensions of 50 mm x 50 mm x 1.6 mm and the other two, 50 mm x 25 mm x 1.6 mm. A drain tap was provided at one side of the bottom end of the inner box. The tap could be opened and closed from the top of the box via a steel rod.

For the outer box, a frame made out of steel RHS (50 mm x 50 mm x 1.6 mm, and 50 mm x 25 mm x 1.6 mm) was constructed, which was then covered with a 1.6 mm, 304 grade stainless steel sheet. An opening (0.5 mm x 0.5 m) was left at the bottom of the outer box to allow drainage. Handles were welded to each corner to be able to attach chains to the box for lifting.

Figure 42. Lysimeter during construction showing the inner box inside the outer box frame.

The inner box was supported inside the outer box by three load cells mounted at the top of the outer box. Placing the load cells at the top, rather than at the bottom, was preferred to be able to replace them in case of malfunction. Load cells can be damaged by events like lighting strike and overloading. If load cells malfunction, It would be required to bring a crane or other type of lifting equipment or machinery to the field to lift the inner box. If the damage occurs after the crop has been planted, it is usually not practical to lift the lysimeters with heavy machinery without damaging the crop in the process.

Because of this issue, the lysimeters were designed so that no heavy equipment was needed to replace the load cells. This was accomplished by designing a special mount for the load cells, as shown in Figure 43. It shows that in addition to the three bolts needed to attach each load cell to the outer and inner boxes, the mount included an additional bolt with double nut (support bolt), which could be used to support the mass of the inner box when replacing the load cell. The support bolt could also be used to protect the load cells from damage by overload, by supporting the mass of the inner box during transport of the lysimeters. It could also be set to only allow so much bending of the load cell to avoid damage by overloading once the lysimeters are installed in the field. With this system, one person can easily replace a load cell in a few minutes.

Figure 43. Detail of load cell mount.

To protect the load cells and cover the gap between the inner and outer box, two covers for each of the four sides of the lysimeter were constructed from 1.6 mm stainless steel sheet. One cover was bolted to the side of the outer box and another cover was bolted to the top of the inner box. The covers could be easily removed to expose and replace the load cells (Figure 44).

Figure 44. Lysimeter during field installation showing removed load cell covers.

Each lysimeter had three model LCSB load cells (PT Limited, Baulkham Hills, BC, Australia), each with a capacity of 1000 kg. The specifications of the load cells are given in Table .

Table 1. Specifications of the Model LCSB load cells (PT Limited, Baulkham Hills, BC, Australia).

Signal Output at Capacity	3±0.25% mV/V
Service Load	100% Capacity
Linearity Error	< 0.020% FSO
Safe Load	150% Capacity
Non-Repeatability	< 0.010% FSO
Safe Side Load	100% Capacity
Combined Error	< 0.030% FSO
Ultimate Load	300% Capacity
Hysteresis	< 0.030% FSO
Input Resistance	350_ ± 3_
Creep/(30 mins.)	< 0.030% FSO
Output Resistance	350_ ± 3_
Zero Balance	< 1 % Capacity
Insulation Resistance	> 5000 M_ (@50 VDC)
Temperature Effect on Span(/10C)	< 0.02% FSO
Excitation Voltage(Rec)	5~15 V AC/DC
Temperature Effect on Zero(/10C)	< 0.02% FSO
Excitation Voltage(Max.)	18 V AC/DC
Operating Temperature Range	-35 ~ +65 C
Cable	4.6m Dia. 5.0 mm
Storage Temperature Range	-50 ~ +85 C
Material	Alloy Tool Steel
Compensated Temperature Range	-10 ~ +40 C
Protection	Nickel plating, IP67
Excitation +ve	RED
Excitation –ve	BLACK
Signal +ve	GREEN
Signal –ve	WHITE

The lysimeters were constructed and assembled in the engineering shop, each as a unit, including the load cells. One of the lysimeters was tested in the shop by attaching the load cells to a datalogger and conducting a quick calibration to see if it was performing correctly. The calibration was conducted by filling the lysimeter with water, and then placing a wooden beam on top of the inner box, adding known weights to beam, and measuring the output of the load cells. A satisfactory performance was obtained, as indicated by the almost perfectly linear response shown in Figure 45 .

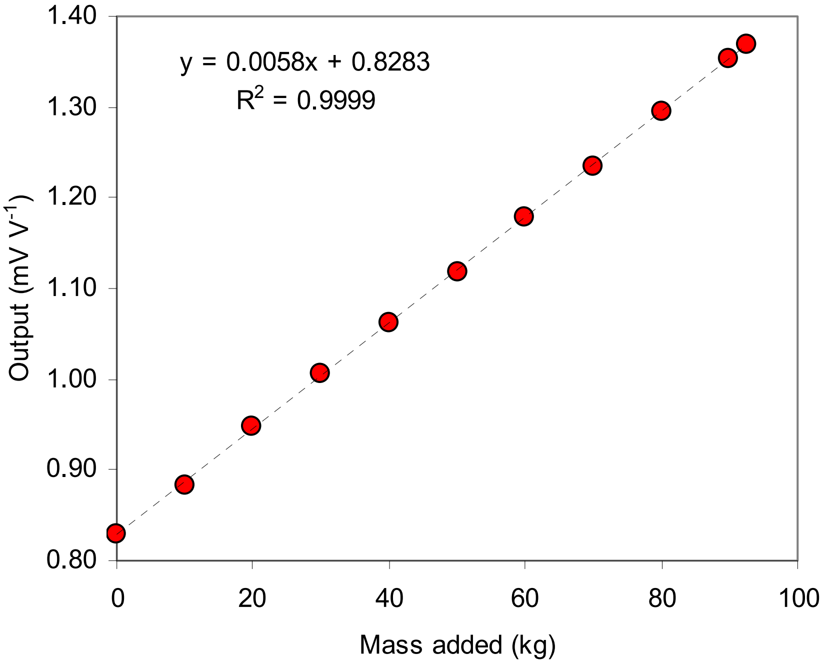


Figure 45. Calibration of one of the lysimeter performed on 12 Sept 2008 in the engineering shop prior to installation of lysimeters in the field at Kingsthorpe.

Field installation

After construction, the lysimeters were transported to the field for installation (Figure 46). Installation of the twelve lysimeters at Kingsthorpe started on 12 November 2008 and was completed in two days. A procedure similar to that described by (Payero and Irmak, 2008) was used for installation. Briefly, a 5-ton excavator was used to dig a pit of appropriate size, keeping layers of soil coming out of the pit in separate piles. Then, the bottom of the pit was leveled as much as possible with the excavator, and a layer of gravel was poured at the bottom of the pit, which was leveled making sure that the distance to the ground surface was adequate. The lysimeter was then lifted into the pit with the excavator, and was aligned with respect to the direction of the plot. The leveling was checked again and additional gravel and soil was added to the difference sides of the pit as needed. A layer of gravel followed by a layer of sand (15 cm each) was placed at the bottom of the inner lysimeter tank to facilitate drainage and to store excess water. Then, both the pit outside the lysimeter and the inner box were repacked with soil (Figure 47). The repacking was done using soil from the different layers, in their original order. Water was added to saturate the soil each time a layer (about 30 cm) was added, trying and maintain soil physical properties as much as possible.

After installation was completed, excess soil was removed from the field. Because of safety reasons, persons were not allowed to get in the pit without a retaining wall. Therefore all the leveling and measurements had to be done from the ground surface using a shovel with a long handle.

Figure 46. Lysimeters at Kingsthorpe prior to installation (12 Nov 2008).

Figure 47. Installing lysimeters at Kingsthorpe (13 Nov 2008).

Figure 7. Continuation

Data collection

The three load cells from each lysimeter were connected to a model PT100SBE-4 junction box (PT Limited, Baulkham Hills, BC, Australia). The junction box sums the output from the three load cells into a single output per lysimeter (Figure 48).

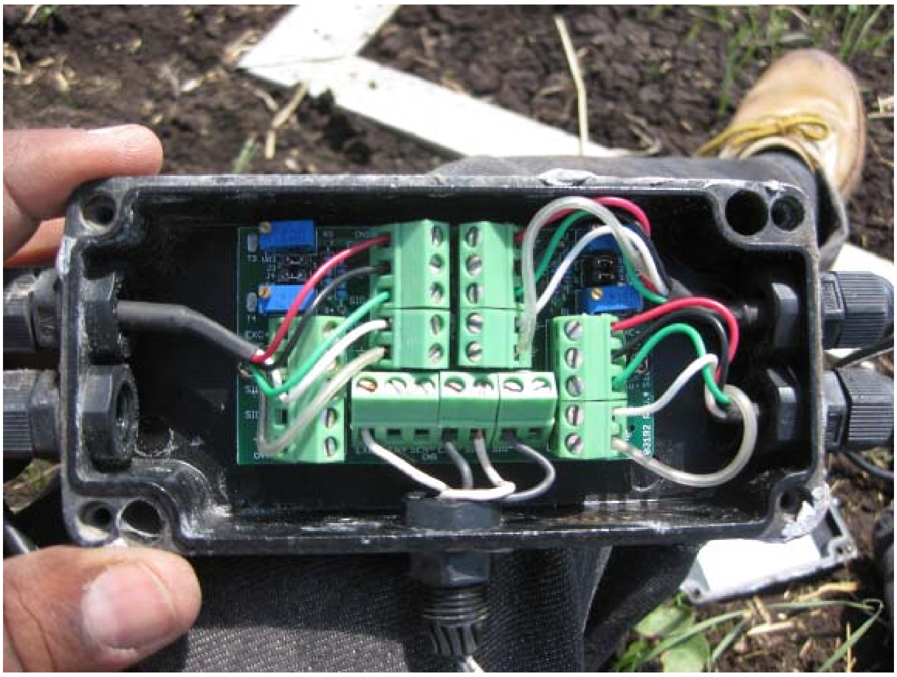


Figure 48. Model PT100SBE-4 junction box

Data from the lysimeters were then collected using a CR3000 datalogger and two AM16/32A multiplexers (Campbell Scientific, Logan, Utah) that were hard-wired to the lysimeters (Figure 49). The three lysimeters in replication 1 and 3 (Figure 41) were connected to the multiplexers and those for replication 2 were connected to the datalogger. The datalogger and multiplexers were placed at one side of the road, midway each replication trying and minimize cable length connecting the lysimeters to the datalogger and multiplexers.

Power to the datalogger was supplied by a 12V deep-cycle marine battery, which was charged by a 30-Watt solar panel. A charge regulator/controller was installed between the datalogger, the battery and the solar panel (Projecta P/No: SC005 12 V 5 Amp, Brown & Watson International Pty Ltd, Knoxfield, Victoria, Australia). The charge controller automatically protects the battery from solar power overcharge, maintains the battery in a fully-charged state, and protects the battery from solar power discharge. The datalogger was programmed to sample the lysimeters using a full bridge configuration, which included sending an excitation voltage (5 V) to the load cells and measuring the returned output (mV/V). The datalogger was programmed to sample each lysimeter every minute and store 30-min averages.

Figure 49. CR3000 datalogger and AM16/32A multiplexer used to sample and record data from lysimeters.

After installation was completed, the field and the area inside the lysimeters were planted to cotton on 15 November 2008. One of the lysimeters planted to cotton is shown in Figure 50.

Figure 50. One of the lysimeters at Kingsthorpe planted to cotton.

Drainage System

When needed, the inner box could be drained by opening the tap, which would normally be closed. The excess water would then drain to the outer box and infiltrate in the soil. There was a distance between the bottom of the inner box and the soil (20 cm) to provide some storage while water infiltrated. However, it was anticipated that during periods of heavy rain, excess water could accumulate at the bottom of the outer box and float the inner box.

A flexible plastic tubing (13 mm diameter) was placed between the inner and outer box, down to the bottom of the outer box that could be used to pump water from the bottom of the outer box (Figure 51). A model LVM105 Amazon in-line and submersible electric pump was used to pump water out of the outer box. This pump is operated with a car battery (12v, 4.5 A) and has a capacity of 1080 liters per hour. It was primed using a manually-operated vacuum pump, commonly used to siphon fuel from vehicles.

Figure 51. Draining water out of the outer box using and electric pump.

Field calibration

After installation, each lysimeter was calibrated to convert the load cell electronic output (mV/V) to its equivalent water depth (mm of water). Calibration was performed by adding objects of known mass to the top of the lysimeter and recording the load cell output. For this calibration, a set of nine 10-kg iron dumbbells was used. The mass of each dumbbell was previously measured in the laboratory using an electronic scale. Several calibrations were conducted during the first growing season after lysimeter installation. Results were always satisfactory showing excellent linear correlation.

Results of calibration performed on 22 April 2009 are shown in Figure 52 and Table . There were small variations in the slope of the line among lysimeters, which was due to the fact that each load cell is shipped from the manufacturer with a unique calibration. Because of this, a calibration needs to be developed for each lysimeter. Differences in the intercept of the lines in Figure 52 and Table 2 are also expected due to differences in the total mass of the lysimeters at the time the calibration was conducted. These differences in total mass result from differences in the mass of the lysimeter boxes themselves, the mass of water, and the mass of soil inside the lysimeters.

Knowing the response of each lysimeters to changes is mass (i.e. the slope of the line), the change in mass of the lysimeter between two times can be calculated (i.e. in kg). This difference in mass can then be coveted to water equivalent (i.e. mm of water) by considering that 1 kg/m^2 = 1 mm. Therefore, daily evapotranspiration can be obtained by taking the differences in lysimeter mass between the same times of consecutive days and converting that difference to mm. During days with rain or irrigation, either data need to be adjusted to account for water input or data for those days should be rejected.

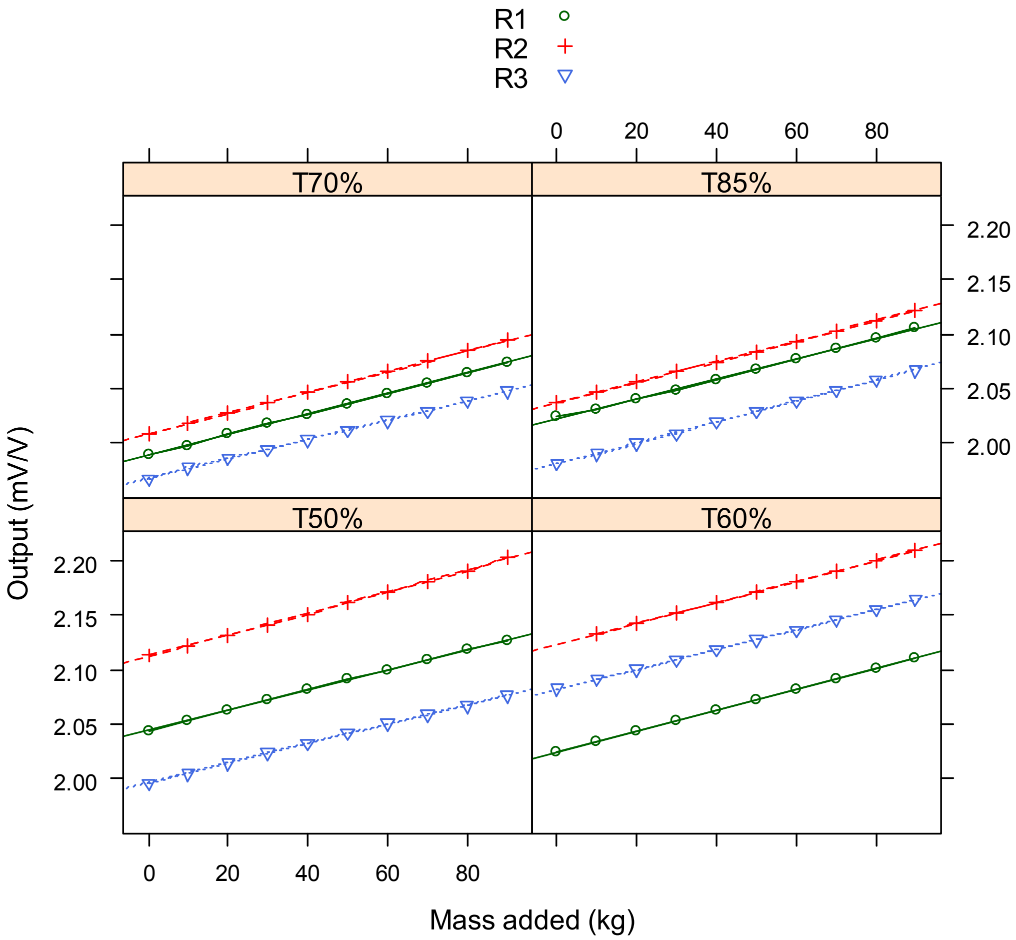


Figure 52. Calibration of twelve lysimeters at Kingsthorpe (22 April 2009). T50%, T60%, T70% and T85% represent the irrigation treatment applied to each lysimeter and R1, R2 and R3 are the replications.

Table 2. Linear regression statistics resulting from calibration of twelve weighing lysimeters at Kingsthorpe, conducted on 22 April 2009.

Lysimeter	Slope [(mV/V)/kg]	Intercept (mV/V)	R^2
T50%-R1[1]	0.000924	2.044202	0.999936
T60%-R1	0.000953	2.024544	0.999944
T70%-R1	0.000946	1.988596	0.999748
T85%-R1	0.000917	2.021774	0.998872
T50%-R2	0.000995	2.112027	0.999097
T60%-R2	0.000966	2.123219	0.999954
T70%-R2	0.000954	2.008005	0.999946
T85%-R2	0.000943	2.036845	0.999877
T50%-R3	0.000898	1.995991	0.999378
T60%-R3	0.000917	2.081895	0.999849
T70%-R3	0.000890	1.967248	0.999643
T85%-R3	0.000969	1.980161	0.999793

[1] T50%, T60%, T70% and T85% represent the irrigation treatment applied to each lysimeter and R1, R2 and R3 are the replications.

Cost

The total material and labour cost of constructing and installing the twelve lysimeters in 2008 was approximately AUS $ 103,915 or an average cost per lysimeter of about AUS $ 8,660. Details of the cost are shown in Table 3, which did not include the significant cost of scientists and technician working in this project.

Table 3. Material and labour cost of constructing and installing twelve weighing lysimeters at Kingsthorpe (in 2008 AUS$).

Item	Unit cost	Number	Total cost	Cost/lysimeter
Load cells	$ 70.00	36	$ 2,520.00	$ 210.00
Summing box	$ 137.00	12	$ 1,644.00	$ 137.00
Inner and outer boxes	$ 7,098.00	12	$ 85,176.00	$ 7,098.00
Datalogger (CR3000-16 bits)	$ 5,000.00	1	$ 5,000.00	$ 416.67
Multiplexers	$ 1,010.00	2	$ 2,020.00	$ 168.33
Solar panel (30 W)	$ 435.00	1	$ 435.00	$ 36.25
Enclosures for datallogger and multiplexers	$ 200.00	3	$ 600.00	$ 50.00
Datalogger Software (LoggerNet)	$ 745.00	1	$ 745.00	$ 62.08
Deep-cycle marine battery	$ 200.00	1	$ 200.00	$ 16.67
Battery charging regulator/controller	$ 75.00	1	$ 75.00	$ 6.25
Electrical Wire (Multi-Conductor)	$ 500.00	1	$ 500.00	$ 41.67
Installation cost	$ 5,000.00	1	$ 5,000.00	$ 416.67
Total			**$ 103,915.00**	**$ 8,659.58**

Conclusions

This paper describes a lysimeter research facility consisting of twelve large (1m x 1m x 1.5 m) repacked weighing lysimeters that was installed in 2008 near Kingsthorpe, Australia. This paper covers aspects related to the design, construction, installation, cost, and performance of the lysimeter research facility. In the literature, normal steel is the most common material for constructing lysimeters. However, in our case, building the lysimeters out of stainless steel presented several advantages, including a lower cost. The focus was on making the lysimeters useful for our purpose at the lowest cost possible. There are improvements that can still be made and will be made in the future when more resources become available.

References

Allen, R.G., and D.K. Fisher. 1990. Low-cost electronic weighing lysimeters. Transactions of the ASAE 33:1823-1833.

R. G. Allen, et al. (ed.) 1991. Proceedings of the 1991 ASCE Specialty Conference on "Lysimeters for Evapotranspiration and Environmental Measurements," Honolulu, HI, USA. July 23-25, 1991.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome.

Anandakumar, K. 1999. Sensible heat flux over a wheat canopy: optical scintillometer measurements and surface renewal analysis estimations. Agricultural and Forest Meteorology 96:145-156.

Castellvi, F., R.L. Snyder, and D.D. Baldocchi. 2008. Surface energy-balance closure over rangeland grass using the eddy covariance method and surface renewal analysis. Agricultural and Forest Meteorology 148:1147-1160.

Doorenbos, J., and W.O. Pruitt. 1977. Crop water requirements. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Goltz, S.M., C.B. Tanner, C.W. Thurtell, and F.E. Jones. 1969. Evaporation measurements by an eddy correlation measurement, p. 45-60, *In* C. B. Tanner and G. W. Thurtell, eds. Anemoclinometer measurements of Reynolds stress and heat transport in the atmospheric surface layer. University of Wisconsin, Madison, Wisconsin.

Heilman, J.L., C.L. Brittin, and C.M.U. Neale. 1989. Fetch requirements for Bowen ratio measurements of latent and sensible heat fluxes. Agricultural and Forest Meteorology 44:261-273.

Howell, T.A., R.L. McCormick, and C.J. Phene. 1985. Design and Installation of Large Weighing Lysimeters. Transactions of the American Society of Agricultural Engineers 28:106-112.

Hunsaker, D. 1999. Basal crop coefficients and water use for early maturity cotton. Transactions of the ASAE 42:927-936.

Hunsaker, D.J., P.J. Pinter Jr, and H. Cai. 2002. Alfalfa Basal Crop Coefficients for FAO-56 Procedures in the Desert Regions of the Southwestern US. Transactions of the ASAE 45:1799-1815.

Ko, J., G. Piccinni, T. Marek, and T. Howell. 2009a. Determination of growth-stage-specific crop coefficients (Kc) of cotton and wheat. Agricultural Water Management 96:1691-1697.

Ko, J., G. Piccinni, T.H. Marek, and T.A. Howell. 2009b. Determination of growth-stage-specific crop coefficients (Kc) of cotton and wheat. Agricultural Water Management In Press.

Li, S., S. Kang, F. Li, and L. Zhang. 2008. Evapotranspiration and crop coefficient of spring maize with plastic mulch using eddy covariance in northwest China. Agricultural Water Management 95:1214-1222.

Marek, T.H., A.D. Schneider, T.A. Howell, and L.L. Ebeling. 1988. Design and construction of large weighing monolithic lysimeters. Transactions of the ASAE 31:477-484.

Meyer, W.S. 1999. Standard reference evaporation calculation for inland, south eastern Australia Technical report 35/98. CSIRO Land and Water, Adelaide, Australia.

Meyer, W.S., and L. Mateos. 1990. Soil type effects on soybean crop water use in weighing lysimeters. III. Effect of lysimeter canopy height discontinuity on evaporation. Irrigation Science 11:233-237.

Meyer, W.S., D.J. Smith, and G. Shell. 1999. Estimating reference evaporation and crop evapotranspiration from weather data and crop coefficients: An addendum to AWRAC research project 84/162 quantifying components of water balance under irrigated crops Technical report 34/98. CSIRO Land and Water, Adelaide, Australia.

Meyer, W.S., F.X. Dunin, C.G. Smith, G.S.G. Shell, and N.S. White. 1987. Characterizing water use by irrigated wheat at Griffith, New South Wales. Australian Journal of Soil Research 25:499-515.

Moran, M.S., W.P. Kustas, A. Vidal, D.I. Stannard, J.H. Blanford, and W.D. Nichols. 1994. Use of ground-based remotely sensed data for surface energy balance evaluation of a semiarid rangeland. Water Resources Research 30:1339-1349.

Paw U, K.T., J. Qiu, H. Su, T. Watanabe, and Y. Brunet. 1995. Surface renewal analysis: a new method to obtain scalar fluxes. Agricultural and Forest Meteorology 74:119-137.

Payero, J.O., and S. Irmak. 2008. Construction, installation, and performance of two repacked weighing lysimeters. Irrigation Science 26:191-202.

Piccinni, G., T.H. Marek, M. Jett, A.D. Schneider, D.A. Dusek, and T.A. Howell. 2006. Construction of three weighing lysimeters for the determination of crop coefficients for improving water use efficiency and managing irrigation of row and vegetable crops in the Winter Garden [Online]. Available by Texas A&M Agricultural Research and Extension Center at Uvalde (verified October).

Simmons, L.J., J. Wang, T.W. Sammis, and D.R. Miller. 2007. An evaluation of two inexpensive energy-balance techniques for measuring water use in flood-irrigated pecans (Carya illinoinensis). Agricultural Water Management 88:181-191.

Suyker, A.E., and S.B. Verma. 2009. Evapotranspiration of irrigated and rainfed maize-soybean cropping systems. Agricultural and Forest Meteorology 149:443-452.

Todd, R.W., S.R. Evett, and T.A. Howell. 2000. The Bowen ratio-energy balance method for estimating latent heat flux of irrigated alfalfa evaluated in a semi-arid, advective environment. Agricultural and Forest Meteorology 103:335-348.

Tomlinson, S.A. 1996. Comparison of Bowen-ratio, eddy-correlation, and weighing-lysimeter evapotranspiration for two sparse-canopy site in Eastern Washington. U.S. Geological Survey, Water-Resources Investigations Report 96-4081, Tacoma, Washington.

Wolf, A., N. Saliendra, K. Akshalov, D.A. Johnson, and E. Laca. 2008. Effects of different eddy covariance correction schemes on energy balance closure and comparisons with modified Bowen ratio system. Agricultural and Forest Meteorology 148:942-952.

Wright, J.L. 1982. New evapotranspiration crop coefficients. Journal of the Irrigation and Drainage Division of ASCE 108:57-74.

Appendix X

Measuring the effect of water stress on wheat evapotranspiration

Jyotiprakash Padhi[1,2], Jose O. Payero[4], Rabindra K. Misra[1,2,3]*

[1] CRC for Irrigation Futures, QLD 4350, Australia
[2] Faculty of Engineering and Surveying, University of Southern Queensland, QLD 4350, Australia
[3] Australian Centre for Sustainable Catchments, University of Southern Queensland, QLD 4350, Australia
[4] Agri-Science Queensland, Department of Employment, Economic Development and Innovation, QLD 4350, Australia
* Corresponding and presenting author, jose.payero@deedi.qld.gov.au

Abstract

Limitation in water supply is one of the most important challenges facing agricultural production in Australia. Therefore, deficit or supplemental irrigation, rather than full irrigation, is a common practice. To be able to schedule irrigations based on weather data, it is necessary to accurately estimate crop evapotranspiration (ETc) for both water-stressed and non-stressed crop conditions. The FAO-56 model (Allen et al., 1998), perhaps the most popular approach used in irrigation scheduling, uses a generic relationship to explain the impact of stress on ETc. The objectives of this study were to: (1) test the performance of the FAO-56 model for wheat subjected to different irrigation regimes and (2) evaluate the effect of water stress on crop development and yield. A glasshouse experiment was conducted with wheat in Toowoomba during the winter of 2008. The experiment had four irrigation treatments, irrigated when soil moisture were 40, 50, 70 or 80% of field capacity, with three replications. Experimental unit consisted of one pot in which three wheat plants were grown. An electronic scale system was constructed to measure and record the mass of each pot every 10 minutes, which allowed calculating daily ETc and crop coefficient (Kc) values. Results showed that changed weather conditions for crops grown in a glasshouse, compared with field conditions, could have a significant impact on crop development and maturity. It was also found that water stress significantly reduced crop ETc, Kc, and accelerated crop maturity. The relationship between the relative Kc and soil water depletion fraction was found to vary between irrigation cycles, especially for crops exposed to severe water stress. It was suggested that the different relationships result from decreased biomass and leaf area index caused by water stress, which in turn translate into decreased ETc. An unique relationship like that suggested by FAO-56 seems to only be applicable to crops subjected to mild stress or when stress occurs only late in the growing season when the plants are fully grown. Seasonal ETc was found to be linearly related to crop biomass production, grain yield and harvest index. These results are important for modeling crop water use and yield under water stressed conditions.

Keywords: Wheat, evapotranspiration, crop coefficient, biomass, harvest index, lysimeter

Introduction

The focus of irrigated agriculture has traditionally been to irrigate crops to meet crop water requirements during the entire growing season, aiming at maximising crop yield. As water becomes scarce in many areas, fully-irrigating crop to meet their water requirement is not a viable option for many growers. Therefore, they have to allow some level of crop water stress, accepting reduced yield (Payero et al., 2008; Payero et al., 2009). The challenge is to know how much and when to stress crops to minimise the impact on yield and profits. This is a difficult question for growers to answer, especially when the stochastic nature of rainfall is considered. Crop growth and irrigation scheduling models can provide some assistance if relationships between water stress and crop evapotranspiration (ETc) (and its relationship to yield) are known for specific crops.

The FAO-56 model (Allen et al., 1998), perhaps the most popular approach used in irrigation scheduling, uses a generic relationship to explain the impact of stress on ETc. This approach does not reduce ETc when soil water depletion is less than a maximum allowable value at which the crop is presumed to have no stress, and when this depletion value is exceeded, ETc is linearly decreased until the soil water reaches the soil permanent wilting point level. The objectives of this study were to: (1) test the performance of the FAO-56 model for wheat subjected to different irrigation regimes and (2) evaluate the effect of water stress on crop development and yield. This information is critical to be able to develop reliable models to predict the impact of water stress on crop development and yield.

Methods

A glasshouse experiment was conducted with wheat in Toowoomba during the winter of 2008. The experiment had four irrigation treatments (T40, T50, T70 and T80) with three replications arranged in a completely randomised experimental design. Each experimental unit consisted of one pot in which three wheat plants were grown (sowing date = 31 July). The treatments were irrigated when the soil moisture reached 40, 50, 70 or 80% of field capacity. The aim was to subject the crop to a range of water stress levels, from severely stressed to non-stressed conditions. For each irrigation event, irrigation and drainage depths were measured for each pot.

An electronic scale system was constructed to measure and record the mass of each pot (Figure 1). The system consisted of a bench with 12 plates. Each plate was mounted on an electronic load cell. The load cells were connected to a CR1000 datalogger via an AM16/32A relay multiplexer (Campbell Scientific, Inc., Logan, Utah). Each plate was calibrated to convert the load cell electronic output (voltage) to its equivalent water depth (mm of water). Each experimental pot was placed on one of the plates and its mass was recorded every 10 minutes during the entire experimental period, which extended from 6 Sept to 4 Dec 2008 (37 to 126 days after sowing (DAS), a total of 89 days). From this information, the daily ETc of each pot was determined by taking the difference between the equivalent water depths measured at midnight of consecutive days.

Figure 1. Electronic scale system used to measure evapotranspiration from each pot.

Weather data were measured concurrently inside the glasshouse using an electronic weather station. Measurements included maximum and minimum air temperature (Tmax and Tmin), relative humidity (RH) and solar radiation (Rs). From the weather data, daily grass-reference evapotranspiration was calculated using the standardized FAO-56 Penman-Monteith method (Allen et al., 1998; ASCE-EWRI, 2005):

$$\mathrm{ETo} = \frac{0.408\Delta(\mathrm{R_n} - \mathrm{G}) + \gamma\,\dfrac{\mathrm{C_n}}{\mathrm{T}+273}\,\mathrm{U_2}\,(\mathrm{e_s} - \mathrm{e_a})}{\left[\Delta + \gamma\,(1 + \mathrm{C_d U_2})\,\right]} \tag{1}$$

where, ETo = grass-reference evapotranspiration (mm d^{-1}), Δ = slope of the saturation vapor pressure versus air temperature curve (kPa $°C^{-1}$), R_n = net radiation at the crop surface (MJ m^{-2} d^{-1}), G = heat flux at the soil surface (MJ m^{-2} d^{-1}), T = mean daily air temperature at 1.5 to 2.5 m height (°C), U_2 = mean daily wind speed at 2 m height (m s^{-1}), e_s = saturation vapor pressure (kPa), e_a = actual vapor pressure (kPa), e_s - e_a = vapor pressure deficit (kPa), γ = psychrometric constant (kPa $°C^{-1}$), C_n = numerator constant (°C mm s^3 Mg^{-1} d^{-1}), C_d = denominator constant (s m^{-1}), 0.408 = coefficient having units of m^2 mm MJ^{-1}. Daily Rn, e_s, and e_a were calculated using the equations given by Allen et al. (1998) and ASCE-EWRI (2005) using measured RH, Tmax, and Tmin, and constant albedo (α = 0.23). Values for the Stefan-Boltzmann constant ($\sigma = 4.901 \times 10^{-9}$ MJ K^{-4} m^{-2} d^{-1}) (for calculating net outgoing longwave radiation (R_{nl})), specific heat at constant temperature ($c_p = 1.013 \times 10^{-3}$ MJ kg^{-1} $°C^{-1}$), and latent heat of vaporization (λ = 2.45 MJ kg^{-1}) followed FAO-56 and ASCE-EWRI (2005). The psychrometric constant (γ) was computed as a function of atmospheric pressure (P), λ, c_p, and the ratio of molecular weight of water vapor to dry air (ε = 0.622). P was calculated as a function of station elevation (z) and daily G = 0 MJ m^{-2} d^{-1} was assumed. Wind speed can be converted to the standard 2-m height using equation 47 in Allen et al. (1998).

Daily measured crop coefficients (Kc) were obtained as:

$$\mathrm{Kc} = \frac{\mathrm{ETc}}{\mathrm{ETo}} \tag{2}$$

Also, daily relative Kc values for each treatment were calculated by dividing the measured treatment Kc by that of the fully-irrigated treatment (T80). Daily Kc values for wheat were also calculated based on the procedure proposed by FAO-56 (FAO Kc) using values in Table 1.

Table 1. Average crop coefficients (Kc) and lengths of crop development stages (LS) for wheat given in FAO-56 (Allen et al., 1998).

Growth Stage	Definition	LS (Days)#	Kc
Initial	Planting to 10% ground cover	15	0.30
Crop Development	10% ground cover to effective Full cover	30	-
Mid-Season	Effective full cover to start of maturity	65	1.15
Late Season	start of maturity to harvest or full senescence	40	0.40
Total		150	

LS, and Kc, values were taken from tables 11, and 12 in FAO-56 for spring wheat.

Daily water depletion fraction (WDF, unitless) was calculated as:

$$\mathrm{WDF} = \frac{\mathrm{mFC} - \mathrm{mSW}}{\mathrm{mFC} - \mathrm{mPWP}} \qquad (3)$$

where, mFC, mPWP, and mSW are the equivalent water depth of the pot at field capacity, permanent wilting point, and at the current soil water content (all in mm).

To evaluate the effect of water stress on crop development and yield several indicators of crop development and yield were measured. At the end of the season the plants from each pot were harvested and the grain yield (Y), plant above-ground dry biomass (DM), and plant height, were measured. Also, the harvest index (HI, unitless) was calculated as:

$$\mathrm{HI} = \frac{\mathrm{Y}}{\mathrm{DM}} \qquad (4)$$

where Y and DM both had units of g/pot.

Analysis of variance (ANOVA) and mean separation were performed to evaluate the significance of treatment effects on the different variables, and linear regression analysis was used to develop relationships between the different variables and the measured seasonal ETc from each treatment. Statistical analyses and plotting for this study were conducted with R version 2.10.1 (The R Foundation for Statistical Computing).

Results and Discussion

Weather conditions inside the glasshouse

The weather conditions, ETo, cumulative ETo and cumulative growing degree days (CGDD) during the period of measurements inside the glasshouse are shown in Figure 2. Temperatures were considerably warm inside the glasshouse, which did not reflect winter growing conditions. On average, the Tmax = 33.5 ^{o}C, Tmin=19.2 ^{o}C and Tavg = 26.4 ^{o}C. No freezing temperatures occurred inside the glasshouse during the study. The relative humidity was quite stable and averaged 52.5%. Rs averaged 3.5 MJ/m^2/d, peaking at about 5 MJ/m^2/d. At this location, the peak Rs during the same period outside the glasshouse was about 30 MJ/m^2/d. Therefore, the Rs inside the glasshouse was only about 17% compared with field conditions. This decrease in Rs would considerably decrease ETo. ETo inside the glasshouse averaged 5.4 mm/d, assuming a fixed wind speed to 5 m/s. Both the cumulative ETo and CGDD increased linearly with DAS. It is noticeable that in the 89 days of the study, a total of 2,372 °C d GDD were accumulated. It usually takes about 150 days to accumulate this number of GDD for wheat planted under field conditions at this location. Therefore, the growing conditions inside the glasshouse would be expected to promote a much faster development compared with the same crop grown under field conditions.

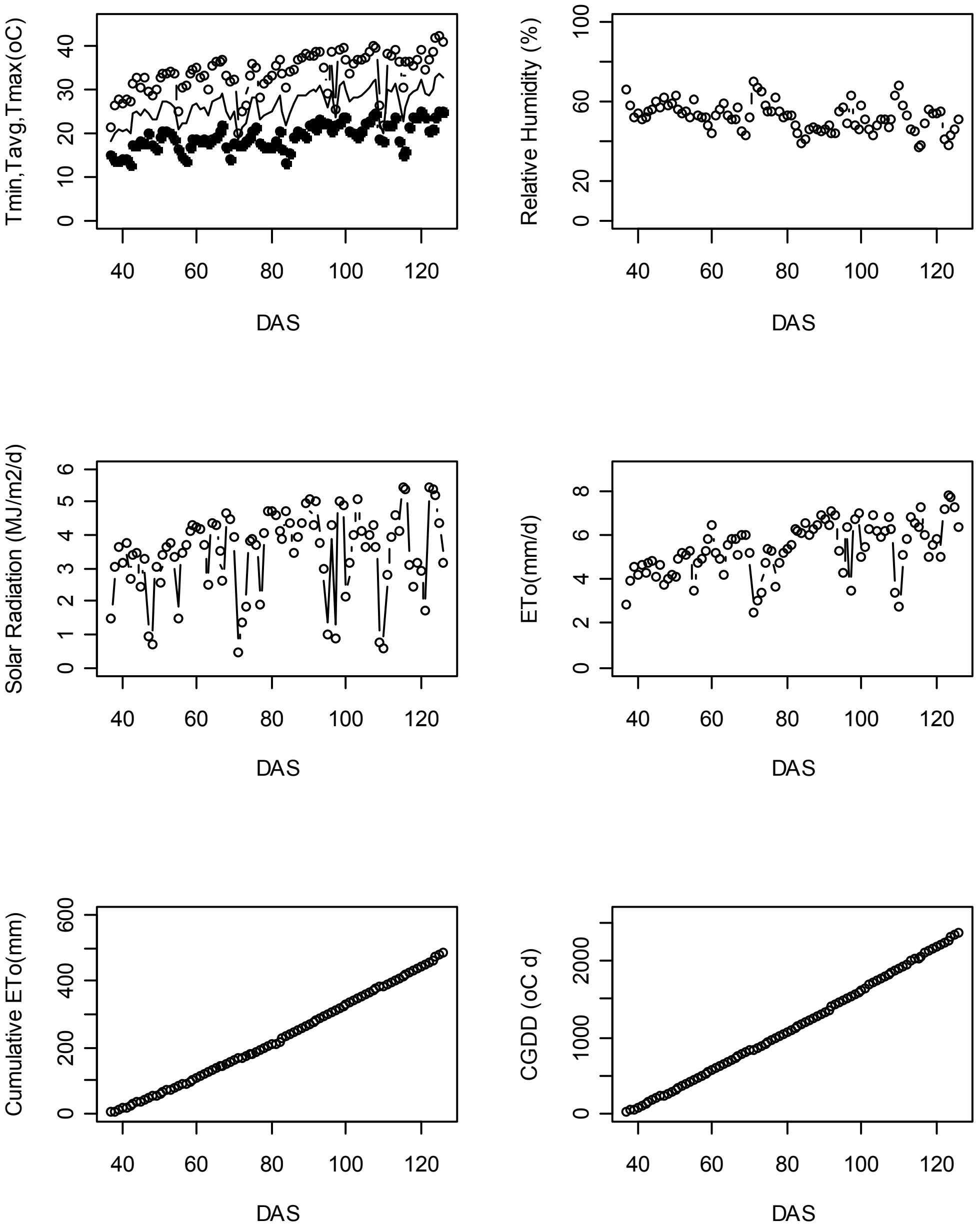


Figure 2. Weather variables, grass-reference evapotranspiration (ETo), cumulative ETo, and cumulative growing degree days (CGDD) as a function of days after sowing (DAS) inside the glasshouse. ETo was calculated assuming a constant wind speed of 5 m/s and GDD = [(Tmax+Tmin)/2-Tb]. Tb = base temperature = 0° C for wheat.

Since wind speed data were not available, daily and cumulative ETo values were calculated using fixed values of 1 to 5 m/s, in 1 m/s increments to test the sensitivity of the ETo calculations to changes in wind speed inside the glasshouse (Figure 3). It was found that wind speed had a big impact on both the daily and cumulative ETo. Figure 3 shows the cumulative ETo during the measurement period would increase by more than 250 mm, an increase of more than 100%, between wind speeds of 1 and 5 m/s. In a previous study (Misra, 2010), it was found that wind speed measurements inside the glasshouse usually resulted in values of less than 0.3 m/s. However, because of the low Rs values, using 0.3 m/s in the calculation of ETo would result in unreasonably low values of daily ETo and unreasonably high Kc values. These results suggest that the Penman-Monteith method (Eq. 1) is not applicable to the glasshouse conditions of this study. In what follows, a fixed wind speed value of 5 m/s was assumed because if produced reasonable daily Kc values. The daily and cumulative ETo values calculated assuming different wind speeds values were found to be well-correlated to each other.

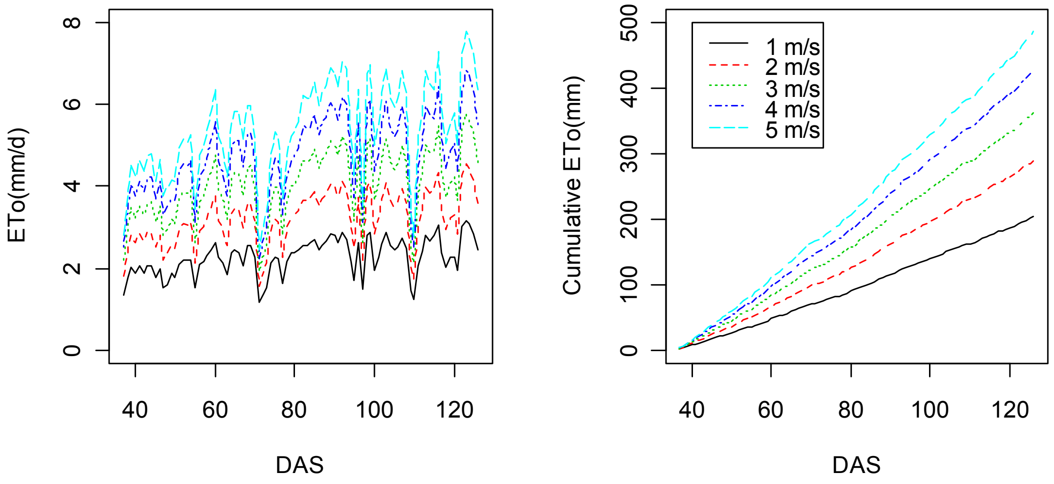
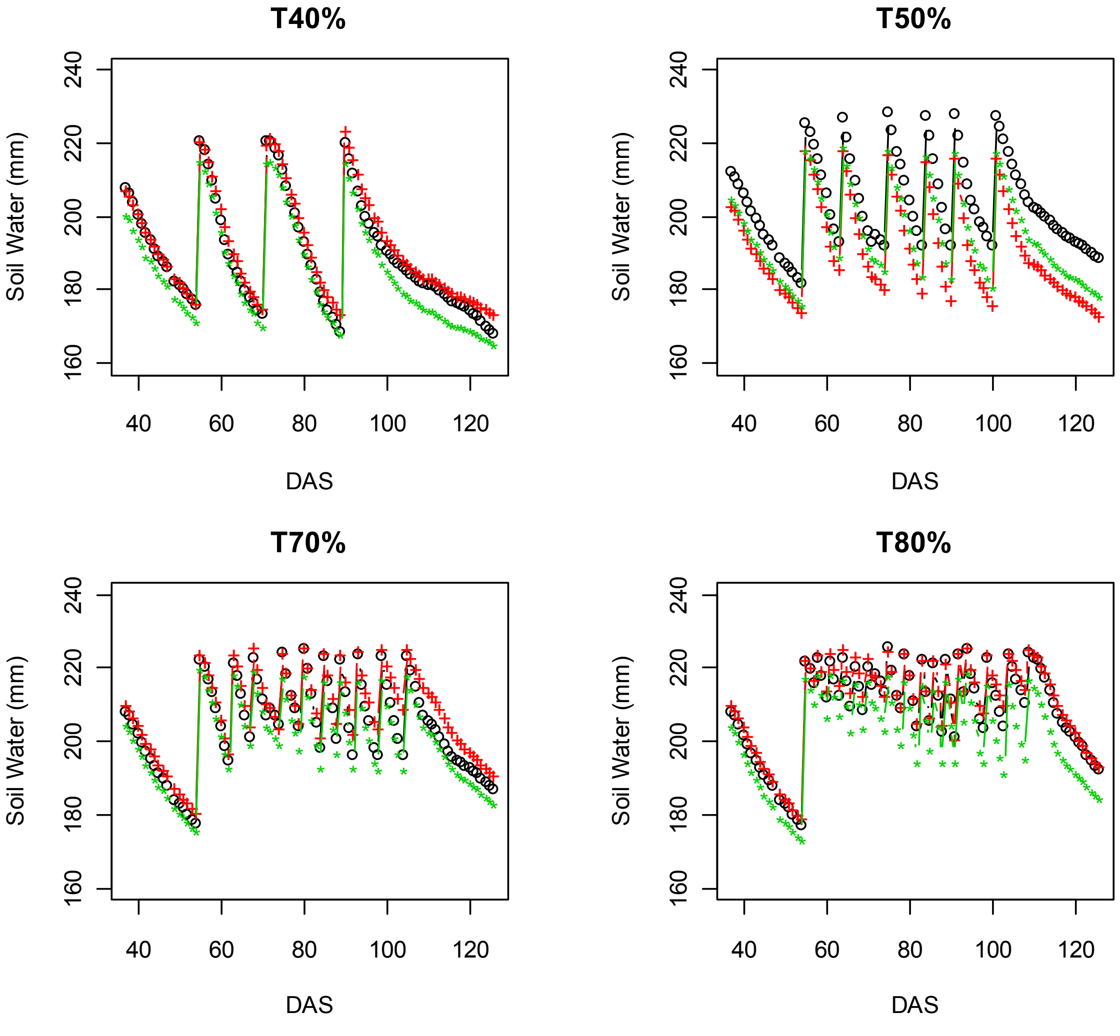


Figure 3. Sensitivity of calculated daily and cumulative grass-reference evapotranspiration (ETo) to changes in wind speed from 1 to 5 m/s during the study period in the glasshouse.

Changes in daily soil water

Midnight values of equivalent soil water depth for each treatment are shown in Figure 4. It shows the timing of irrigation applied to each treatment. Treatments T40, T50, T70 and T80 went through 4, 7, 8 and 9 drying cycles, respectively. Data in Figure 4 for the T40 treatment was used to estimate values for mFC and mPWP (Eq. 3), with mFC taken as the soil water value after irrigation (after drainage had stopped) and mPWP as the value at the end of the drying cycle, when the crop was obviously stressed. Soil water in all treatments was similar during the first drying cycle and differences started after the first irrigation. Seasonal irrigation depths in Table 2 show a range from 211 to 438 mm for T40 and T80, respectively. There was not significant difference in seasonal irrigation depths between T50 and T70. However, T70 received each irrigation event at a higher frequently and with a smaller water depth. Because of this, the T50 was exposed to more water stress between consecutive irrigations.


T40%

T50%

T70%

T80%

Figure 4. Daily changes in soil water as a function of days after sowing (DAS) for each irrigation treatment. The irrigation treatments are T40, T50, T70, and T80. Lines within treatments are replications.

Daily, cumulative and seasonal crop ETc

Treatment averages for daily and cumulative crop ETc, calculated from data in Figure 4, are shown in Figure 5 and 6. They show considerable difference in daily and cumulative ETc values for the T40 and T50 treatments, which were water stressed, with respect to fully-irrigated treatment (T80). There was little difference in daily and cumulative ETc between the T70 and T80 treatments. Considerable reductions in ETc started about 70 DAS for the T40 treatments and about 95 DAS for the T50 treatment with respect to T80. A small difference in cumulative ETc between T70 and T80 only occurred after 110 DAS. While the peak ETc for the T80 treatment was about 11 mm/d, the corresponding value for the more severely stressed treatment (T40) was less than 6 mm/d. Table 2 shows significant difference in seasonal ETc among the T40 and all the other treatments. Water stress reduced the seasonal ETc from 284 mm to 176 mm (38% reduction) for T40 compared to T80.

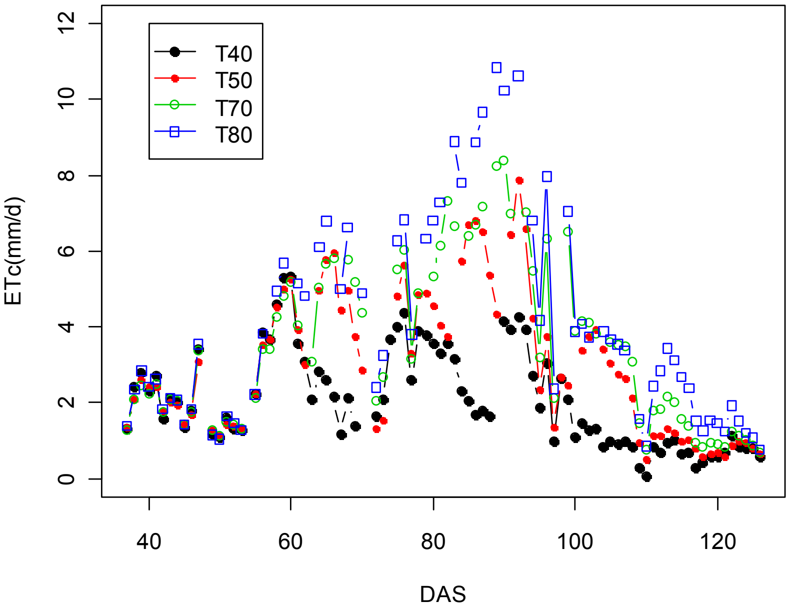


Figure 5. Average daily wheat evapotranspiration measured for each irrigation treatment (T40%-T80%) in a glasshouse as a function of days after sowing (DAS).

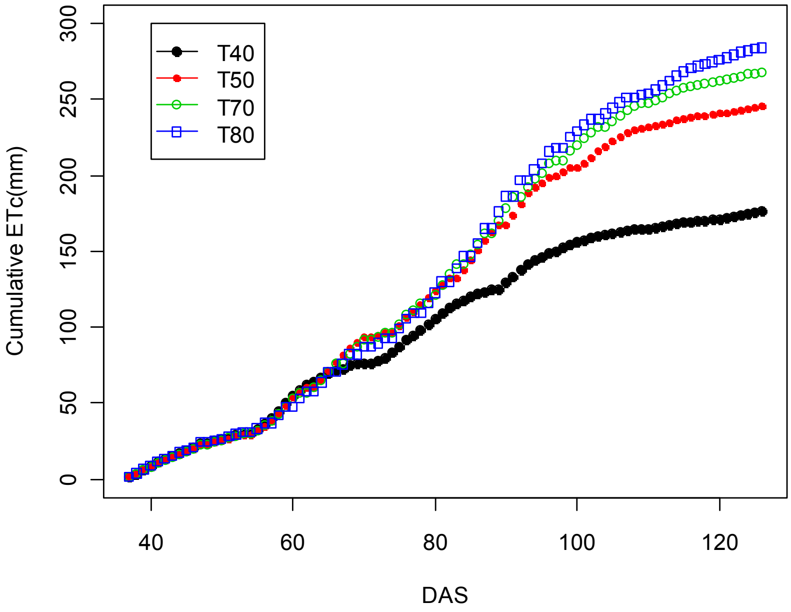


Figure 6. Cumulative wheat evapotranspiration measured for each irrigation treatment (T40%-T80%) in a glasshouse as a function of days after sowing (DAS).

Table 2. Seasonal summary from wheat experiment.

Treat	ETc (mm)	Irrigation (mm)	Drainage (mm)	Dry Biomass (g/plant)	Plant Height (cm)	Grain Yield (g/plant)	HI
T40	176.3b	210.5c	9.9	21.5a	54.1b	6.8 c	0.32b
T50	246.1a	310.9b	17.6	26.4b	59.1a	9.6 b	0.36ab
T70	268.8a	362.7b	15.2	29.7c	60.7a	11.7ab	0.39a
T80	284.8a	437.8a	20.1	33.3d	63.2a	12.4 a	0.37ab
				ANOVA			
P>F	<0.001	<0.001	ns	<0.001	<0.05	<0.001	<0.05

ANOVA= Analysis of variance, ns = not significant, Treatment means with the same letter were not significantly different at the P = 0.05 level., HI = harvest index (grain yield/above-ground dry biomass), ETc= seasonal evapotranspiration

Kc values

Water stress and the fact the crop was grown in a glasshouse, with higher temperatures compared to normal field conditions, had a considerable effect on the way the crop developed and in the Kc curve. Figure 7 shows the measured Kc values (points), the Kc curve proposed in FAO-56 (green line) and the Kc curve fitted to the data for the T80 treatment (red line). Water stress had the effect of reducing the Kc values as indicated by the sharp reduction in Kc between irrigation events for the deficit-irrigated treatments, especially for T40 and T50. Water stress also had the effect of accelerating crop maturity with respect to the fully-irrigated treatment (T80). This is noticeable for both the T40 and T50 treatments, for which their Kc started decreasing sooner during the late-season period compared with the T70 and T80 treatments. The T40 treatment matured about 2 weeks earlier than the T80 treatment.

The higher temperatures inside the glasshouse accelerated crop development and maturity. Figure 7 shows that the measured Kc curve followed more of a triangular shape than the typical trapezoidal shape of the FAO-56 Kc curve. Also, the fully-irrigated treatment matured about 20 days sooner compared with the Kc curve proposed by FAO-56 for crops grown in the field. As indicated above, the T40 and T50 treatments had an even shorter season due to water stress.

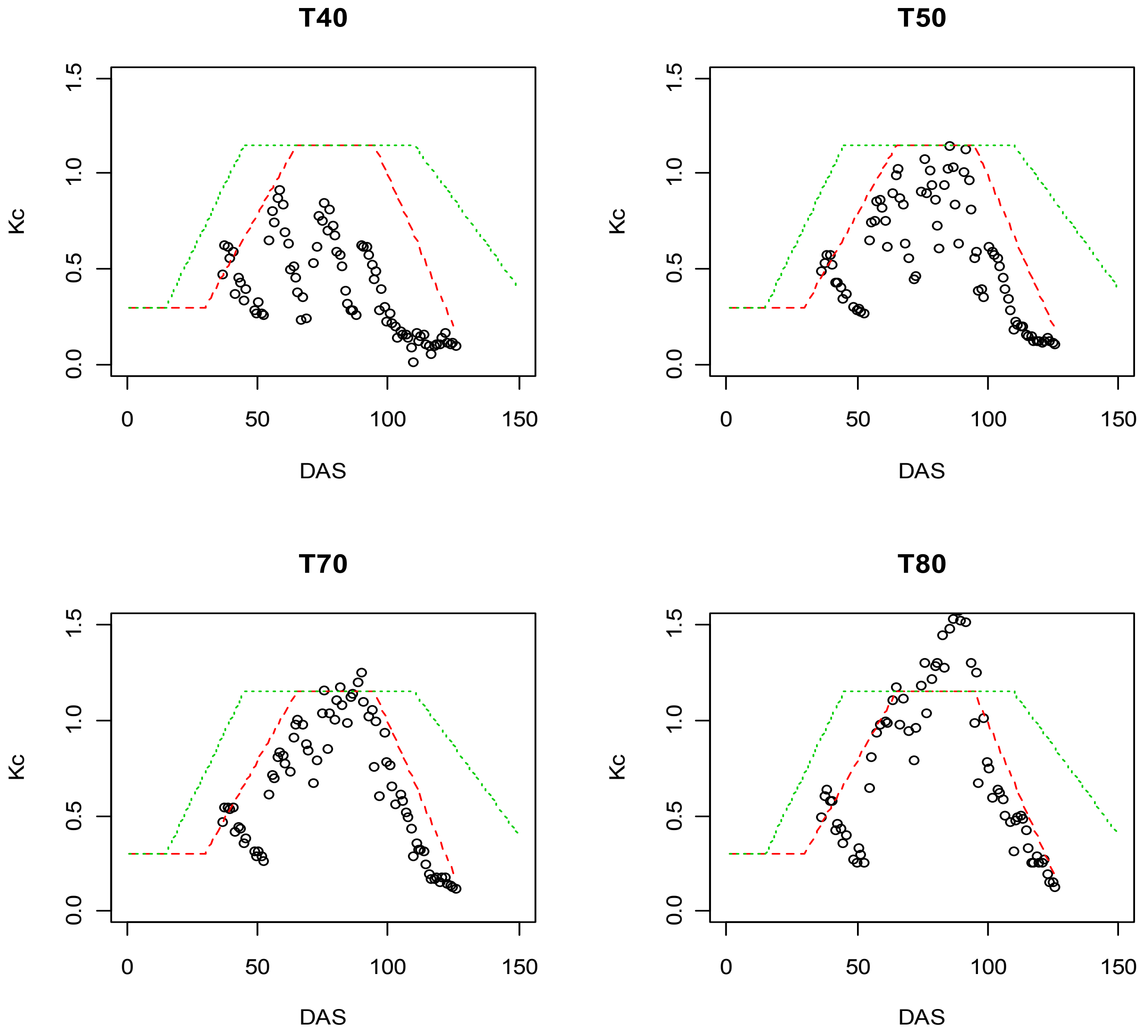


Figure 7. Wheat crop coefficient (Kc=ETc/ETo) curve measured for each irrigation treatment in a glasshouse. The green line is the Kc function suggested by FAO-56 (FAO Kc) and the red line is the Kc fitted to the data (to the T80 treatment). DAS = Days after sowing.

Relative Kc values and WDF

Relative Kc values for the deficit-irrigated treatments as a function of DAS are shown in Figure 8. Relative Kc values for all the three treatments tended to decrease as the season progressed, with sharper decrease for the more stressed treatments. Irrigation increased the relative Kc, although for the more stressed treatments (T40 and T50), irrigation did not bring the relative Kc back to the original value of around 1.0, indicating a different behaviour during each soil drying cycle. The increasing relative Kc values at the end of the season (after about 110 DAS) are indicative of the fact that irrigation was ceased at that time for all treatments, including the T80 treatment.

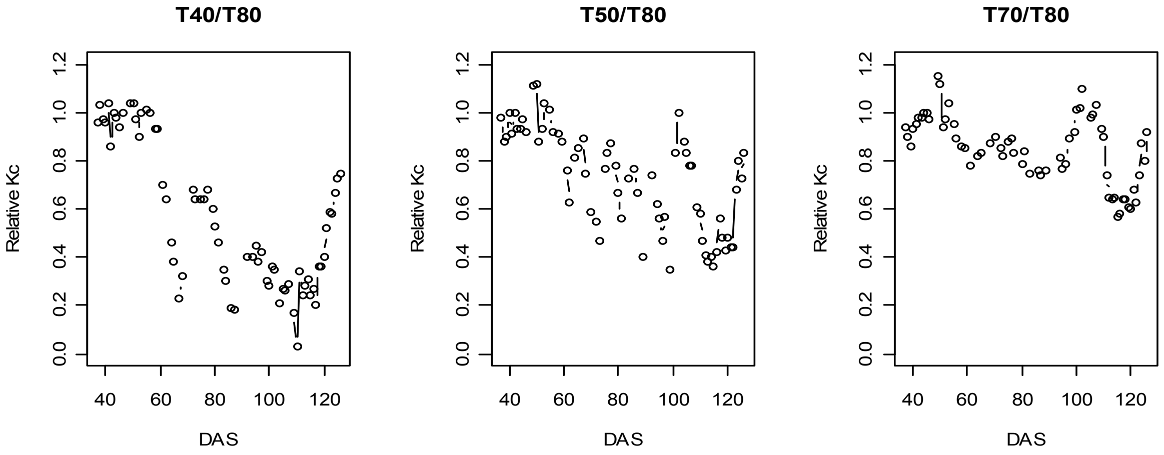


Figure 8. Relative wheat crop coefficient (Kc) of three deficit-irrigated treatments (T40, T50 and T70) with respect to a fully-irrigated treatment (T80) as a function of days after sowing (DAS) measured in a glasshouse.

Figure 9 shows the relative Kc values for the deficit-irrigated treatments plotted as a function of soil water depletion fraction (WDF) (WDF = 0 = Field capacity and WDF = 1.0 = permanent wilting point) separated by soil drying cycles. Figure 9 does not include data for the first and last soil drying cycles when the T80 treatment was probably stressed. Figure 9 shows that the response to water stress was different for the three irrigation treatments and for each soil drying cycle within each treatment.

The most severely-stressed treatment (T40) showed distinctly different responses for each drying cycle. These results indicate that for crops subjected to severe stress conditions, the unique relationship suggested by FAO-56 does not apply. For the T40 treatment, the relative Kc after each irrigation event decreased from an initial value of 1.0 for the first drying cycle to about 0.65 for the second, and about 0.4 for the third drying cycle. These results can be explained by a reduction in leaf area index and a corresponding reduction in ETc as the crop is stressed.

For the T50 treatment, which had less stress than T40, although showing distinct relationships for each drying cycle, the general response roughly followed that proposed in FAO-56, with the relative Kc starting to decrease at a value of WDF ≈ 0.35. However, for this treatment the relative Kc after irrigation tended to decrease with soil drying cycle from an initial value of 1.0 for the first irrigation to about 0.75 for the last. Similar results regarding the relative Kc after irrigation were observed for the T70 treatment.

These results suggest that more mechanistic approaches need to be developed to adjust evapotranspiration under water stress conditions, which not only consider water depletion fraction, but also take into account the impact of decreased biomass or leaf area index resulting from water stress during each drying cycle, especially for severely-stressed crops. The unique relationship proposed in FAO-56, however, could be a reasonable approximation for crops subjected low to moderate stress in situations where stress occurs late in the season after the crop is fully grown.

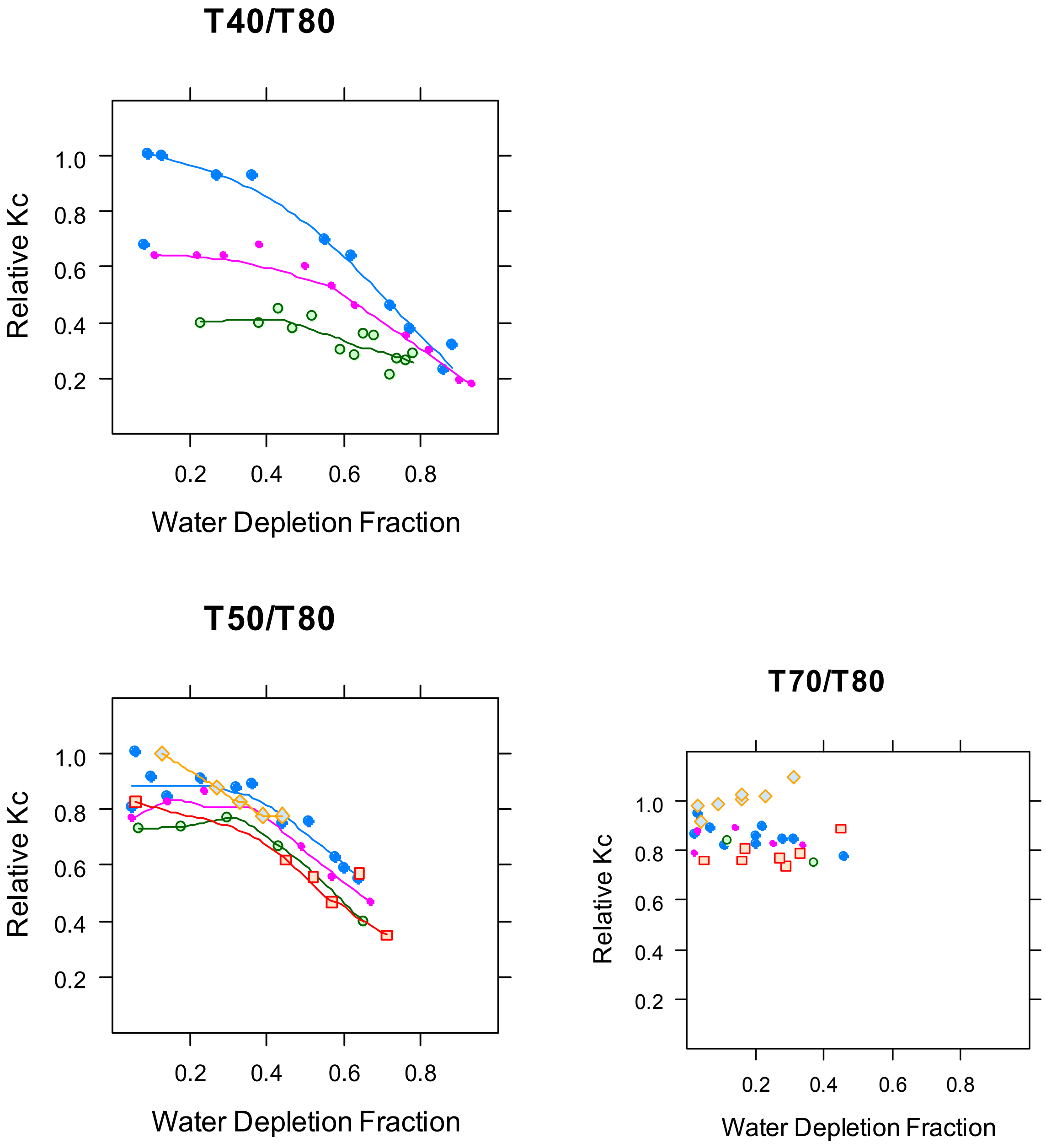


Figure 9. Relative wheat crop coefficient (Kc) of three deficit-irrigated treatments (T40, T50 and T70) with respect to a fully-irrigated treatment (T80) as a function of soil water depletion fraction measured in a glasshouse. (FC = 0 WDF, pwp = 1 WDF). Points and lines of different colors represent different soil drying cycles.

Effect of water stress on yield and crop development

Table 2 shows that irrigation significantly increased crop evapotranspiration, which in turn significantly increased crop dry biomass, plant height, grain yield and harvest index. Figure 10 shows that among treatments, dry biomass and grain yield increased linearly with seasonal

ETc at a rate 0.032 g/plant/mm. Dry biomass was also linearly related to grain yield and plant height. Harvest index was not a fixed value, but tended to increase with seasonal ETc and dry biomass, although it was better related to ETc (r^2=0.53, P <0.01) than to dry biomass (r^2=0.37, P <0.05).

Conclusions

This study showed that changed weather conditions for crops grown in a glasshouse compared with field conditions could have a significant impact on crop development and maturity. It also found that water stress significantly reduced crop evapotranspiration, crop coefficient, and accelerated crop maturity. The relationship between the relative Kc and water depletion fraction was found to vary between irrigation cycles, especially for crops exposed to severe water stress. It was suggested that the different relationships result from decreased biomass and leaf area index caused by water stress, which in turn translate into decreased ETc. An unique relationships like that suggested by FAO-56 seem to only be applicable to crops subjected to mild stress or when stress occurs late in the growing season when the plants are fully grown. Crop evapotranspiration was found to be linearly related to crop biomass production, grain yield and harvest index. These results are important for modeling crop water use and yield under water stressed conditions.

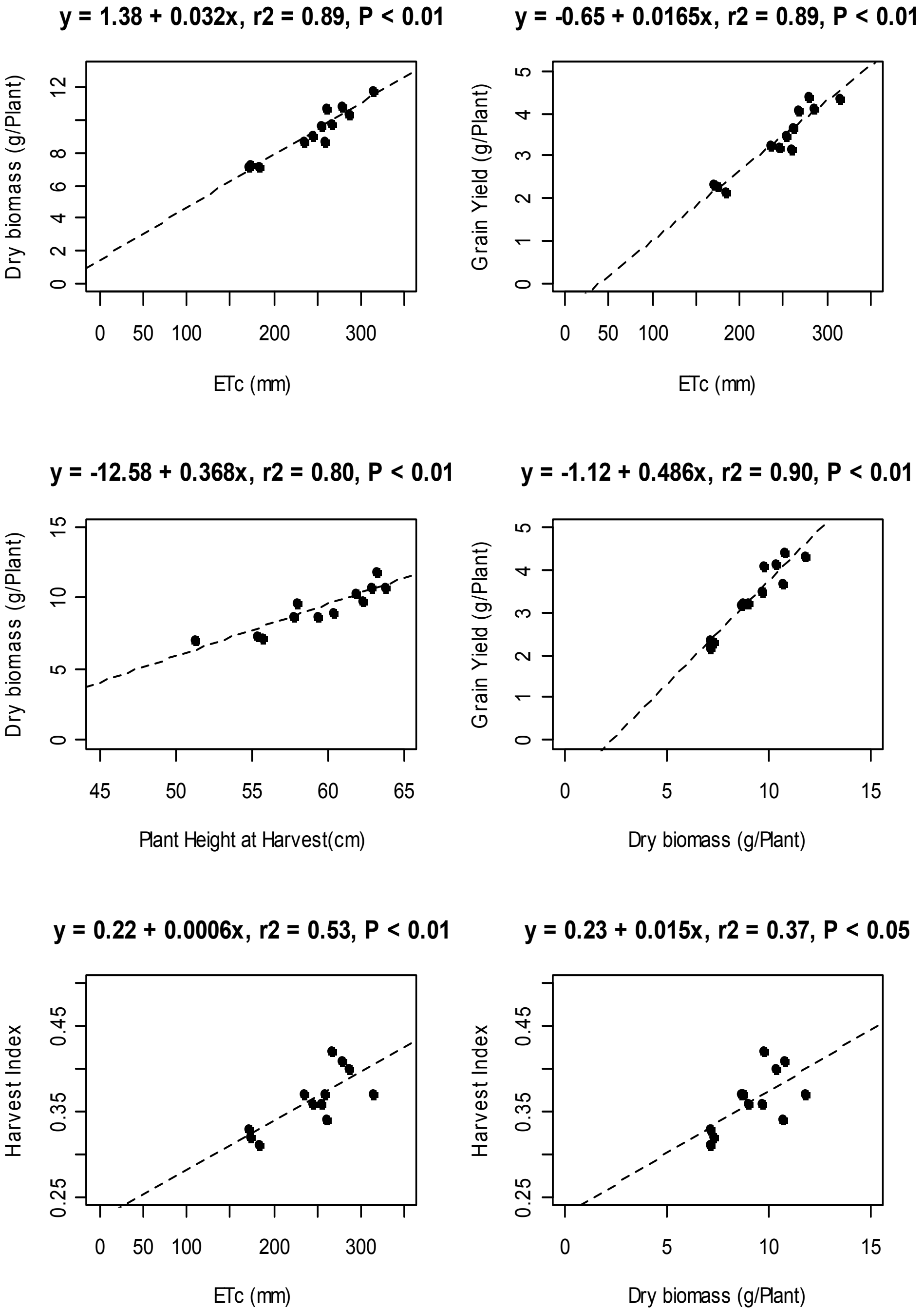


Figure 10. Relationships obtained per wheat plant in the 2008 glasshouse experiment.

References

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome.

ASCE-EWRI (Editor), 2005. The ASCE standardized reference evapotranspiration equation. Standardization of reference evapotranspiration task committee final report. American Society of Civil Engineering (ASCE)'s Environmental and Water Resources Institute (EWRI), Reston, Va.

Payero, J.O., Tarkalson, D.D., Irmak, S., Davison, D. and Petersen, J.L., 2008. Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate. Agricultural Water Management, 95: 895-908.

Payero, J.O., Tarkalson, D.D., Irmak, S., Davison, D. and Petersen, J.L., 2009. Effect of timing of a deficit-irrigation allocation on corn evapotranspiration, yield, water use efficiency and dry mass. Agricultural Water Management, 96(10): 1387-1397.

Appendix XI

Measuring crop evapotranspiration and crop coefficients of Bollgard® II cotton under four irrigation regimes using weighing lysimeters

Jose Payero, Graham Harris and Geoff Robinson

Agri-Science Queensland, Department of Employment, Economic Development and Innovation (DEEDI)

Abstract

Measuring daily crop evapotranspiration (ETc) at the farm level is difficult, and good procedures to estimate ETc are needed, especially for crops grown under dryland and deficit-irrigation conditions. These procedures need to be incorporated into appropriate tools to assist farmers make better irrigation scheduling decisions. The objectives of this paper were to (1) quantify the magnitude of daily ETc of Bollgard®II cotton grown under different water regimes, (2) determine daily values of local crop coefficients (Kc) for Bollgard®II cotton, and (3) evaluate the effect of water stress on Bollgard®II cotton crop coefficients. A cotton field experiment with four irrigation treatments and three replications was conducted at Kingsthorpe in 2008-09. Twelve weighing lysimeters (one per plot) were used to measure ETc. It was found that daily ETc and Kc were very sensitive to rain and irrigation, which affected evaporation, and by crop stress, which affected crop transpiration. A curvilinear, rather than linear, decrease in relative Kc as a function of soil water depletion fraction seems to describe the effect of water stress on crop Kc.

Keywords: Cotton, crop stress, lysimeter, Evapotranspiration, crop coefficient

Introduction

In times of decreased water availability in many parts of the world, there is a pressing need to make efficient use of limited water resources. This is especially important in agricultural production, which uses a large proportion of the extracted water for irrigation. To use irrigation water more efficiently, it is necessary to irrigate crops according to their water demand, which requires a good understanding of crop evapotranspiration (ETc). Measuring crop ETc at the farm level is difficult, and good procedures to estimate ETc are needed to assist farmers make better irrigation scheduling decisions. To calibrate these procedures, direct ETc measurements, such as done with weighing lysimeters, are needed. Crop coefficients (Kc) functions for local crops and varieties are needed to be able to calculate daily crop ETc from weather data. Although international Kc values for cotton are available from FAO-56 (Allen et al., 1998), these values have not been locally validated in Australia, where cotton production has changed from conventional varieties to genetically modified (GM) varieties over the last decade. These GM varieties differ from conventional varieties in their fruiting pattern, having higher boll retention, which would probably impact on daily crop water use. The objectives of this paper were to (1) quantify the magnitude of daily ETc of Bollgard®II cotton grown under different water regimes, and (2) determine daily values of local crop coefficients (Kc) for Bollgard®II cotton, and (3) evaluate the effect of water stress on Bollgard®II cotton crop coefficients.

Methods

Site description

A cotton experiment was conducted during the 2008-09 cotton season at the Agri-Science Queensland, Department of Employment, Economic Development & Innovation (DEEDI) Kingsthorpe research station. The station is located in a sub-tropical climatic zone, about 20 km north-west of the city of Toowoomba, Queensland, Australia (27°30’44.5” Latitude South, 151°46’54.5” Longitude East, 431 m above mean sea level). The soil at the site is a haplic, self-mulching, black, vertisol. It has a heavy clay texture in the 1.5 m root zone profile, with a distinct change in soil color from brownish black (10YR22) in the top 90 cm to dark brown (7.5YR33) deeper in the profile. The soil is of alluvial fan and basalt rock origin, slowly permeable, with a surface slope of about 0.5%.

Experimental design

The experiment was conducted using four irrigation treatments and three replications arranged in a randomized complete block design. Each experimental plot was 13 m wide x 20 m long, with the crop planted in the North-South direction. A 4-m border was allowed between plots and a 4 m road was located at the centre of the research area. A refuge crop (6 rows) was planted at the East and West sides of the plots. The plots were irrigated individually with bore water using a sprinkler system. The irrigation treatments were T50%, T60%, T70% and T85%, which were irrigated when 50%, 60%, 70% or 85% of the plant available water capacity (PAWC), respectively, was depleted.

Measurement of crop evapotranspiration

Crop evapotranspiration (ETc) was measured with weighing lysimeters installed at the centre of each experimental plot. Figure 1 shows one of the lysimeters during installation and planted to cotton. The inner box of the lysimeters had inside dimensions of 1 m x 1 m x 1.5 m, and the outer box had outside dimensions of 1.2 m x 1.2 m x 1.7 m.

(A)

(B)

Figure 1. One of the lysimeters at Kingsthorpe (A) during installation and (B) planted to cotton in 2008-09.

The lysimeter mass was measured with three model LCSB load cells (PT Limited, Baulkham Hills, BC, Australia), each with a capacity of 1000 kg. The load cells were connected to a model PT100SBE-4 junction box (PT Limited, Baulkham Hills, BC, Australia). The junction box summed the output from the three load cells into a single output per lysimeter. Output from the lysimeter load cells were then collected using a CR3000 datalogger and two AM16/32A multiplexers (Campbell Scientific, Logan, Utah) that were hard-wired to the lysimeters.

Power to the datalogger was supplied by a 12 V deep-cycle marine battery, which was charged by a 30-Watt solar panel. A charge regulator/controller was installed between the datalogger, the battery and the solar panel (Projecta P/No: SC005 12 V 5 Amp, Brown & Watson International Pty Ltd, Knoxfield, Victoria, Australia). The charge controller automatically protects the battery from solar power overcharge, maintains the battery in a fully-charged state, and protects the battery from solar power discharge. The datalogger was programmed to sample the lysimeters using a full bridge configuration, which included sending an excitation voltage (5 V) to the load cells and measuring the returned output voltage. The datalogger was programmed to sample each lysimeter every minute and store 30-min averages.

Each lysimeter was calibrated to convert the load cell electronic output (mV/V) to its equivalent water depth (mm of water). Calibration was performed by adding objects of known mass to the top of the lysimeter and recording the load cell output. For this calibration, a set of nine 10-kg iron dumbbells was used. The mass of each dumbbell was previously measured in the laboratory using an electronic scale.

Weather data and reference evapotranspiration

An EnviroStation (ICT International Pty Ltd, Armidale, NSW, Australia) weather station was installed next to the research plots. The station recorded hourly values of solar radiation, air temperature (maximum, minimum, and average), relative humidity, wind speed, and rainfall. From the weather data, daily grass-reference evapotranspiration values were calculated using the standardized FAO-56 Penman-Monteith method as (Allen et al., 1998):

$$\mathrm{ETo} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T+273} U_2\,(e_s - e_a)}{\left[\Delta + \gamma\,(1 + C_d U_2)\right]} \tag{1}$$

where, ETo = grass-reference evapotranspiration (mm d^{-1}), Δ = slope of the saturation vapor pressure versus air temperature curve (kPa $°C^{-1}$), R_n = net radiation at the crop surface (MJ m^{-2} d^{-1}), G = heat flux at the soil surface (MJ m^{-2} d^{-1}), T = mean daily air temperature at 1.5 to 2.5 m height (°C), U_2 = mean daily wind speed at 2 m height (m s^{-1}), es = saturation vapor pressure (kPa), ea = actual vapor pressure (kPa), $e_s - e_a$ = vapor pressure deficit (kPa), γ = psychrometric constant (kPa $°C^{-1}$), C_n = numerator constant (°C mm s^3 Mg^{-1} d^{-1}), C_d = denominator constant (s m^{-1}), 0.408 = coefficient having units of m^2 mm MJ^{-1}. Daily R_n, es, and ea were calculated using the equations given by Allen et al. (1998) and (ASCE-EWRI,

2005) using measured RH, T_{max}, and T_{min}, and constant albedo ($\alpha = 0.23$). Values for the Stefan-Boltzmann constant ($\sigma = 4.901 \times 10\text{-}9$ MJ K^{-4} m^{-2} d^{-1}) (for calculating net outgoing longwave radiation (R_{nl})), specific heat at constant temperature (cp = 1.013×10^{-3} MJ kg^{-1} $°C^{-1}$), and latent heat of vaporization ($\lambda = 2.45$ MJ kg^{-1}) followed FAO-56 and ASCE-EWRI (2005). The psychrometric constant (γ) was computed as a function of atmospheric pressure (P), λ, cp, and the ratio of molecular weight of water vapor to dry air ($\varepsilon = 0.622$). P was calculated as a function of station elevation (z) and an assumed value of daily G=0 MJ m^{-2} d^{-1}. Wind speed was converted to the standard 2-m height using equation 47 in (Allen et al., 1998).

From the daily ETo information, crop evapotranspiration (ETc) can be calculated using either the single or the dual crop coefficient concepts (Allen et al., 1998). Under fully-irrigated situations, ETc can be calculated using the single crop coefficient approach as:

$$\mathrm{ETc} = \mathrm{ETo}\,\mathrm{x}\,\mathrm{Kc} \qquad (2)$$

where, Kc = crop coefficient (unitless), ETo = grass-reference evapotranspiration (mm/d). This approach, however, is not adequate for dealing with day-to-day irrigation scheduling since it does not account for soil evaporation and crop stress. To account for these factors, ETc can be calculated using the dual crop coefficient approach as (Allen et al, 1998):

$$\mathrm{ETc} = (\mathrm{K_s}\,\mathrm{K_{cb}} + \mathrm{K_e})\,\mathrm{ETo} \qquad (3)$$

where, K_s = factor describing the effect of water stress on crop transpiration (unitless), K_{cb} = basal crop coefficient (unitless), which is ETc/ETo when the soil surface is dry but transpiration is occurring at a potential rate such as water stress is not limiting transpiration, and K_e = soil evaporation coefficient (unitless).

Also, daily relative Kc values for each treatment were calculated by dividing the measured treatment Kc (from Eq. 2) by that of a fully-irrigated cotton crop, as suggested in FAO-56 (Allen et al., 1998), fitted to the data from the fully-irrigated treatment (T50%)

Daily soil water depletion fraction (WDF, unitless) was calculated as:

$$\mathrm{WDF} = \frac{\mathrm{mFC} - \mathrm{mSW}}{\mathrm{mFC} - \mathrm{mPWP}} \qquad (4)$$

where, mFC, mPWP, and mSW are the equivalent water depth of the lysimeter at field capacity, permanent wilting point, and at the current soil water content (all in mm).

Crop management practices

Cotton was planted on 15 Nov 2008, within the Bollgard® II cotton planting window for the Darling Downs. Rain immediately following sowing germinated the seeds. The cotton hybrid Sicala 60 BRF, which is a Bollgard® II Roundup Ready Flex® variety, was planted. Six rows of the conventional (non-Bollgard) variety Sicot 43 RRF were planted as the refuge crop on each of the two long sides of the experimental block. Sicala 60 BRF is classified as a medium maturity variety with very good yield potential for late planting, excellent fibre quality characteristics, and a long and strong fibre with mid range micronaire (Cotton Seed Distributors, 2007).

Seeds were planted at a density of approximately 17 seeds/m, a depth of 4 cm and a row spacing of 1 m. The aim was to establish a stand of 11-12 plants/m, which is the recommended density for Bollgard® II varieties, which is higher than the 5-10 plant/m recommended for conventional varieties. The actual population achieved in the plots was approximately 10 plants/m. The lysimeters were hand-planted to a higher population and later thinned to12 plants/m. The seeds were rated at a germination rate of at least 70% and were coated with the “Peridiam” seed treatment that included protection with fungicide and insecticide.

The plots and lysimeters were fertilized with urea (68 kg N/ha) immediately prior to planting (15 Nov 2008). A further application of urea (102 kg N/ha) was applied between 21 and 27 Jan 2009 when the crop was at the 1st bloom growth stage. The total seasonal nitrogen application was 170 kg N/ha.

The crop was sprayed twice with Roundup herbicide to control volunteer wheat seedlings from the previous crop and a range of broadleaf weeds. Applications were on 27 Nov 2008 (glyphosate 360 g/kg, 1L/100L) and on 15 Jan 2009 (glyphosate 690 g/kg, 1.5 kg/ha). Each of these applications achieved excellent control of the targeted weeds. Strategic hand weeding and chipping was used throughout the remainder of the season to maintain the crop in a weed-free condition. Insects remained well below threshold levels so no control measures were necessary.

The experimental plots were irrigated individually with bore water using a hand-shift sprinkler system. Partial-circle sprinkler heads were used to avoid irrigating adjacent plots. Irrigations were applied during times with low wind speeds, to assure good application uniformity. Irrigation depths were measured using three rain gauges per plot. Irrigations were scheduled based on weekly neutron probe soil water content measurements. Table 2 shows the dates and depths of irrigation applied to each treatment.

Table 1. Irrigation applied to each treatment in 2008-2009 (mm).

	Treatment			
Date	**T50%**	**T60%**	**T70%**	**T85%**
21/01/09	31			
22/01/09	23	29		
23/01/09			27	
27/01/09				23
10/02/09	17			
11/02/09	47			
12/02/09		37	6	
16/02/09			25	
1/03/09	58			
31/03/09	38	37		
Total (mm)	**214**	**103**	**58**	**23**

On 19 January 2009 damage from off site drift of a group I herbicide (mild leaf curling) was noticed on the foliage of the entire cotton experiment. By 27 Jan the foliage damage had progressed to severe leaf curling and cupping (Fig. 2). The crop never recovered completely from this herbicide drift damage, which resulted in severe shedding of flowers, bolls and stunting of plant growth.

Figure 2. Pictures taken on 5 February 2009 at Kingsthorpe showing a healthy leaf and leaves affected by severe 2,4-D herbicide damage.

Because of this, crop development measurements were limited to measuring plant height. However, since the crop did not died and was still using water, lysimeter data collection continued until the end of the season to test the performance of the lysimeters and to test the effect of crop water stress on ETc and Kc. Irrigation applications were also continued to maintain differences between treatments.

Also, because of the herbicide damage, yield was not measured and the experiment was terminated early (5 May 2009). The soil moisture monitoring equipment and the irrigation system was removed from the site on 30 April 2009. A flail mower with catcher was used to remove the crop and residue from the field. The soil was then deep ripped to 30 cm on 12 May 2009 to kill the cotton root system and comply with pupae busting requirements.

Results and discussion

Lysimeter calibration

To make sure that the lysimeters were working correctly, several calibrations were performed after lysimeter installation. The results were always found to be satisfactory, since the correlation coefficient between added mass and load cell response was always very close to 1.0. For example, results of calibration performed on 22 April 2009 is shown in Figure 2. Each lysimeter was calibrated individually, and although they were constructed with the same type of load cells, each load cell had a slightly different response, which reflected on differences in responses among lysimeters.

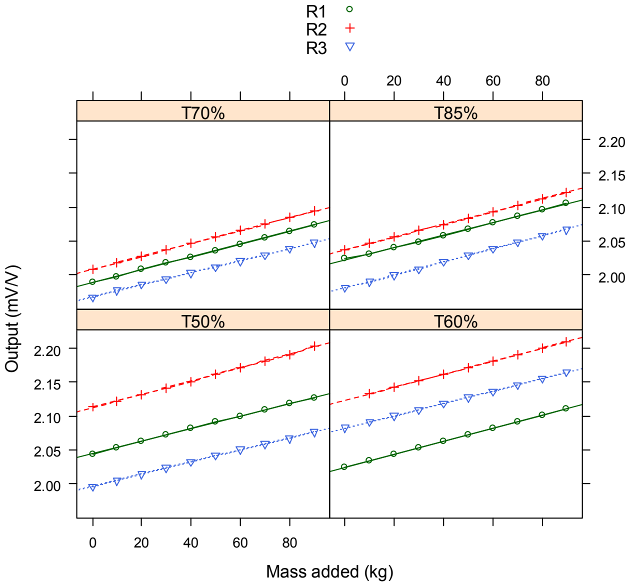


Figure 3. Calibration of twelve lysimeters at Kingsthorpe (22 April 2009). T50% to T85% is the irrigation treatment and R1 to R3 is the replication.

Weather conditions and ETo

Weather conditions prevailing during the 2008-09 cotton season at Kingsthorpe, and the calculated ETo values are shown in Figure 4. Monthly summaries are given in Table 3. The season started very wet, with 171 mm of rain occurring in the second half of November, right after sowing, followed by 88 mm in December. Except for November, monthly rainfall was much less than ETo. Therefore there was a need for irrigation to supply the deficit in crop water requirements. For the season, rain supplied about 58% of ETo, which averaged 4.84 mm/d and 135 mm/month. Since the season started with a full profile and there was plenty of rain early in the season, irrigation was not required until mid January.

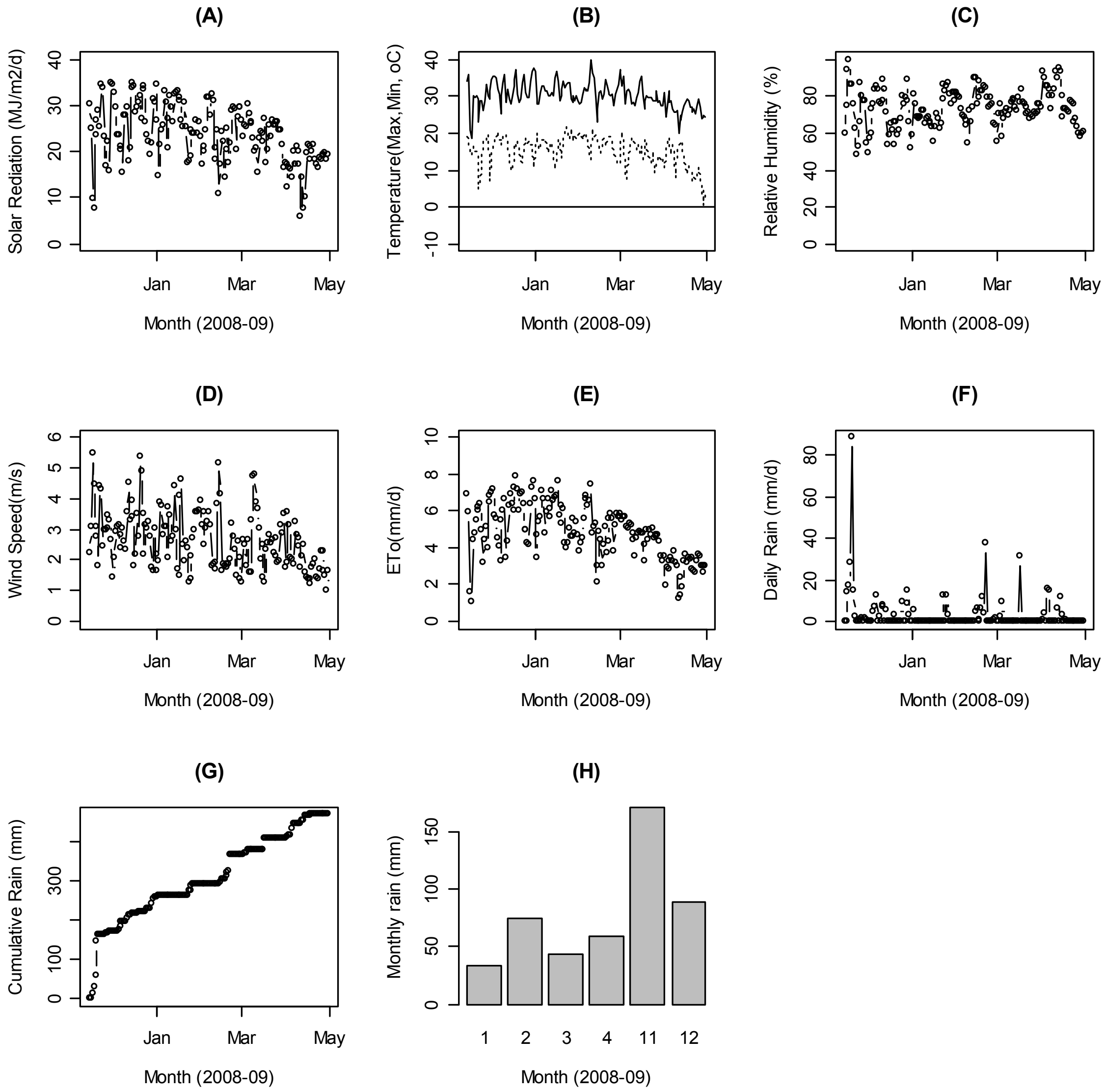


Figure 4. Weather variables measured at Kingsthorpe during the 2008-09 cotton season.

Table 2. Summary weather conditions during the 2008-09 cotton season at Kingsthorpe.

Variable [a]	**Month**						**Avg**	**Total**
	Nov	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**		
Tmax (°C)	28.53	32.23	31.4	31.18	30.38	26.58	30.05	-
Tmin (°C)	14.51	15.79	17.33	17.35	14.63	11.48	15.18	-
Rs (MJ/m2/d)	23.81	27.56	26.14	23.95	23.74	17.27	23.75	-
RH (%)	74.13	70.26	72.15	75.88	72.47	76.94	73.64	-
u (m/s)	3.28	2.94	2.88	2.55	2.58	2	2.71	-
Daily ETo (mm)	4.84	5.92	5.62	4.98	4.73	2.97	4.84	-
Monthly ETo (mm)	77.38	183.67	174.1	139.53	146.63	88.99	135.05	945.4
Monthly Rain (mm)	171.4	88.4	34.2	75.2	43	59	78.53	549.7

[a]Tmax, Tmin = Maximum and minimum air temperatures, Rs = Solar radiation
RH= Relative humidity, u = Wind speed, ETo = Grass-reference evapotranspiration

[b] For Nov, only data within the cotton growing season was included.

Crop development

Crop canopy height in figure 5 shows that there was significant difference in crop development among irrigation treatments. There was also considerable variability among replications for some of the treatments, especially T70% and T85%. As expected, canopy height tended to increase with irrigation, which should also reflect on daily crop ETc and Kc values. Figure 5 also shows that despite the herbicide damage, the crop for the T50% treatment still grew to a height of more than 1 m, which was a reasonably tall crop.

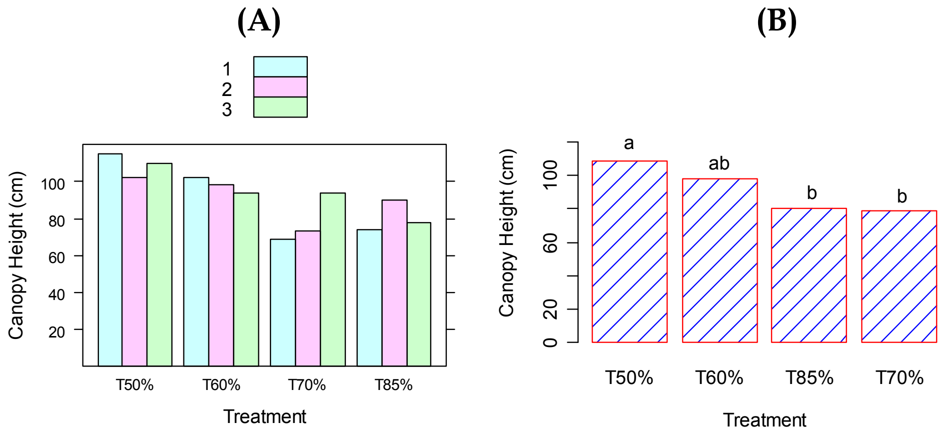


Figure 5. Cotton canopy height at 143 days after sowing by treatment and replication measured at Kingsthorpe during 2008-09. Treatment means with the same letter were not significantly different.

Lysimeter soil water

Daily soil water contents inside the lysimeters by treatment and replication, as indicated by changes in the lysimeter mass, are shown in Fig.6. Differences among replications within the same treatment are indicative of a variety of potential issues, including differences in crop growth inside the lysimeters, non-uniformity of irrigation application (probably caused by wind), and differences in the amount of runoff from rain intercepted by each lysimeter. Some missing data resulted for some lysimeters, especially for the T50% treatment, due to water condensing inside the load cell junction box during irrigation events.

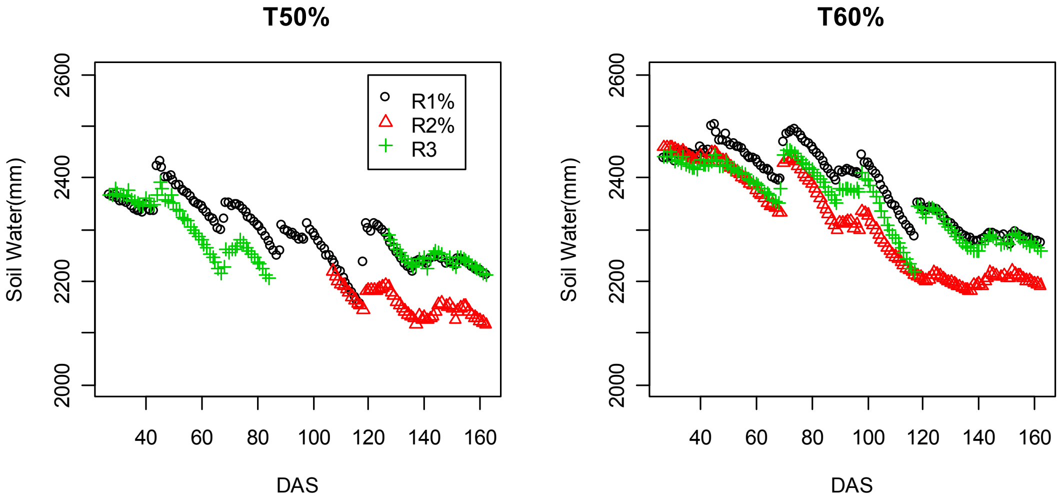


Figure 6. Daily output of twelve lysimeters planted to cotton under four irrigation treatments (T50%-T85%) at Kingsthorpe during 2008-09. R1, R2, and R3 are replications within each treatment. DAS=Days after sowing.

Measured crop evapotranspiration

From data in Fig 6, daily values of measured ETc from each lysimeter were obtained, which are shown in Fig. 7. ETc values were quite high during some days early in the season. This is due to evaporation taking place when the soil surface was wet due to rainfall, even though crop transpiration was still small. For the fully-irrigated treatment (T50%) during the mid season, the ETc was average peak ETc was about 10 mm/d, with some extreme values as high as 13 mm/d. ETc for the stressed treatments (T70% and T85%) was significantly reduced, compared to T50% and T60%, during the second half of the growing season. It is noticeable that ETc for T70%-R3 was higher than for the other two replications, due to a taller crop, as shown in Fig. 5.

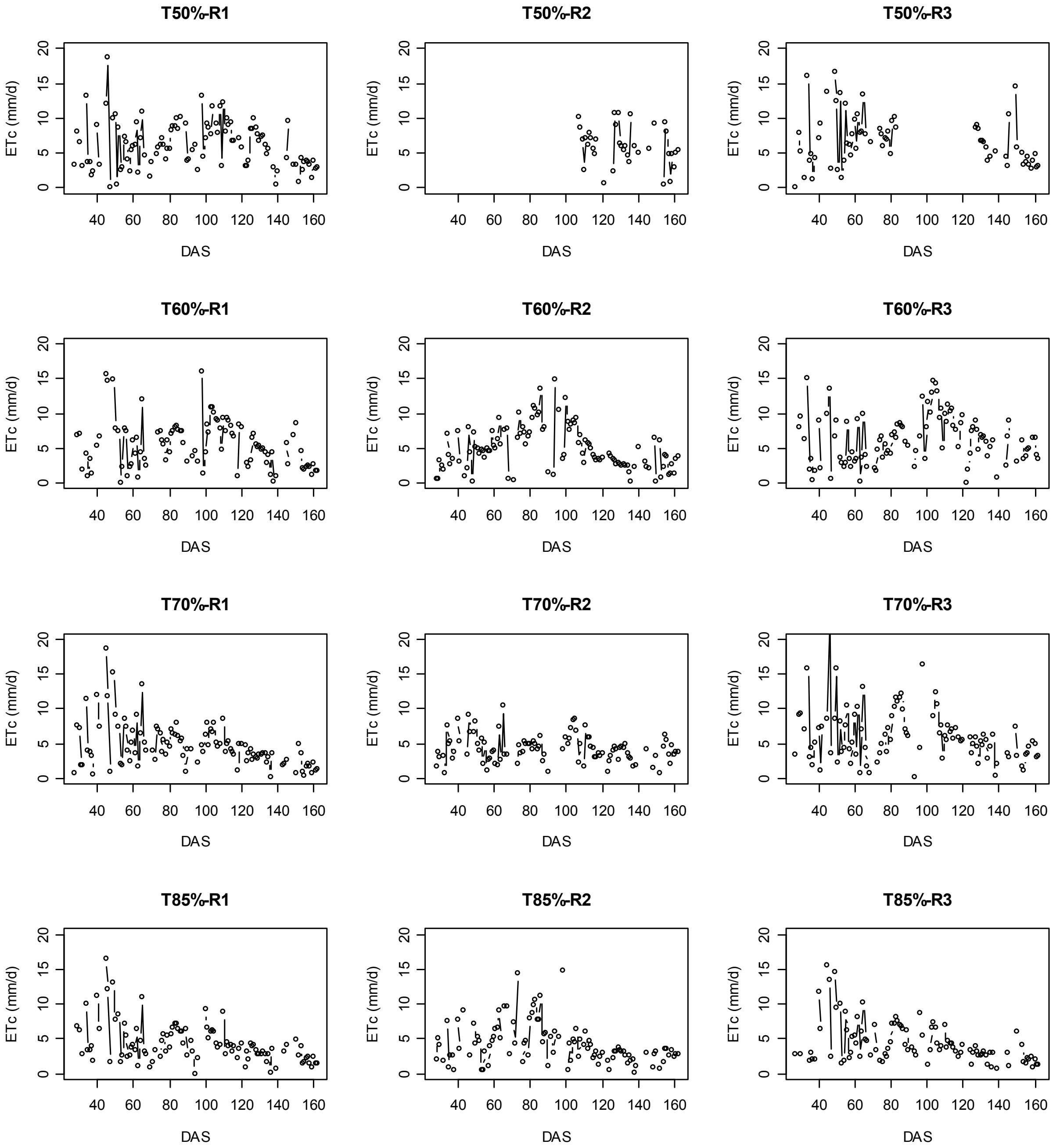


Figure 7. Daily cotton evapotranspiration (ETc) as a function of days after sowing (DAS) for four irrigation treatments (T50%-T85%) and three replications (R1, R2, R3), measured with lysimeters at Kingsthorpe during 2008-09 (rainy days included).

Crop coefficients

Daily crop coefficients were calculated from ETo and the ETc values measured by each lysimeter (Kc = ETc/ETo). Daily basal crop coefficient (K_{cb}) values (as per Eq. 3) were fitted to the data for the fully-irrigated treatment (T50%), as shown in Table 3. These values are different from those in FAO-56, which could be due to differences in varieties and environmental conditions. FAO-56 suggests K_{cb} values for cotton of 0.5, 1.10-1.15, and 0.50-0.40 for the initial, mid, and late season, respectively. Also, the lengths of the different growth stages, which seem to vary by location, are different (see Table 11 and 17 in Allen et al., 1998).

The measured daily Kc and the Kcb for each lysimeter are shown in Fig. 8. Differences in Kc and K_{cb} are due to soil evaporation (K_e in Eq. 3) and by crop stress (K_s in Eq. 3). These results suggest the need to use the dual crop coefficient (Eq. 3) rather than the single Kc values (Eq. 2) to calculate ETc when using this information for irrigation scheduling. The single Kc could result in large errors in ETc for individual days.

Table 3. Basal crop coefficients (K_{cb}) and lengths of crop development stages (LS) for Bollgard®II cotton fitted to data for fully-irrigated cotton obtained at Kinsthorpe during 2008-09.

Growth Stage	Definition	LS (Days)#	K_{cb}
Initial	Planting to 10% ground cover	40	0.20
Crop Development	10% ground cover to effective Full cover	40	
Mid-Season	Effective full cover to start of maturity	70	1.25
Late Season	start of maturity to harvest or full senescence	30	0.30
Total		180	

Effect of water stress on crop coefficients

To evaluate the effect of water stress on crop coefficient, a relative Kc for the deficit-irrigated treatments (T60%, T70%, T85%) were related to the soil water depletion fraction (WDF, Eq. 4) during a drying cycle. The relative Kc was calculated as the measured Kc divided by the K_{cb}. Data in Fig. 9 shows that the relative Kc decreased with WDF. FAO-56 suggests a linear decrease in Ks (similar to relative Kc) for WDF > 0.6. This linear decrease roughly fits the data in Fig 9, but a second degree polynomial provided a better fit.

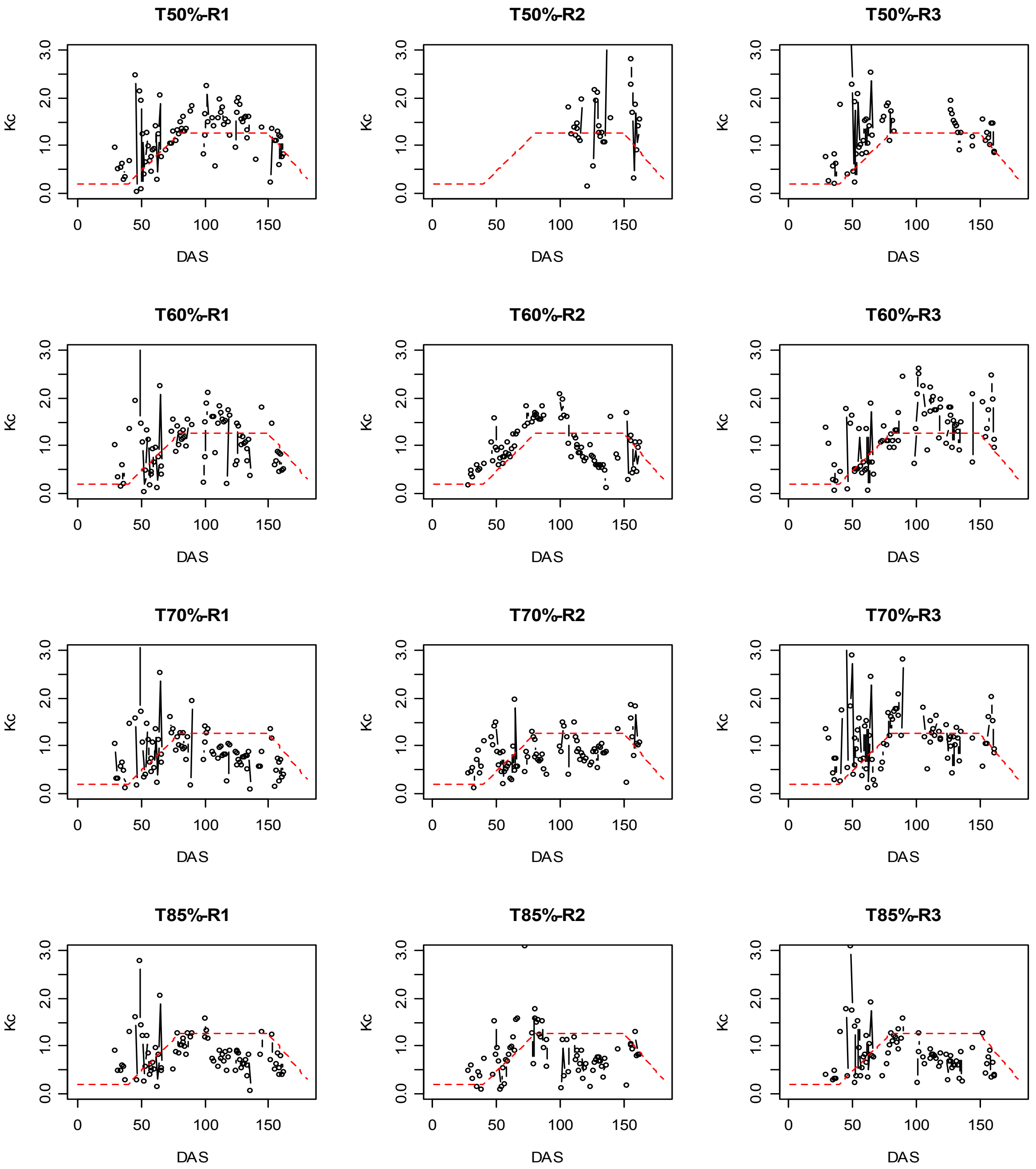


Figure 8. Cotton crop coefficients (Kc) measured from four irrigation treatments (T50%-T85%) and three replications (R1, R2, R3) at Kingsthorpe during 2008-09 (rainy days excluded). The dashed line is the K_{cb} curve fitted to the data. K_{cb} values are 0.20, 1.25 and 0.3 for the initial, mid, and end of season periods. The lengths for the initial, development, mid, end of season periods are 40, 40, 70, and 30 day, respectively.

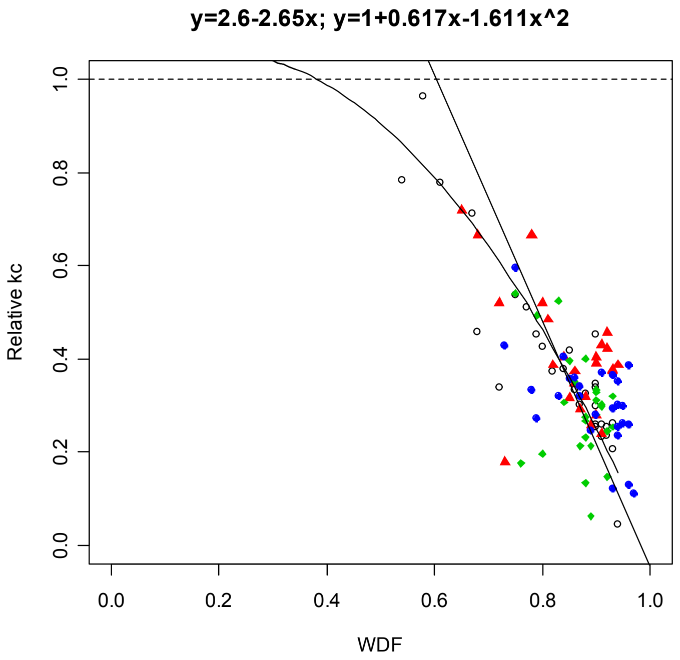


Figure 9. Relative Kc as a function of water depletion fraction (WDF) for cotton. Points of different colour indicate different irrigation treatments.

Conclusions

In this study, daily crop evapotranspiration and crop coefficients for Bollgard®II cotton grown under four irrigation regimes were measured using twelve weighing lysimeters. The lysimeters performed well in measuring crop ETc, except for some issues with water condensing inside the load cell junction boxes of some of the lysimeters, which resulted in invalid data during some periods. This issue, once detected was easily corrected by protecting the junction boxes from water. The measured ETc showed the expected normal daily variability associated with changes in weather conditions, crop growth, soil moisture, and crop stress. The measured daily ETc and Kc values were very sensitive to rain and irrigation, which affected evaporation, and by crop stress, which affected crop transpiration. Basal crop coefficients fitted to the data for the fully-irrigated treatment was different from values suggested in FAO-56 for cotton, both as related to the K_{cb} values for each growth stage and also as related to the length of the growth stages. Differences could be due to both variety (Bollgard®II rather than conventional) and environmental conditions. Our data suggests that a curvilinear, rather than linear, decrease in relative Kc as a function of soil water depletion fraction seems to describe the effect of water stress on relative crop Kc better than the linear function suggested in FAO-56 for WDF>0.6.

References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome.

ASCE-EWRI, (ed.) 2005. The ASCE standardized reference evapotranspiration equation. American Society of Civil Engineering (ASCE)'s Environmental and Water Resources Institute (EWRI), Reston, Va.

Cotton Seed Distributors. 2007. 2007 Variety Guide, pp. 1-18. Cotton Seed Distributors, Toowoomba, Australia.