Final Report

Guidelines for efficient and sustainable trickle irrigation systems

Funding Agency **Land & Water Australia**

Project Reference **CTC10**

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Project Title

Guidelines for efficient and sustainable trickle irrigation systems.

Third Parties

- CRC for Sustainable Sugar Production
- Campbell Scientific Australia

Collaborators

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Project Objectives and Achievements

The long-term success of sustainable irrigated agriculture depends on efficient use of resources and minimal off-site impacts. It is widely recognised that trickle irrigation systems have the *potential* to improve water and nutrient use efficiency, reducing off-site impacts and increasing crop growth. However, recent experience in the sugarcane industry shows that productivity and water use efficiency are not necessarily improved by the adoption of trickle irrigation. To capture these benefits a trickle system must be tailored to soil type and crop water demand (which depends on growth stage and weather). Adequate water and nutrient is needed for the crop, but too much may give leaching and groundwater pollution in light soils. In clay soils, low soil permeability may lead to water logging or insufficient water supply. These problems may arise because both the volume and shape of soil wet during application from a trickle emitter differs greatly, depending on soil type and water content, so the interaction between the trickle systems and the crop and environment is variable. There are currently few *soundly* based guidelines for the design and management of trickle irrigation for any crops in north-eastern Australia. Additionally, much current and previous research on trickle irrigation is empirical, so only applies to the *specific* crop, soil type, management regime and climate during the study period, and can not be readily extended to formulate widely applicable management advice.

Despite these apparent problems, the principals of water and chemical movement through soils and crop growth in relation to soil water and nitrogen availability are well understood. Additionally, there have been advances in computing, software and modelling that make this body of knowledge more applicable to management problems. This project aimed to study agronomically-oriented field experiments on trickle irrigation of sugarcane and apply our current knowledge of the principles of soil water and chemical movement and crop growth to (1) provide widely applicable tools to improve both design and management of trickle irrigation systems and increase water and nutrient use efficiencies and reduce nitrate leaching, and (2) assess the long-term (eg, decades) benefits of trickle irrigation to irrigated agriculture in north-eastern Australia.

Specific Objectives

- Determine the soil properties primarily responsible for controlling the response of trickle irrigated systems to variations in management strategies.
- Develop practical methods for rapid field assessment of these properties to allow optimisation of trickle irrigation design and management.
- Determine the optimum location of soil water sensors relative to the three dimensional wetting patterns from trickle emitters in different soils and for different crop growth stages for designing systems to control water and nutrient application via trickle irrigation.
- Investigate the utility of recent advances in sapflow sensors as indicators of plant stress for designing systems to schedule trickle irrigation.
- Measure nitrogen leaching rates under trickle irrigation systems, and compare these with rates under conventional systems.
- Use field data to define parameter values for water, nitrogen and crop components of a cropping system model (APSIM) across a range of soil types.
- Assess the long-term environmental and production benefits of trickle irrigation for a range of agricultural systems in north-eastern Australia and define the conditions under which trickle systems will be most beneficial in terms of production and water and nutrient use efficiency.

These specific objectives were pursued through four main areas of work:

- Soil wetting and chemical movement – Objectives 1, 2, 3 and 5.
- Determination of sapflow – Objective 4.
- Experimental determination of N response and N losses in sugarcane – Objectives 5 and 6.
- Cropping system modelling – Objectives 6 and 7.

Because of the integrated nature of the activities undertaken in this project, the project's methods and results will be generally considered under these work areas.

Summary of achievements against objectives *(referenced, by numbers in parentheses, to publications from the project)*

- Soil properties primarily responsible for controlling wetting patterns in trickle irrigated systems were identified, and shown to be highly variable within and across soils types and textures *(# 5, 11, 12, 13)*. The software tool WetUp *(# 19, 13, 2)* was developed to capture this information and make it readily available to generalists.
- It is more appropriate to identify wetting patterns in specific fields than to determine soil properties controlling wetting patterns *(# 5, 11, 12, 13)*.
- Pilot studies conducted to identify wetting patterns in specific fields will provide the best information to determine the optimum location of soil water sensors and times of water application relative to the three dimensional wetting patterns from trickle emitters *(# 5)*.

- Current sap flow methodologies were tested and found unsuitable for obtaining reliable indicators of water stress in filed crops which could be used for designing systems to schedule trickle irrigation *(# 20, 21)*.
- At "standard recommended" rates of N fertiliser application, environmental losses of N were similar whether N was applied conventionally or by sub-surface fertigation *(# 6, 9, 14)*. Results also suggested that the high soil water contents maintained with daily application of irrigation water through the trickle system will promote mineralisation of soil organic matter that, if not accounted for through adjustments to fertiliser applied N, could result in considerable quantities of N being lost to the environment *(# 6)*.
- The APSIM cropping system model was modified to represent sub-surface trickle irrigation. Field data was used to define parameter values for water, nitrogen and crop components of the model and agreement with experimental data was good *(# 7)*.
- Long-term simulated yields and partial gross margins in sugarcane production systems were almost always greater when N was applied by sub-surface fertigation than conventionally on the soil surface, although the optimum N application rate was similar in both systems. As N applications were increased above this optimum value, environmental losses were simulated to increase faster in the conventional system than in the sub-surface fertigation system *(# 7)*.

Methods

The methodology adopted in this project involved both modelling and experimentation, including laboratory/glasshouse and field experiments. Objectives 1, 3, 6 and 7 were primarily modelling based; Objective 4 was laboratory based; and Objective 5 was based on results from a major field experiment. Objective 2 was originally envisaged as a field activity. However, results from work conducted for Objective 1 showed that the initial concepts behind Objective 2 were not applicable, and resources were channelled into the development of a wetting pattern visualisation software package.

[Note:In the following sections numbers in parentheses refer to publications arising from the project, which are listed below.]

Soil wetting and solute movement

The analytical modelling framework of Philip (1984) was used to determine the soil properties primarily controlling wetting. While numerical models could have been used for this purpose (eg, HYDRUS 2D) these models would not have provided the same integrated insights into the properties controlling wetting behaviour as given by the analytical models. To identify the soil properties primarily controlling wetting the analytical modelling framework of Philip (1984) was extended to provide solutions for horizontal wetting from buried emitters *(# 5)* and a practical implication of an important assumption in the model, that of uniform water content in the wetted zone, was assessed and found satisfactory for most practical purposes *(# 3)*. The modelling underpinning the display of approximate wetting patterns from drippers *(WetUp; # 19)* was based on the assumption that wetting patterns from drippers are approximately elliptical in shape. This assumption was also tested and found to be suitable for most practical applications *(# 2)*.

In addition to the work on soil wetting, the numerical model HYDRUS 2D was used for studying solute movement through soils (as it included descriptions of important processes not represented in the analytical model). Specifically, the timing of solute applications during an irrigation event was simulated to explore simple methods of minimising chemical losses during and after fertigation *(# 4, 8, 16)*.

Sapflow

The sapflow sensing technologies used in this project employed heat as a tracer of sap velocity in sugarcane stems. Heat-based sapflow sensors fall into two general categories; those in which the heat is applied to the stem and sensed externally, and those in which this is done internally. Both approaches were used in this study *(# 20, 21)*. External sensors are generally quite expensive. However, some advances made in sensor control in the mid-1990's offered the possibility of substantially cheaper sensors. This technology was tested, but was found unreliable *(# 20)*. Internal sensors, commonly known as the heat pulse method, are generally applied to woody plants with relatively large (> 20 mm diameter) stems. However, they offered a possible method for large stemmed field crops (like sugarcane) and so were tested. Heat pulse sensors work best with evenly distributed xylem vessels in the stem/stalk, so an important process in this testing was determining the distribution of xylem vessels in sugarcane stems *(# 20)*.

Sapflow estimates obtained from the heat-based sensors were tested against measurements of evapotranspiration from sugarcane growing in pots. Measurements of evapotranspiration were taken from changes in pot weight or water content through time. The vascular anatomy of sugarcane was determined from observations of stained cross sections of the sugarcane stem.

Experimental determination of N response and N losses in sugarcane
The nitrogen-related aspects of this project were based on a large field experiment (conducted in collaboration with Bundaberg Sugar and CRC Sugar), which aimed to determine the nitrogen response of trickle irrigated sugarcane. The experimental site was 3.5 ha in size and located approximately 9 km north of Bundaberg, Australia (latitude 24^{o}48' S, longitude 152^{o}21' E) in a block that had been in production for > 40 years. The experiment consisted of six N application treatments with three replications in a randomised block design. Irrigation was applied (by an electronic controller) daily, except during, and soon after rain. Immediately prior to the mechanical harvest, stalks were hand-harvested from small areas within each plot for determination of biomass and N concentration of different components (eg, leaves, stem, etc.) of the crop. The mass of cane mechanically harvested from each plot was also calculated from records of bin weights. The total mass of N in the above-ground biomass components of the crop in the whole plot was scaled from the ratio of cane mass in the small hand-harvested areas to the mass harvested from the whole plot. Sugar concentration was determined in the juice samples taken from the harvested cane, and expressed as Commercial Cane Sugar (CCS). CCS is a measure of the commercially extractable sugar and, with cane yield, is the basis of payment in the Australian sugar industry. Soil mineral nitrogen (SMN) and total N were determined on soil sampled from the experiment prior to planting (in August 1996) and immediately following harvest. Soil N mineralisation potential was determined by measuring the amount of NO_3-N and NH_4-N mineralised during 7 day incubations at field moisture content and a constant temperature of 20^{o}C. Total N and total C in the soil were determined by combustion with a Europa ANA mass spectrometer. The volume of soil from each sample and its oven dry weight were also determined, and used to calculate soil bulk density. The mean (across locations and sampling times) bulk density for each plot was used to express SMN results in units of kg ha^{-1} to a given depth. More complete details are given in *project publication 6.*

Cropping systems modelling
There were three main elements to this section of the project. First, the APSIM cropping systems model was modified to allow irrigation water to be applied at depth in the soil to simulate buried trickle irrigated systems. The model explicitly described soil organic matter, N, water (Probert *et al.* 1998) and crop residue (Thorburn et al. 2001) dynamics and sugarcane growth (Keating *et al.* 1999). In the second element, the yield, soil N and soil water results from the field experiment described above *(# 6)* were simulated with the model to determine whether the processes occurring in the fertigated and conventionally fertilised treatments were reproduced by the model. Finally, long-term simulations of both fertigated and conventionally fertilised sugarcane productions were undertaken. Details of the field experiment and the APSIM model, together with descriptions of the model's modifications, configuration and parameterisation, and the experiment and long-term simulations are given in *project publication 7*.

Results

Soil wetting and solute movement (*from project publications 2, 4, 5, 8, 18 and 19)*
For trickle irrigation systems to deliver improved water and nutrient use efficiency, distance between emitters and emitter flow rates must be matched to the soil's wetting characteristics and the amount and timing of water to be supplied to the crop. Broad soil texture ranges (e.g., sand, loam, clay) are usually the only information related to soil wetting used in trickle system designs. In this study, dimensions of wetted soil were calculated from hydraulic properties of 29 soils covering a wide range of textures and soil hydraulic properties to assess the impact of soil texture and/or type on soil wetting patterns. The soils came from two groups that differed in the extent to which hydraulic properties depended on soil texture. Vertical and radial distances to the wetting front from both surface and buried emitters were calculated for conditions commonly associated with daily irrigation applications in a widely spaced row crop (sugarcane) and horticultural crops. In the first group of soils, which had least expression of field structure, the wetted volume became more spherical (i.e., the wetted radius increased relative to the depth of wetting below the emitter) with increasing clay content, as is commonly accepted. However, in the second group of soils in which field structure was preserved, there was no such

relationship between wetted dimensions and texture. For example, five soils with the same texture had as great a variation in wetting pattern, as did all 11 soils in the first group, indicating the considerable impact of field structure on wetting patterns. The implications of the results for system design and management were illustrated by comparing current recommendations for trickle irrigation systems in coastal northeastern Australia with the calculated wetted dimensions. The results suggest that (1) emitter spacings recommended for sugarcane are generally too large to allow complete wetting between emitters, and (2) the depth of wetting may be greater than the active root-zone for both sugarcane and small crops in many soils, resulting in losses of water and chemicals below the root-zone. We conclude that texture is an unreliable predictor of wetting and there is no basis for adopting different dripper spacing soils of different textures in the absence of site-specific information on soil wetting. Such information, which can be obtained by the methods of Battam (2002), is crucial for the design of efficient trickle irrigation systems, yet rarely obtained prior to designing trickle irrigation systems.

Given these results, the question must be asked what needs to be done to convince irrigators and/or trickle irrigation system designers to invest resources into obtaining the required soils information? We felt that development of a user-friendly software tool, or "calculator", that could be used to illustrate the variability in wetting between individual soils would be one way to help people appreciate the need for soil-specific information to be built into the design of trickle irrigation systems. The software tool, **WetUp**, determines the approximate radial and vertical wetting distances from an emitter in homogeneous soils calculated using analytical models, and then uses an elliptical plotting function to approximate the expected wetted perimeter. In comparison with the wetted perimeter predicted explicitly by the model of by Philip (1984), the wetting pattern described by the ellipsoidal approximation in **WetUp** is accurate for slowly permeable soils. However, it tends to underestimate the radial wetting in highly permeable soils, particularly as the volume of applied water increases. The error is small in most cases, and of minimal concern when applying **WetUp** to illustrate the important role soil hydraulic properties play in determining wetting patterns.

As well as inadequate description of soil hydraulic properties during design of trickle irrigation systems, soil solute transport properties and soil profile characteristics are also not adequately incorporated in the design and management of trickle systems. We undertook a simulation study designed to highlight the impacts of soil properties on solute transport from buried trickle emitters. The analysis addressed the influence of soil texture, soil hydraulic properties, soil layering, trickle discharge rate, irrigation frequency, and timing of nutrient application on solute distribution. We found that changing the fertigation strategy for coarse-textured soils to apply nutrients at the beginning of an irrigation cycle can maintain larger amounts of nutrient near to and above the emitter, thereby making them less susceptible to leaching losses. The results demonstrate (1) the need to account for differences in soil properties and solute transport when designing irrigation and fertigation management strategies, and (2) that understanding the system can result in simple, yet effective management strategies to improve the management of trickle irrigation/fertigation systems.

Sapflow (*from project publications 20 and 21)*

A detailed assessment of sapflow measurement techniques was conducted using potted sugarcane plants in glasshouses. Initial efforts were directed at the heat balance (HB) technique. Sapflow recorded by the HB technique was substantially different from two independent measures of water loss from the pots. Although minor changes made to the HB technique improved the accuracy of the system, results were still unacceptable.

The problem with the HB technique prevented sapflow measurements from being made in the field, and led to investigations being conducted into the heat pulse (HP) method of sapflow estimation. Because of the intrusive nature of this technique, it is crucial to understand the vascular anatomy of the species to which it is being applied. The vascular anatomy of monocots (ie, grasses) is generally not well suited to the heat pulse method, as vessels are usually sparsely distributed throughout the stem. However because of its large stem diameter, it was thought the methods might have been applicable to sugarcane.

Unfortunately, in common with other monocots vessels were sparsely distributed throughout the stem in sugarcane and the vessel frequency was low, especially at depths greater than 1 mm from the external stem surface. Preliminary experiments with the heat pulse system conducted subsequent to the anatomical work confirmed that the accuracy of sap flow estimates was very low. Thus, the tested method would not be useful in field water balance studies with sugarcane. We concluded therefore that current sap flow methodologies were not suitable for obtaining reliable indicators of plant water stress that could be used for designing systems to schedule trickle irrigation.

Experimental determination of N response and N losses in sugarcane (*from project publications 6 and 9)*
Fertigation can be a more efficient means of applying crop nutrients, particularly nitrogen (N), so nutrient application rates should be reduced in fertigated crops. However, there is little information on the extent of the possible reduction in N application for fertigated sugarcane, one of the major row crops grown under trickle irrigation, nor the fate of N when N application rates are not reduced. An experiment was established to determine the response of cane and sugar production to different rates (0-240 kg ha^{-1} yr^{-1}) of applied N, which spanned that recommended for conventional irrigation systems (160 kg ha^{-1} yr^{-1}). As well as yield, N removed in the crop and changes in soil mineral N were determined annually for four crops (a plant and three ratoon crops). $\delta^{15}N$ values were also measured in selected treatments at selected times to assess possible N inputs to the experiment via biological N fixation (BNF). Yields of cane and sugar responded to application of N fertiliser in the three ratoon crops, but were not significantly increased by applying more than 80 kg ha^{-1} of N, which is half the conventional rate. There were no N responses in the plant crop as there was > 200 kg ha^{-1} of soil mineral N (SMN) to 2 m depth at the site prior to planting and SMN concentrations were relatively high (~ 20 mg kg^{-1}) in the surface soil. Depletion of the SMN occurred most slowly during the plant crop with higher rates of N application, particularly in soil between the crop rows. However, there was no difference in SMN between treatments or row position (row *v.* inter-row) at harvest of the ratoon crops. There was no evidence of N input from BNF in the experiment. During the four crops, net removal of N from the treatment with no applied N totalled 207 kg ha^{-1}. When 80 or 120 kg ha^{-1} yr^{-1} of N was applied to ratoon crops outputs of N from the harvested crop approximately balanced inputs from fertiliser and depletion of SMN during the experiment. Inputs clearly exceeded output at higher N application rates. Assuming that the net removal of N from the treatment with no applied N was the same as the net mineralisation of N from soil organic matter in all treatments in the experiment, from 204 to 639 kg ha^{-1} of N was unaccounted for in the treatments with applied N over the whole of the experiment. While some of this N (eg, 45 kg ha^{-1}) may have resulted in small (and undetectable) increases in total soil N, much would have been lost to the environment. We suggest that the high soil water contents maintained with daily application of irrigation water through the trickle system promotes mineralisation of soil organic matter and that if not accounted for through adjustments to fertiliser applied N, could result in considerable quantities of N being lost to the environment. Thus, particular care is required to avoid over-application of N in fertigated sugarcane.

Cropping systems modelling (*from project publication 7)*
It is commonly accepted that efficiency of fertiliser use can be higher when fertiliser is applied by fertigation. However, few studies provide a comprehensive comparison of the fate (ie, crop uptake and environmental losses) of applied nutrients in conventional and fertigated systems. The APSIM cropping systems model was used simulate the results of a sugarcane-N fertigation experiment, to verify that the model could represent the dynamics of N in a fertigated system. Then, the efficiencies gained in, and optimum management of fertigated sugarcane grown in Australia were examined with the model in comparison to production of sugarcane with conventional N application.

The model well represented trends in daily soil moisture, above ground biomass and N concentrations of sugarcane crops, and annual profiles of soil mineral N over a wide range of N fertiliser application rates. In additional, the differences in sugarcane production between N applied by sub-surface fertigation and conventional means were also well predicted.

Simulations were then performed for two contrasting soil types (a grey clay and a red loam) and five climatic regions (northern NSW, Bundaberg, Mackay, Burdekin and Ingham) spanning irrigation areas in the Australian sugar industry using historical climate data. In all scenarios simulated, maximum yields in both systems occurred at similar N application rates (generally 150 kg/ha applied to ratoon crops) but the yield was higher where N was applied by fertigation. The difference in yields between the conventional and fertigated systems were highest at N application rates (90 to 120 kg/ha applied to ratoon crops) lower than those giving maximum yields. In fact improvements in yield given by fertigation were lost at lower and higher N application rates. As expected, environmental losses of N became increasingly significant as N application rates increased above those providing maximum yields in all scenarios. Losses were always higher from the convention system than the fertigated system at all rates of applied N, but this difference also became more pronounced as N application rates increased above those providing maximum yields.

A partial financial analysis was undertaken on the yield results from the long-term simulations, where the costs of N fertiliser and harvesting were balanced against returns from the sale of sugarcane (at 2001 prices) to determine an approximate gross margin. Generally, maximum gross margins in both systems occurred at similar N application rates (generally 90 to 120 kg/ha applied to ratoon crops), but the gross margin was higher (approximately 10 %) where N was applied by fertigation.

The study clearly showed that sub-surface application of N by fertigation has consistent production and environmental benefits in sugarcane production systems at almost all rates of applied N fertiliser. However, the production benefits are reduced by over (and under) applications of N.

Summary of key 'take home messages' arising from the project

- "Static" guidelines are inappropriate for assessing wetting from trickle emitters, and texture is not a good predictor of wetting. Efficient designs will only be achieved by incorporating information on wetting in the specific field under consideration gained from a pilot study of water movement of wetting from trickle emitters.
- The wetting pattern visualisation software package, WetUp, can help designers, growers and students appreciate the above concepts and accept the need for pilot studies. WetUp is not a design tools and will not replace pilot studies.
- Information gained from pilot studies will indicate the best location of soil moistures sensors.
- Sub-surface application of N by fertigation has consistent production and environmental benefits in sugarcane production systems at almost all rates of applied N fertiliser. However, the production benefits are reduced by over (and under) applications of N. Thus, effort must be directed to establishing this optimum in fertigated cropping systems.
- Cropping systems models provide a valuable tool in establishing the optimum for sugarcane systems. It is likely that these models would prove similarly useful in other crops.
- Fertigation chemicals (eg, nutrients) will be will be most effectively retained in the rootzone (and their leaching losses minimised) if they are applied at the beginning of the application cycle, not at the end (after most of water has been applied).

References (not listed in publications section)

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Adoption

Several pathways were used to ensure dissemination of information during the project's life. These included:

- Formation and regular meetings with a project steering committee. Committee members included trickle irrigation farmers, extension officers from the sugar and horticultural industries and representatives from trickle sales/design industry.
- Presentation of project results at irrigation and sugar industry conferences and meetings (eg, Queensland Irrigation Technical workshop) in Australia *(eg, project publications 9, 10, 11, 16, 17, 18)*.
- Linking with the Technology Transfer program of the CRC-Sugar.
- Undertaking field experimental activities collaboratively with trickle irrigators.
- Directly involving trickle irrigation extension staff in project developments (eg, a prototype of the WetUp program was tested by irrigation extension staff).

Communication of the project's results will continue after its completion. For example:

- The project results will form the basis of the information on trickle irrigation to be presented at the forthcoming CRC Sugar Short Courses on *Best Practice Irrigation Management*. The courses are aimed to "train the trainer", and are planned to be run at least twice, with the first in Townsville in July 2002.

- WetUp is being made publicly available, via download from a web page (still under construction).

To date, the project has had the following impacts on the irrigation industry:
- Irrigation extension staff in many parts of Australia (and scientists in other countries) now recognise that conventional methods for designing trickle irrigation systems will often lead to poor system performance (yields, water use efficiency, etc) and that site-specific information is required.
- The WetUp software tool has been requested by extension officers and researchers in Queensland, other Australian states and other countries, and identified (in Australia and overseas) by academics as an important teaching aid.
- Irrigation extension staff in the sugar industry acknowledge that N applications rates in trickle irrigated-fertigated sugarcane should be reduced by 25-30 % relative to applications rates in conventional systems.

Commercial Potential

There are no easily recognisable commercialisation opportunities arising from this project, and benefits will be more quickly implemented and have greater impact by making results and products of the project available as widely and easily as possible.

Publications Arising From the Project

* Indicates the publication is given as an Appendix to this report.

Journal volume

1. Thorburn P.J., Bristow K.L. and Annandale J. (Editors) (2002). Micro-irrigation: Advances in system design and management. *Irrigation Science* Special Issue, in press.

Journal papers

2. *Cook F.J., Thorburn P.J., Fitch P. and Bristow K.L. (2002). WetUp – A software tool to display approximate wetting patterns from drippers. In: Thorburn, P.J., Bristow, K.L. and Annandale, J. (Ed.s) Micro-irrigation: Advances in system design and management. *Irrigation Science*, in press.
3. Cook F.J., Thorburn P.J. Bristow K.L. and Cote C. (2002). Infiltration from surface and buried point sources: The average wetting water content. *Water Resources Research*, submitted.
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Referred conference papers

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9. Dart I.K, Baillie C.P. and Thorburn P.J. (2000). Assessing nitrogen application rates for subsurface trickle irrigated cane at Bundaberg. *Proceedings Australian Society Sugar Cane Technologists*, 22: 230-235.
10. *Thorburn P.J., Sweeney C.A., and Bristow K.L. (1998). Production and environmental benefits of trickle irrigation for sugarcane: A review. *Proceedings Australian Society Sugar Cane Technologists* 20: 169-175.
11. Thorburn P.J., Cook F.J., and Bristow K.L. (2000). Assessing soil wetting patterns for improved design of trickle irrigation. *Proceedings Australian Society Sugar Cane Technologists*, 22: 236-243.
12. Thorburn P.J., Cook F.J., and Bristow K.L. (2000). Variations in wetting patterns from trickle emitters in soils of different texture. In: Proceedings of the 6th International Micro-irrigation Congress, 23-26

October, 2000, Cape Town. South African National Association of Irrigation and Drainage, Cape Town, pp 4.4.1-4.4.10.

13. Thorburn P.J., Cook F.J., and Bristow K.L. (2002). New water-saving production technologies: Advances in trickle irrigation. In: Yajima M. et al., Water for Sustainable Agricultural in Developing Regions. Proc. 8th JIRCAS International Symposium, Tsukuba, Japan Nov 2001. JIRCAS, Tsukuba (in press). ***Invited paper.***
14. Thorburn P.J., Dart I.K, and Baillie C.P. (2000). Nitrogen balances in trickle irrigated sugarcane. In: Proceedings of the 6th International Micro-irrigation Congress, 23-26 October, 2000, Cape Town. South African National Association of Irrigation and Drainage, Cape Town, pp 1.3.1-1.3.9.

Other conference papers

15. Bristow K.L, Thorburn P.J, Cook F.J. and Kluitenberg, G.J. (1999). Water and nutrient management in drip irrigation systems. Proceedings of the ASA-SSSA National Conference, 31 October – 4 November 1999, Salt Lake City, Utah, USA. *Agronony Abstracts*, 91: 15.
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