FILLING THE RESEARCH GAP PROGRAM

RESEARCH PROJECT - FINAL PROGRESS REPORT 6

PERIOD October 2015 to June 2016

PROJECT INFORMATION	
Project title:	Indirect emissions of nitrous oxide from broad-acre irrigated agriculture
Term:	3 Years

CONTACT INFORMATION	
Grantee:	Cotton Research & Development Corporation
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	Jane Trindall	R&D Manager	
Signature of authorised representative	**Name**	**Position**	**Date**

SECTION A – BUDGET STATEMENT

Note: Within 60 days of the end of the Term, the Grantee must, at the Grantee's own cost, provide the Commonwealth with a Final Financial Report, including independently audited financial statements. The report needs to be signed and certified as being true and correct by the Grantee's Chief Financial Officer or Deputy Chief Financial Officer. It is not sufficient for the said officers to just sight the report.

The Final Financial Report needs to contain:

a) financial statements for the receipt, holding, expenditure and commitment of the Funding for the entire Program, including a full reconciliation against the Budget and a statement of the balance of the Bank account (these statements must clearly show expenditure against Commonwealth funding);

b) a report of the receipt of Other Contributions (including the Grantee's own contributions) for the entire Program, or, if such Other Contributions were not received as programmed, an explanation of action taken by the Grantee in response to this shortfall; and

c) the interest that the Grantee has earned on the Funds.

a) Summary of the Funding (GST exclusive)

Please provide information about the Funding and expenditure to date.

Definition:	*Funding refers only to funds provided by the Commonwealth through the Filling the Research Gap program as detailed in the Information Table of the Schedule.*

Total Funding approved for the term of the project	A	
Funding received to date	B	
Funding to be received for this reporting period	C	
Funding yet to be received	D	A - B
Funding expended to date	E	
Balance of funding	F +/-	B - E
Outstanding expenditure, including liabilities	G	
Projected funding balance at completion of project	H +/-	D+F - G

Summary of Projected Funding Balance (G)
If there is an underspend or overspend in relation to the Projected funding balance (G), please describe how this situation arose. Underspends will be returned to the Commonwealth once confirmed by the Final Financial Report. No additional program funding is available to cover overspends.

b) Summary of the Other Contributions

Have Other Contributions been received as described in the Budget in Part C of the Funding Deed?

Definition:	*Other Contributions refers to cash and in-kind contributions received from organisations other than the Commonwealth and include the Grantee's own contributions.*

Summary of Other Contributions
☐ Yes ☐ No
If NO, please provide reason(s) for Other Contributions not being made as per the Funding Deed.

c) Budget Variance

Has a reallocation of funding occurred between headline budget items (salary, operational, travel and assets /other) during the reporting period that increased or decreased by more than 10 per cent the budget allocated for the financial year (see Clause 5.2 of the Funding Deed)?

Budget Variance
☐ Yes ☐ No
If YES, please detail what budget reallocation/s occurred and describe the reasons for the change/s.

d) Assets (items with a value of $5,000 or more – see Clause 9 of the Funding Deed)

Have any assets that cost $5,000 or more been purchased with Funding provided to your project during the reporting period? If YES, please list these items and the date that the item was purchased (*do not list items under leasing arrangements)*.

Project Assets Purchased >$5000		
☐ Yes ☐ No		
Item purchased	**Date of purchase**	**Purchase price (GST exclusive)**

e) Staffing Description

Have there been any changes to the personnel employed for the project from those nominated in the Funding Deed?

Staffing Description
☐ Yes ☒ No
If YES, please describe the change in personnel and why it was necessary.

SECTION B – INTELLECTUAL PROPERTY AND PROJECT MATERIAL

a) Intellectual Property

Has any intellectual property been created during the reporting period that the organisation intends to exploit and/or commercialise, and for which the Intellectual Property Rights should be legally protected under Statutory and/or Common Law?

Intellectual Property
☐ Yes ☒ No

N/A

b) Project Material

Has any significant project material been created during the reporting period? Significant project material includes material produced for the media, publications and scientific reports. It does not include general project documentation.

Project Material
☒ Yes ☐ No
Research Papers Macdonald, BCT, Nachimuthu, G, Chang, YF, Nadelko, AJ, Tuomi, S, and Watkins, M (Submitted) Modifying fertiliser placement to reduce nitrogen run-off losses in furrow irrigated agriculture. Science of the Total Environment. Macdonald B, Chang YF, Nadelko A, Tuomi S, Glover M (Submitted) Tracking fertiliser and soil nitrogen in irrigated cotton: uptake, losses and the soil N stock. Soil Research. Chang, YF, Macdonald, BCT, Nadelko, T, Tuomi, S, Wilson, J (submitted for internal review). Estimating indirect nitrous oxide emissions from irrigated cotton. Macdonald BCT, Chang YF, Warneke S (2016) Potential contributions of surface and ground water to nitrous oxide emissions from irrigated cotton production systems. Agricultural Water Management 168, 78-84. Macdonald BCT, Nadelko A, Chang Y, Glover M, Warneke S (In-press) The contribution of the cotton irrigation network to farm nitrous oxide emissions. Soil Research. Macdonald BCT, Ringrose-Voase A, Nadelko A, Farrell M, Tuomi S, Nachimuthu G (In press) Dissolved organic nitrogen contributes significantly to leaching from furrow irrigated cotton-wheat-maize rotations. Soil Research. ***Datasets*** Macdonald, BCT; Chang, YF; Nadelko, A; Tuomi, S; Glover, M; McLachlan, G; Smith, DJ (2016): Nitrogen isotope budgeting in furrow-irrigated cotton, Narrabri NSW. v1. CSIRO. Data Collection. ***Presentations*** Chang, Y.Y.F., 2016 The fate of applied N in the cotton field. CRDC Responsible landscape management R&D review. May 2016 Brisbane. Macdonald, B.C.T., 2016. Nitrogen loss pathways in irrigated cotton. CRDC Nitrogen Nutrition Tour: Gunnedah, Warren, Griffith, Emerald and Moree. February14-19 2016. Macdonald B.C.T. 2015. Nitrogen loss pathways in the irrigated cotton. Fertcare® Nitrogen Use Efficiency Workshop. Dalby Queensland. 27th August 2015 Macdonald B.C.T. 2015. Nitrogen loss pathways in the irrigated cotton. Fertcare® Nitrogen Use Efficiency Workshop. Forbes, NSW. 27th August 2015. Macdonald, B.C.T. 2015. Mitigating Nitrogen loss pathways in the irrigated cotton. CRDC and CottonInfo Southern nutrition workshop. Griffith, NSW. 15th September 2015. Macdonald, B.C.T. 2015. Mitigating Nitrogen loss pathways in the irrigated cotton. CRDC and CottonInfo Southern nutrition workshop. Hillston, NSW. 16th September 2015.

Devlin, A., Chang, Y.Y.F., Macdonald, B.C.T. 2015. The effect of cotton management practices on indirect nitrous oxide emissions and nitrate losses. 17th Australian Agronomy Conference, Hobart Tasmania, 20-24th September 2015.

Macdonald, B.C.T., 2015. Nitrogen loss pathways in irrigated cotton. CRDC CFI Workshop: Moree.

Macdonald, B.C.T., 2014. Nitrogen loss pathways in irrigated cotton. CRDC Grower workshop Workshop: Gondiwindi.

Industry Publications

Macdonald, B.C.T. et al. 2015. Measuring nitrogen losses and indirect emissions. Spotlight, CRDC. Winter 2015:22-24.

Macdonald, B.C.T et al 2016. Where does it go? Fertiliser N uptake, losses and the soil N stock. Australian Cotton grower.

SECTION C – PROGRESS STATEMENT

a) Progress Overview

Please provide a statement of the progress of the project during this reporting period, identifying any highlights and/or issues.

During the last 6 months the project team has:

- Publicised the project to 20% of the industry through 5 nitrogen workshops and Australian Cotton grower publication and to the science and consultant community through the Agronomy conference and journal papers.
- Completed collection and analysing of data from the 2015-2016 cotton season
- Publishing research findings in Scientific journals and preparing manuscripts
- Written the final report.

b) Progress against Key Performance Indicators (KPI's) (as per the milestone table in the Funding Deed)

Please provide a statement of progress against each of the projects KPIs relevant to the reporting period. This must include providing a progress update for all KPIs not fully achieved in any previous reporting period.

KPI number	KPI description *1. Insert description of the KPI*	Due date for completion	Status against KPIs & Date Achieved ***2.** Select box and insert date KPI achieved or expected date achieved*	Progress achieved against all KPIs *3. If a KPI has been achieved, provide a brief statement of achievement against the KPI* *4. If a KPI has not been achieved, provide a reason for the delay and state the action that will be taken to meet the KPI. The milestone is not considered to be met until all KPIs have been achieved.*
6.1	Quantification of indirect losses components of the irrigation network during both the filling and emptying stages in the cotton season whole of farm and as a function of farm practice: Final Report	7 June 2016	☒ *Achieved* ☐ *Partially Achieved* ☐ *Not Achieved* Date: 7 June 2016	The final report has been completed; all objectives meet.

6.2	Journal Paper Submitted focusing on the relationship between indirect nitrous oxide losses and farm practice	7 June 2016	☒ *Achieved* ☐ *Partially Achieved* ☐ *Not Achieved* Date: 30 June 2016	The manuscript entitled "Modifying fertiliser placement to reduce nitrogen run-off losses in furrow irrigated agriculture" submitted to Science of the Total Environment
6.3	Annual Steering Committee meeting held in conjunction with workshop investigating farm practice and nitrous oxide indirect emissions and workshop report produced (including agreed best management practices to reduce indirect nitrous oxide emissions, and any requirements for scientific / field validation prior to incorporation into myBMP)	7 June 2016	☒ *Achieved* ☐ *Partially Achieved* ☐ *Not Achieved* Date: 7 June 2016	The steering committee meeting was not held, but discussions were had between CRDC and CSIRO in regard to farm practice, fertiliser losses and emissions from surface waters. Workshop report was delivered as a journal paper "Modifying fertiliser placement to reduce nitrogen run-off losses in furrow irrigated agriculture".
6.4	Industry Communication focusing on the relationship between indirect nitrous oxide losses and farm practice	30 June 2016	☒ *Achieved* ☐ *Partially Achieved* ☐ *Not Achieved* Date: 30 June 2016	Industry communication on indirect nitrous oxide losses and farm practice presented the Nitrogen Nutrition Workshop Tour (Moree, Emerald, Griffith, Warren, and Gunnedah). The workshops were attended by 20% of industry's growers.
6.5	Final Report submitted to the Commonwealth	7 June 2016	☒ *Achieved* ☐ *Partially Achieved* ☐ *Not Achieved* Date: 7 June 2016	Final Report submitted

c) Progress against outputs

Please provide a statement of progress against the scheduled outputs for the project. Include a list of activities undertaken during the reporting period to progress towards the outputs.

Output number	Output description	Activity to deliver output	Status against output	Date	Progress achieved against all outputs

	5. Insert description of the output	***6.*** *Insert description of the activity directly related to the output*	*7. Achieved* *8. Partially Achieved* ***9.*** *Not Achieved*	**10.** *Insert date achieved or the expected date the output will be achieved*	*11. If an output has been achieved, provide a brief statement of achievement against the output* *12. If an output has not been addressed, provide a reason for the delay and state the action that will be taken to meet the output*
1	Data sets to provide the basis for identifying the relative contributions of each of the components of the irrigation system to the total nitrous oxide emissions, and how these emissions are affected by different water management and crop management strategies.	Activity 1 and 3	Achieved	1 June 2016	Water and crop management data collected and analysed. Datasets used for journal publications
2	A paper will be submitted to a peer reviewed biogeochemical and atmospheric scientific journal. The paper will analyse the data sets produced by the project to determine 1) the effect of different water and crop management practices on the level of indirect nitrous oxide emissions from the surface waters of an irrigated cotton farm and 2) the relationship (if any) between the levels of nitrate, dissolved organic nitrogen and	Activity 1	Achieved	30 June 2016	This component of the work commenced during the 2014-15 cotton season and will be completed in June 2016. The manuscript has been written and is under internal review at CSIRO.

	dissolvedorganic carbon in the surface water, and the levels of nitrous oxide emissions from the surface water				
3	A paper will be submitted to a peer reviewed biogeochemical and atmospheric scientific journal. The paper will analyse the data sets produced by the project to describe the extent of movement of nitrous oxide from irrigation water to deep ground water.	Activity 2	Achieved	1 June 2016	Experiment completed and paper submitted to Soil Research. Macdonald BCT, Ringrose-Voase A, Nadelko A, Farrell M, Tuomi S, Nachimuthu G (In press) Dissolved organic nitrogen contributes significantly to leaching from furrow irrigated cotton-wheat-maize rotations. Soil Research.
4	Presentations will be made to government forums as required (e.g. Nitrous Oxide Working Group), to the annual project workshops and to the 2014 Australian Cotton Conference that describe the findings of the project.	Activity 1 and Activity 2	Achieved	1 June 2016	Presentation made at the -Project Reference Group meeting -CRDC Nitrogen Forum held on 28/29 August. 62 cotton industry (researchers, consultants, growers and Regional Development Officers) personnel attended. -2014 -17th Australian Cotton Industry Conference -Annual project workshops -Fertcare workshops and Nitrogen Nutrition Tour 2-16
5	Published best management practice – pending scientific validation – will be derived from project activities.	Activity 1, Activity 2 and Activity 3	Achieved	1 June 2016	Industry management practice was discussed and outlined at the industry workshops.

6	Industry workshop reports that cover the results of the research, workshop discussions and potential best management practice/s will be produced.	Activity 3	Achieved	1 June 2016	Results were presented at the -2014 -17th Australian Cotton Industry Conference -CRDC Nitrogen Forum held at Goondiwindi. -CRDC Southern Nutrition workshop (Griffith, Forbes) -Fertcare Nitrogen Workshops (Dalby, Forbes) -Agronomy conference -Nitrogen Nutrition Tour -CRDC CFI Workshops (2014-2016) -CRDC Responsible landscape management R&D review
7	Communications material highlighting findings of the research will be developed through Activity 3. An article will be published annually in Spotlight.	Activity 3.	Achieved	1 June 2016	Presentations were given at the -2014 -17th Australian Cotton Industry Conference -CRDC Nitrogen Forum held at Goondiwindi. -CRDC Southern Nutrition workshop (Griffith, Forbes) -Fertcare Nitrogen Workshops (Dalby, Forbes) -Agronomy conference

					-Nitrogen Nutrition Tour (Moree, Emerald, Griffith, Warren, and Gunnedah) -3 CRDC CFI Workshops (Moree, Narrabri, Toowoomba 2014-2016) -CRDC Responsible landscape management R&D review

d) Project Variation

If the project is not on track in accordance with the current agreed Schedule (this includes the payments table, completion dates, milestones, outputs etc), is a project variation required?

Project Variation
☐ **Yes** ☒ **No**
N/A

a) Lessons Learnt

Please provide a brief statement of lessons learnt over the reporting period. The statement could include any unanticipated events or technical/resourcing difficulties and how these were overcome and whether or not there was a need to change the research methodology, including; monitoring and sampling equipment used and how data was collected/managed.

This was an ambitious project which aimed to measure nitrogen run-off and its transformation to nitrous oxide. We focused on manual methods to undertake measurements but there is a need to undertake automatic methods to measure and quantify indirect nitrous oxide and N losses from the cotton fields and storages. It is evident that the main indirect emission will occur when N enrich run-off water is used to irrigate other fields. This aspect has not been quantified in this project or in other direct emission measurement papers. This is an area of future work.

SECTION D – FINAL RESEARCH REPORT

Please provide a research report covering the life of the project that, at a minimum, includes the following topics/headings:

PROJECT DETAILS

Project Title:

Indirect emissions of nitrous oxide from broad-acre irrigated agriculture

Lead organisation and partner organisations:

Cotton Research Development Corporation

Primary contact and contact details:

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Acknowledgements:

Ben Macdonald, Yvonne Chang, Tony Nadelko, Seija Tuomi, Gordon McLachlan (CSIRO Agriculture)

Mark Glover (CSIRO Land and Water)

Jon Baird, Tim Grant, Rosie Holcombe, Guna Nachimuthu and Mark Watkins (NSW Department of Primary Industries)

We would also like to thank the farm staff at ACRI; and the staff and cooperating grower, Mr Rod Smith, at Ruvigne Farm (Gunnedah).

Financial support from the Cotton Research and Development Corporation, CSIRO and NSW Department of Industries is gratefully acknowledged.

EXECUTIVE SUMMARY (200 word limit)

The cotton plant derived a large proportion of N nutrition from the soil organic pool (up to 70%) which is composed of N sourced from previous fertiliser application and the soil N pool that has built up over the millennia. The soil base is developing an equilibrium with the current land use. Over the last century for Australian agriculture has benefited from some soil chemical and physical properties inherited from the pre European condition. The size of the soil organic N pool is declining with the decline in soil organic carbon stocks, which means that in the future a greater rates on N fertiliser will need to be used to maintain agricultural yields. During the season 143 kg N ha^{-1} was lost, via atmospheric losses, run-off and deep drainage; and by far the largest losses were N_2 from the soil surface. Nitrogen present in the run-off water equated ~8% of the applied fertiliser and this could be transformed into indirect N_2O-N. The IPCC estimates of flux overestimate indirect emissions by a factor of at least 3.7. Applications of IPCC methodology to estimate indirect N_2O emissions are unlikely to be accurate. A better understanding of the processes controlling N_2O production, and attempts to reconcile top-down and bottom-up estimates are necessary if we are to develop better estimate and mitigate indirect N_2O emissions.

INDIRECT EMISSIONS OF NITROUS OXIDE FROM BROAD-ACRE IRRIGATED AGRICULTURE.

REPORT OUTLINE

PROJECT BACKGROUND

Nitrogen Losses

Nitrogen (N) fertiliser is required to produce high yielding dryland and irrigated crops; without this fertiliser it is estimated that only 60% of the world's current population could be supported (Scharf 2015). Production and consumption of N has grown exponentially (Mulvaney et al. 2009) and between 1890 and 1990, anthropogenic production of N_r increased 10-fold (Galloway et al. 2004).

The use of N fertiliser is not without economic, social and environmental cost. The chemical production of N fertiliser is an energy intensive process utilising fossil fuels and producing greenhouse gases. Poor N use efficiency at the farm scale can result in offsite impacts due to leaching, run-off and greenhouse gas (namely, N_2O) production (Smil 1999).

Nitrous Oxide

Nitrous oxide is a key greenhouse gas, with a 100 year global warming potential 298 times that of carbon dioxide; and is the single most important substance responsible for the depletion of stratospheric ozone (Butterbach-Bahl et al., 2013, Ravishankara et al. 2009). Atmospheric levels of N_2O are currently at 121% of preindustrial (1750) levels (World Meteorological Organisation 2015).

Agriculture remains the largest producer of N_2O, contributing between 56 and 70% of global emissions (Butterbach-Bahl et al. 2013, Skiba and Rees 2014, Syakila and Kroeze 2011). N_2O emissions are likely to increase as a result of intensification and expansion of agricultural practices (Reay et al. 2012).

Production of N_2O results from biogeochemical cycling of nitrogen, in particular through the processes of nitrification and denitrification (Firestone and Davidson 1989, Hu et al. 2015). Rates of N_2O emission are controlled by various environmental factors, including soil porosity, oxygen saturation, carbon content, temperature, microbial community, pH and inorganic N availability e.g. (Eichner 1990, Bouwman 1994, Butterbach-Bahl et al. 2013).

Indirect Nitrous Oxide Emissions

Emissions of N_2O which occur as a result of the transformation of N species lost from the field (e.g. via volatilisation, run-off and leaching) or movement of dissolved N_2O from the field are termed indirect N_2O emissions (IPCC 2006, Reay et al. 2005). Indirect emissions may be 29 to 67% the magnitude of direct, land-surface, emissions (Macdonald et al., 2016, Syakila and Kroeze, 2011). Current estimates of indirect N_2O emissions are based on a bottom-up approach which assume a linear relationship between N runoff concentrations and rates of emission (IPCC, 2006). The current 'Tier 1', or universal, emission factor for indirect N_2O emissions from leaching or run-off (EF_5) is 0.0075. That is for every kg of N in leachate/runoff 0.0075 kg of N_2O-N will be produced. The EF_5 comprises of three emission factor components: surface drainage and groundwater (EF_{5g} = 0.0025), rivers (EF_r = 0.0025) and estuaries (EF_{5e} = 0.0025) (IPCC, 2006).

IPCC emission factors provide a simple way to estimate indirect emissions, though they require good estimates of nitrogen runoff/leaching which may be unknown. However, even with good measures of N runoff/leaching, these estimates are surrounded by a large degree of uncertainty (IPCC, 2006). IPCC-derived estimates and top-down measurements differ widely (e.g. Clough et al., 2006, Macdonald et al. in press, Turner et al. 2015). This discrepancy may be due to two reasons:

- Firstly, variation in climatic and geographical parameters can influence rates of N2O production. Whilst it is encouraged that country specific emission factors be used, data for regional (or 'Tier 2') emission factors is still lacking (Reay et al. 2012).

- Secondly, the use of these emission factors (EFs) assume a linear relationship between N concentrations and N_2O production (IPCC 2006). Such assumptions may not hold true. Nitrous oxide is produced as an intermediate compound during microbial nitrification and denitrification (Firestone and Davidson 1989, Hu et al. 2015). Rates of both nitrification and denitrification are controlled by environmental factors such as soil porosity, temperature, carbon availability, oxygen saturation and mineral N availability (e.g. Baulch et al. 2011, Eichner 1990). Furthermore, whilst alteration of nitrification and denitrification rates will affect the amount of N_2O produced, the relative yield of N_2O compared to NO_3 or N_2 is not static (Firestone and Davidson 1989).

Accurate estimates of regional and national scale N2O budgets remains a key priority, and will require greater coverage of all climates, major agricultural land-use types and management practices (Reay et al. 2012).

Project Rationale

In Australia, irrigated cotton (*Gossypium hirsutum* L.) is significant export crop. Approximately 10 to 20% of land used for irrigated cropping may be used to produce cotton (ABARES 2015, Cotton Australia 2016). Cotton is a high yielding crop which is highly dependent on application of nitrogen fertiliser. Recorded nitrogen application rates range between 93 to 370 $kgNha^{-1}$ (Roth Rural 2013), though higher rates up to $500kgNha^{-1}$ have been observed.

Over-fertilisation of N is problematic (e.g. Rochester 2012). Environmental losses of N and N_2O emissions may be large. In Australian furrow-irrigated cotton under a N rate around $250kgNha^{-1}$, approximately 15 kg N ha^{-1} may be lost as nitrate in surface water run-off (McHugh et al. 2008) and greater than 10 kg NO_3-N ha^{-1} lost via deep drainage (Ringrose-Voase & Nadelko, personal communication). Research by Harrison & Matson (2003) has shown that there are significant N_2O emissions from surface water N run-off in flood irrigated wheat production in Mexico. Indirect N_2O emissions resulting from the use of surface or groundwater extraction in irrigated cotton may be substantial.

A rough estimate of indirect emissions using IPCC methodology and N runoff concentrations based on McHugh et al. (2008) suggest that approximately 0.038 kg N_2O-N ha^{-1} will be produced. However, use of IPCC methodology to estimate indirect losses is problematic. Firstly, because there are no measures of nitrogen runoff losses from irrigated cotton, excepting McHugh et al. (2008). Secondly, estimates rely on the universal IPCC EFs which are based on climatic conditions vastly different to the semi-arid climate under which Australian cotton is grown. The studies on which the universal IPCC emission factors are derived are generally wetter and cooler climates compared to those experienced within the Australian cotton growing regions and elsewhere. Furthermore, much of the foundational work for EFs come from riverine and estuarine measurements. This is a contrast to the cotton irrigation network, where irrigation water remains isolated from external water bodies. Indirect emissions from irrigated agriculture may be greater than the IPCC estimates, due the common practice of recycling of irrigation water in Australian agricultural production systems. Recycling and storage of N rich water in irrigation canals and storages increases the potential for N_2O production via denitrification.

Edaphic and climatic factors may significantly influence rates of N_2O production and outgassing (e.g. Eichner, 1990). The need for region specific emission factors is well recognised (IPCC, 2006), though detailed, fine-scale information on nitrous oxide emissions remains lacking (Reay et al., 2012). There remains a need to quantify and understand the controls on indirect N2O emissions from Australian irrigated cotton production. This project will address a gap in the knowledge regarding total N_2O emissions from irrigated cotton agriculture.

Project Aims

The project seeks to quantify, and better understand the controls on the production of, indirect N_2O emissions from broad-acre irrigated cotton agriculture.

The objectives of the project are to:

- Understand and monitor nitrogen losses from irrigated cotton agriculture.
- Measure the indirect emissions of nitrous oxide from the surface waters of each of the major components of an irrigated cotton farm (water storages, supply canals and tail drains).
- Measure indirect nitrous oxide losses from surface water to deep ground water.
- Quantify the relationship between nitrous oxide emission and, nitrate, and dissolved organic nitrogen in surface water.
- Investigate the effects of water and crop management on indirect emissions.

Information gained from the project will be used to:

- Provide a better understanding of the total N losses associated with irrigation and recycling of the irrigation water, and support management practices which promote greater NUE.
- Quantify the relative contribution of indirect N_2O emissions from irrigation water to the total emissions from irrigated cotton farming.
- Identify potential management strategies to reduce GHG emissions that are targeted at the most significant sources of GHG emissions, and which are appropriate in light of the overall contribution of indirect emissions to the total emissions from irrigated cropping.

WHERE DOES THE N GO?

Tracking fertiliser and soil nitrogen in irrigated cotton: uptake, losses and the soil N stock

Introduction

N application in Australian irrigated cotton ranges between 93 to 370 kgN ha^{-1} (Roth Rural), though higher rates up to 500 kgN ha^{-1} have been reported. Under soils not limited by major physical/structural and chemical constraints, N rates above 200-250 kgN ha^{-1} are in excess of crop requirements (Rochester 2011).

The fate of applied fertiliser N is varied. Some is taken up by the plant, some may be stored within the soil, some leached below the vadose zone (Macdonald et al. 2016b), some is lost via surface run-off (McHugh et al. 2008) and atmospheric losses of N_2 or N_2O gas from soil or water surfaces (Macdonald et al. 2015, Macdonald et al. 2016a).

In a NUE ^{15}N experiment, Rochester *et al.* (1993) demonstrated that under optimum N rates (derived by Constable *et al*. 1990) fertiliser uptake was only 30%. Other ^{15}N studies have demonstrated similar recovery rates of 30-35% in China (Yang *et al.* 2013), 30% in Australia (Constable *et al.* 1988, Rochester *et al.* 1993) and 30-38% (Navarro-Ainza 2007) and 42-49% (Fritschi *et al.* 2004) in the United States of America. Whilst these studies demonstrate that plant recovery of fertiliser N is low, the proportion of N retained in soils or lost is unknown.

This study explores the challenge posed by Rochester *et al.* (1993) to determine the importance of the N loss pathways and the importance of immobilization and soil mineral N supply.

Method

Location and Soil

The experiment was conducted at the tension lysimeter facility located within a long term minimum tillage-crop rotation experiment (trial description detailed by Hulugalle *et al.* 2010; Hulugalle *et al.* 2012). The lysimeter facility is located at the Australian Cotton Research Institute (ACRI) near Narrabri in northern New South Wales (ACRI; 149°36’E 30°12’S). ACRI is within the Namoi Catchment and the climate is semi-arid with a mild winter and a hot summer (Figure 1.1). The mean annual rainfall is 593 mm and summer cotton production often requires 6 to 7 additional 100 mm irrigations over the season.

The soil at the experimental site is deep uniform grey clay and was classified as a fine, thermic, montmorillonitic, Typic Haplustert (Soil Survey Staff, 1996). Particle size distribution in the 0.00–0.30 m depth is 53 g/100 g clay (<2 µm), 21 g/100 g silt (2–20 µm) and 26 g/100 g sand (20 µm–2 mm). There is a compacted layer at 0.3-0.7 m and the soil is slightly sodic below a depth of 1.5 m. The surface soil is slightly alkaline (pH 7.2) but this varies when the irrigation water is switched between surface and ground water supplies. The soil at the site is described in detail by Ringrose-Voase and Nadelko (2006) and Hulugalle et al. (2012).

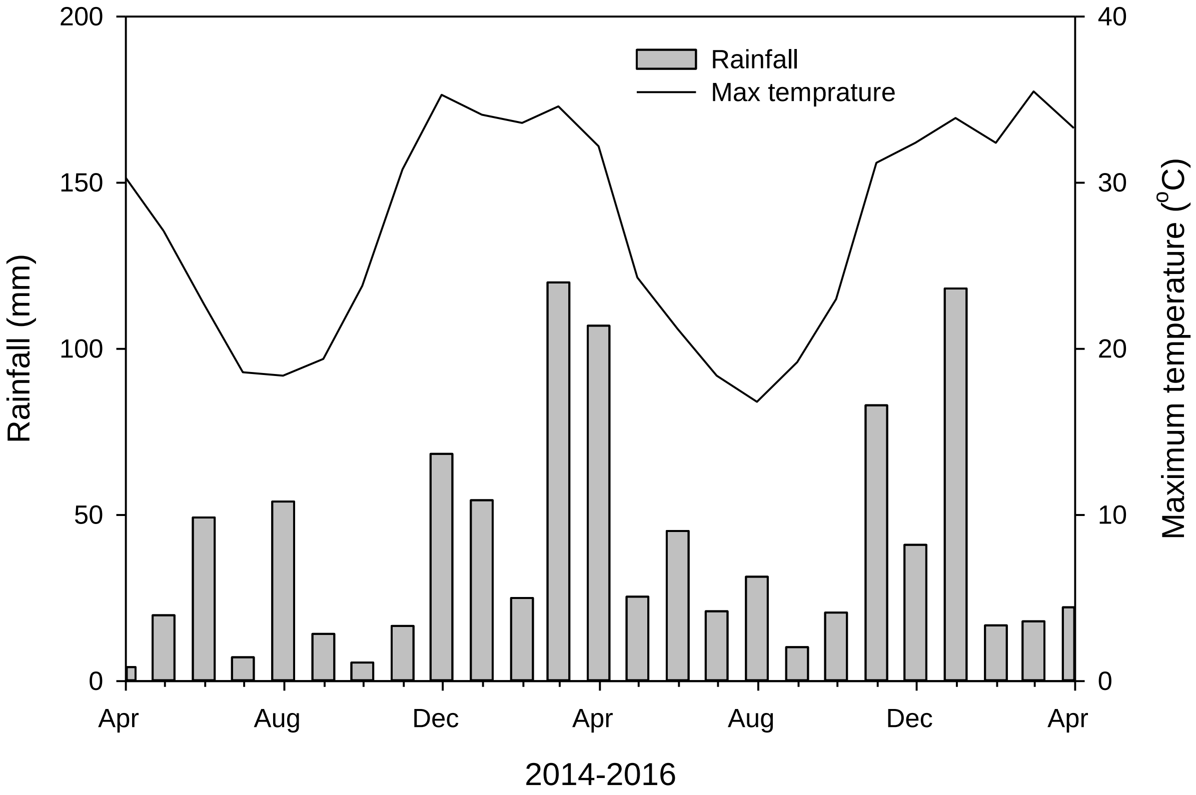

Figure 1.1. Total monthly precipitation and mean monthly air temperatures April 2014 through April 2016 (Narrabri Airport AWS Station Number 54038).

Field Set-Up

This study spans a single cotton crop grown in the 2014-2015 season, which is grown in a cotton-wheat-corn-fallow rotation. The cotton and other rotation crops stubble were mulched back to the field after the harvest of cotton lint or wheat/corn.

In this study the field was planted with cotton (*Gossypium hirsutum* L.) on the 20/10/2016 and the lysimeter was planted a few days earlier on the 16/10/2014. The crop was fertilised with urea in two applications, 180 kg N ha^{-1} at sowing on 21/10/2014 and 52 kg N ha^{-1} at squaring on 13/01/2015. The crop were grown using skip row irrigation and irrigations were triggered when the soil water deficit was approximately 65-75 mm. In total the crop received 492 mm over 7 irrigations and 144 mm rainfall through the season until defoliation and harvest (2/3/2015).

^{15}N plots and application

Two ^{15}N plots were established at the facility (Figure 1.1). The first plot was 9 m^2 located over the lysimeter and fertilised with 180 kg urea-N ha^{-1} which had 35 atom % ^{15}N. The second 4 m^2 plot was located 15 m downstream and two rows away from the lysimeter with 180 kg Urea-N ha^{-1} which had

10 atom % ^{15}N. The final ^{15}N enrichment of the 9 m^2 and 4 m^2 plots after the addition of the mid-season application was 26.8 atom % and 8 atom % ^{15}N, respectively. The second plot was used for soil sampling because the lysimeter plot soil cannot be disturbed.

Two further micro-plots (0.25 m^2) were established near the facility (Figure 1.2) to measure ammonification, nitrification and organic pool uptake. A 0.25 m^2 stainless steel chamber base (h=0.2 m) was inserted into the ground, spanning the centre of the hill to the centre of the furrow, and formed the boundary of each micro-plot. Both micro-plots were fertilised with 180 kg urea-N ha^{-1} which had 35 atom % ^{15}N.

In the laboratory the labelled fertiliser was weighed and stored in individual containers for each plot. In the field the fertiliser for the 9 m^2 and 4 m^2 plots was dissolved in 4500 mL of water and 5 mL of labelled solution was injected into the soil to a depth of 2.5 cm at a 10 cm spacing. For the smaller plots a similar procedure was employed but the fertiliser was dissolved in 250 mL of water. A 5 mL drenching gun fitted with an udder infusion stainless steel needle was used to inject the labelled fertiliser solution into the soil.

Plant sampling

Total above ground plant biomass over the labelled plots (9 m^2 and 4 m^2) was harvested at the end of the season. In total 60 and 28 from each plot respectively plants were collected, material was split into reproductive (seed, and lint) and vegetative (stem and leaves, and senesced leaves) sections and mulched. Two representative sub-samples from each of the plant sections for each of the two labelled plots were taken and finely ground. The plant samples were analysed for total N and ^{15}N enrichment using the same methods described below for the soil analysis.

^{15}N plots soil sampling and analysis

Triplicate intact soil cores (0-2000 mm depth) were taken in the centre of non-irrigated furrow, the irrigated furrow and the hill (Figure 1.2) in the 8 atom % ^{15}N plot only. Each core was divided in the field into 100 mm discrete depths, sealed in plastic bags, and stored at approximately 3 ^{O}C until analysis. Once at the laboratory, the samples were weighed and then oven dried for 2 weeks at $65^{0}C$. Samples were reweighed and, prior to grinding, arranged by core and depth. The samples were ground in a puck mill starting with the deepest sample of each core. Between each sample the mill was cleaned using a brush and vacuum. After each soil core was ground, sand was ground and the mill was then vacuumed and wiped clean with ethanol. This procedure was used to prevent sample contamination. A ground sub-sample was taken and used to determine soil NO_3^- and NH_4^+ content using 1:5 soil: 2 M KCl extract. A second subsample was collected and ^{15}N enrichment determined using a Europa (PDZ Europa) 20/20 stable isotope mass-spectrometer with an ANCA solid liquid preparation module. A third subsample was collected and measured on a LECO TruMac to determine total nitrogen (TN).

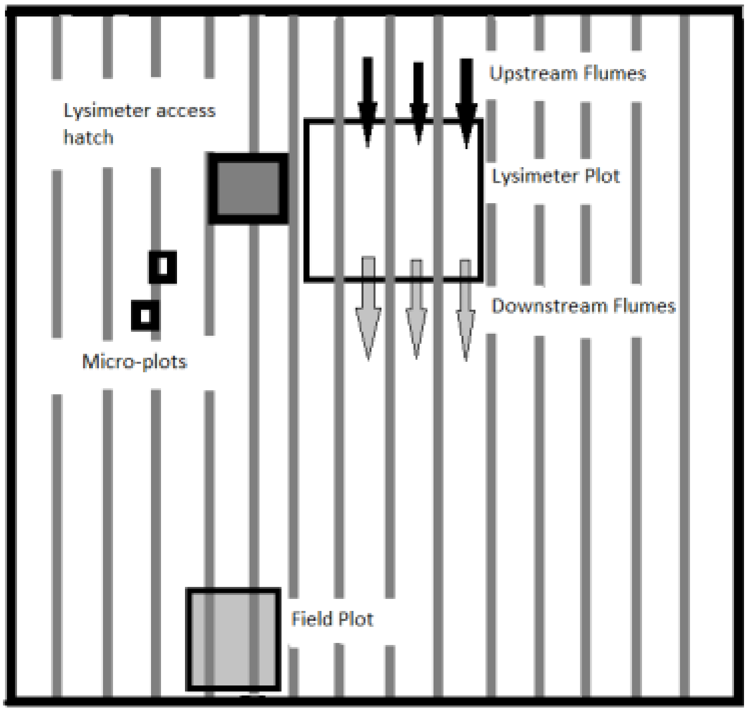

Figure 1.2. Location diagram of lysimeter, ^{15}N plots and micro-plots and the hills (grey lines)

Water

Lysimeter Design and Deep Drainage Sampling

The lysimeter is located half-way along a 200 m long by 24 m wide plot. The first 4 of the 1 m spaced rows of the plot comprise of a buffer strip and the lysimeter trays extend from 4.34 to 6.16 m into the plot. The trays intersect two hills (ridges) and two furrows, an irrigation and a skip furrow. There are no walls and the irrigated and drainage water can pass unimpeded over and through the soil.

The design and operation of the variable tension drainage lysimeter at the site has been described in detail by Ringrose-Voase and Nadelko (2013). Briefly, the lysimeter consists of six adjacent trays installed at 2.1 m depth that intercept drainage over an area of 1.58 m^2. To accurately measure the drainage the trays were installed through tunnels horizontally excavated from an access shaft so that the soil overlying the lysimeter was not disturbed. The collection trays are in contact with the soil via a silica flour contact material and there are no vertical walls encasing the soil above the trays which might interfere with natural cracking patterns.

To ensure one dimensional flow into the trays, the hydraulic gradient in the soil above the trays is maintained the same as the surrounding soil by applying a vacuum to the trays equal to the suction at tray depth (Ringrose-Voase *et al.* 2013). The vacuum is adjusted every 15 minutes with reference to two tensiometers at 2.1 m depth located 1 m from the trays.

The drain from each trays was connected by Telfon® tubing to an individual collection tank that was positioned in the lysimeter access shaft to collect drainage by gravity. The weight of each tank was quantified every 15 minutes by a load cell. The tanks can be isolated from the variable vacuum which is constantly applied to the lysimeter to allow them to be emptied via a tap at their base. The tanks were periodically sampled to determine nitrogen concentrations. The mass of the drainage sample collected was determined from the difference in tank weight immediately before and after sampling.

Surface run-off sampling and flow measurements

Portable RBC flumes (n=6, trapezoidal section, throat width of 50mm, throat length of 150mm) were used to measure the flow rate of irrigation water entering and leaving each of the furrows (Clemmens *et al.* 1984) surrounding the ^{15}N labelled lysimeter plot. Change in water head height in the flumes was measured using 0.5m Odyssey Capacitance Water Level Loggers. Flowrate was calculated from change in water head height using the manufacturer's calibration values. Where individual flow data was absent, mean flowrate data from similar furrow types from the same irrigation event was used. Total water volume passing through each flumes was calculated by integrating flow-rate by total irrigation time. Infiltration volume was calculated as the difference between the volume of water leaving and entering the lysimeter plot.

Water samples (n=4) were collected at each of the flume locations during each irrigation, returned to the laboratory, filtered (0.45 µm) and analysed for dissolved nitrogen species. Nitrate/Nitrite-N (NO_x-N) and Ammonium-N were analysed simultaneously on separate channels with the cadmium reduction method (Method 4500-Nitrate E, Rice *et al.* 2012) and with the alkaline phenol method (Method 4500-Ammonia F; Rice *et al.* 2012) respectively. Total nitrogen (TN) was analysed on a duplicate sample which was first digested using the persulfate oxidation method (Method 4500-Nitrogen C, Rice *et al.* 2012) and NO_x-N concentration was subsequently determined by the cadmium reduction method (Method 4500-Nitrate E, Rice *et al.* 2012). All of the dissolved nitrogen species in the drainage water were analysed with an Alpkem Segmented Flow Analyser, Alpkem Corporation, Perstorp Analytical Company, Wilsonville, OR 97070 USA.

The DON (mg L^{-1}) in each sample was calculated according to equation 1.1.

$$DON = TN - [x + y] \qquad \text{Eq1.1.}$$

Where x = NO_x-N and y = NH_4-N and all the concentrations are in mg L^{-1}. Samples were re-analysed if the calculated DON value was negative or greater than 5 % of the TN value.

Dissolved N_2O-N_d concentrations were determined using the headspace equilibrium technique (Weiss & Price 1980, Roper et al. 2013) and the approach has been described in detail by Macdonald *et al.* (2016a).

The chemical load of water entering and leaving each furrow was estimated by multiplying the volume of water moving through the flumes during a set interval by the concentration of the relevant chemical species in the water sample taken during that interval. The net nitrogen load in the run-off was calculated as the difference between the amounts of various nitrogen species entering and leaving the lysimeter plot.

Determination of the ^{15}N content of the water samples and soil extracts.

The diffusion method was used to prepare water samples for automated ^{15}N analysis (Brooks *et al.* 1989) of the total dissolved N (TDN) pool. The water samples were digested and the ^{15}N enrichment of the total dissolved nitrogen pool was determined by the same instrumentation used for the bulk soil analysis. The soil extracts underwent sequential diffusion extraction and the ^{15}N enrichment was determined for the NH_4-N, NO_3-N, DON-N pools.

^{15}N enrichment and partitioning calculations.

The proportion N derived from fertiliser (Ndff) within each of the pools was calculated as the ratio between the atom % ^{15}N excess in the plant to the atom % ^{15}N excess applied during the cotton season (IAEA 2001). The total amount of N derived from the fertiliser was calculated using the Ndff multiplied by total N yield in plants. The amount of N derived from soil N was given as the total N minus N derived from fertiliser.

Atmospheric N losses: Mass Balance

Fertiliser lost to the atmosphere was calculated as the difference between total fertiliser N applied and the sum of fertiliser N present in all other pools.

Atmospheric N losses: Estimated

The direct N_2O emissions from the published field experiments were calculated using the emission factor (Equation 1.2) derived from measurements in Australian cotton production systems (Shcherbak *et al.* 2016).

$$EF\ (\%) = 0.31 + e^{-4.8}(e^{N/27.5} - 1)/N \quad \text{Eq 1.2.}$$

where N is the applied fertiliser rate kg N ha^{-1}.

The potential N_2 emission was calculated from the published N_2O:N_2 ratio of 0.024 (Rochester 2003) for alkaline soils at the site and the calculated N_2O emission (Eq 2.) from the fertiliser application of 232 kg N ha^{-1}.

Indirect Atmospheric losses

Potential indirect N_2O emissions from the surface run-off water nitrogen concentration from the lysimeter plot were calculated using the current emission factor (EF_5; De Klein et al., 2006). The IPCC emission factor for leaching and run-off (EF_5) is 0.0075, which is composed of three components, emission factor for groundwater and surface drainage (EF_{5g} = 0.0025), rivers (EF_{5r} = 0.0025) and estuaries (EF_{5e} = 0.0025) (IPCC 2006). Given water for cotton irrigation usually remains on site, EF_{5G} was used to calculate the indirect emissions.

Fertiliser nitrogen partitioning and budgeting

The contribution of the soil organic N (ON) ($kgha^{-1}$) to the crop nutrition was calculated using mass balance.

$$Soil\ ON = TN\ Plant - Fert\ N\ Plant \quad \text{Eq1.3}$$

Where the Fert N plant is the average of the total fertiliser N in the harvested plants and TN plant is the total nitrogen in same plants (see Table 1).

The net change in soil N (ΔSoil N (kg ha^{-1}) was calculated using mass balance where

$$\Delta Soil\ N\ (kg\ ha^{-1}) = TN\ input\ and\ storage\ - TN\ loss\ and\ export \quad \text{Eq 1.4}$$

Where,

TN loss & export (kg ha^{-1})

$$= Atmospheric + Run\text{-}off + Deep\ drainage + Soil\ N + Plant\ Seed\&Lint\ N \quad \text{Eq1.5}$$

TN inputs and storage (kg ha^{-1})

$$= Dead\ Leaves\ N + Plant\ N + Soil\ fertiliser\ N + Fertiliser\ N \quad \text{Eq1.6}$$

We estimated the N_2-N loss from the ^{15}N mass balance calculation (88 kg ha^{-1}).

Results and Discussion

N Fertiliser recovery

The average fertiliser recovery in plants, from both ^{15}N plots, was 32%; which is similar to other published ^{15}N studies in cotton and other production systems (Constable *et al.* 1990; Rochester *et al.* 1993). More N was stored in seed than other plant components and more N was derived from the soil over the lysimeter plot than the field plot (Table 1.1). However, total N uptake by the crop was similar between both sites (Table 1.1). The percentage of N in the plant derived from fertiliser N was around 16% at the lysimeter plot and 30% from the field plot (Table 1.1). This indicates that soil N mineralisation is a key source of N for irrigated cotton production systems.

Table 1.1. Fertiliser N yield in cotton plants for 2014/15 season

Plot	Plant Section	Dry Weight (g)	Sample Weight (g)	TN (mg)	%TN	Atom % N15	Ndff (%N derived from fertiliser)	Yield (kg/ha)	Total Crop N (kg N/ha)	Crop N derived from fertiliser (kg N/ha)
LYS	Dead leaves	2712.19	2.07	18.50	0.90	5.65	15.32	3013.54	27.03	4.14
LYS	Lint	2496.04	2.01	6.00	0.30	6.55	17.94	2773.38	8.29	1.49
LYS	Vegetative	5329.49	2.09	21.70	1.04	6.46	17.67	5921.66	61.59	10.88
LYS	Seed	3127.72	2.17	86.70	3.99	5.96	16.24	3475.24	138.66	22.51
LYS	**Total**							**15183.82**	**235.57**	**39.02**
Field	Dead leaves	1954.36	4.17	36.80	0.88	1.61	27.29	3257.27	28.75	7.85
Field	Lint	1580.93	2.10	6.00	0.29	1.85	32.50	2634.88	7.56	2.46
Field	Vegetative	3602.43	2.07	26.50	1.28	2.01	35.80	6004.05	76.85	27.51
Field	Seed	1830.83	2.08	79.40	3.81	4.07	80.06	3051.38	116.26	93.07
Field	**Total**							**14947.58**	**229.42**	**130.89**

If only 32% of the applied fertiliser is recovered in the plant (60 kg ha^{-1}) the remainder must either be lost or be retained in the soil. At the end of the cotton season, 62 kg N ha^{-1} (Figure 1.3) is retained in the soil. The majority of fertiliser N remaining in the soil was located within the surface soil of the hill (Figure 1.4). During the season there has been redistribution of the applied N from the wheel and the water furrow to the hill. The redistribution of N by semi-arid shrubs (Charley *et al.* 1977) and in-crop cultivation can move soil from the furrows to the hills and could explain the observed distribution (Figure 1.3). Alternatively greater losses of N occurred in the furrows relative to the hill. Over the course of the 7 irrigations during the cotton growing season 22 kg ha^{-1} of the applied fertiliser is lost from the soil profile in the run-off water.

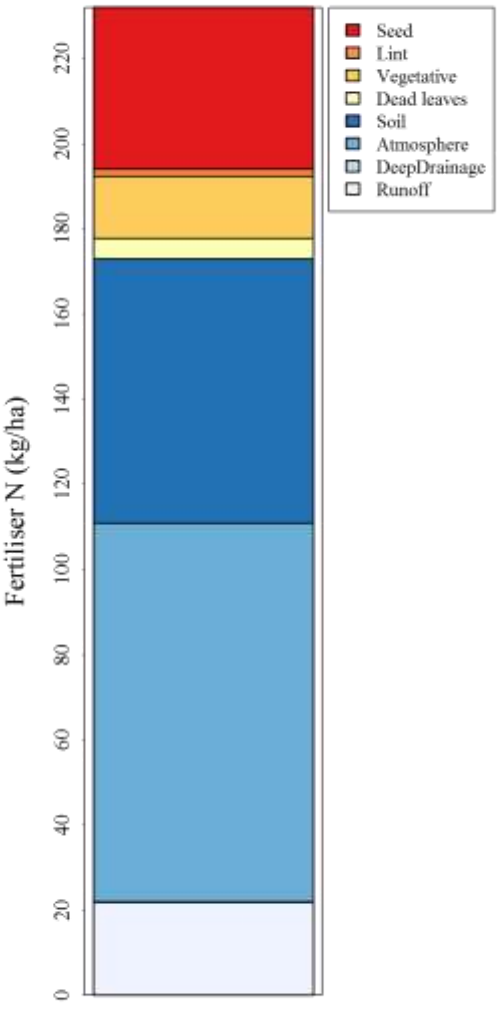

Figure 1.3. The fate of the applied fertiliser (232 kg ha^{-1}) at the lysimeter plot

The measured fertiliser N loss and total N during 2014-2015 season in the drainage water was very small <0.04 and 1.4 kg ha^{-1} respectively, relative to previous average total nitrogen flux measurements (5 kg ha^{-1}) at the site (Macdonald *et al.* 2016b). Investigations have revealed that during the 2014-

2015 incomplete drainage occurred at the site due to a faulty tensiometer on the lysimeter. Therefore the measured 2014-2015 drainage loss will be an underestimate for the site. Nevertheless, we expect drainage losses to be a very small component of the over N budget.

The calculated atmospheric loss, using the ^{15}N mass balance approach, was 88 kg N ha^{-1}. The majority of which is expected to be N_2-N. The calculated N_2O-N loss using Shcherbak *et al.* (2016) approach was 1.1 kg N ha^{-1}. Based on the N_2O:N_2 relationship developed by (Rochester 2003) a further 46 kg N ha^{-1} would have been lost as N_2. The mole fraction approach of Rochester (2003) may underestimate the potential N_2 approach due to variations in the edaphic factors at the site. The N_2O/N_2 mole fraction is not fixed and can decrease when soil moisture increases and dissolved organic C is elevated. The discrepancy between our mass balance approach and the combination of methods described in Shcherbak et al. (2016) and Rochester (2003) suggests that use of emission factors and N_2:N_2O mole ratios may not provide accurate estimates of atmospheric N loss.

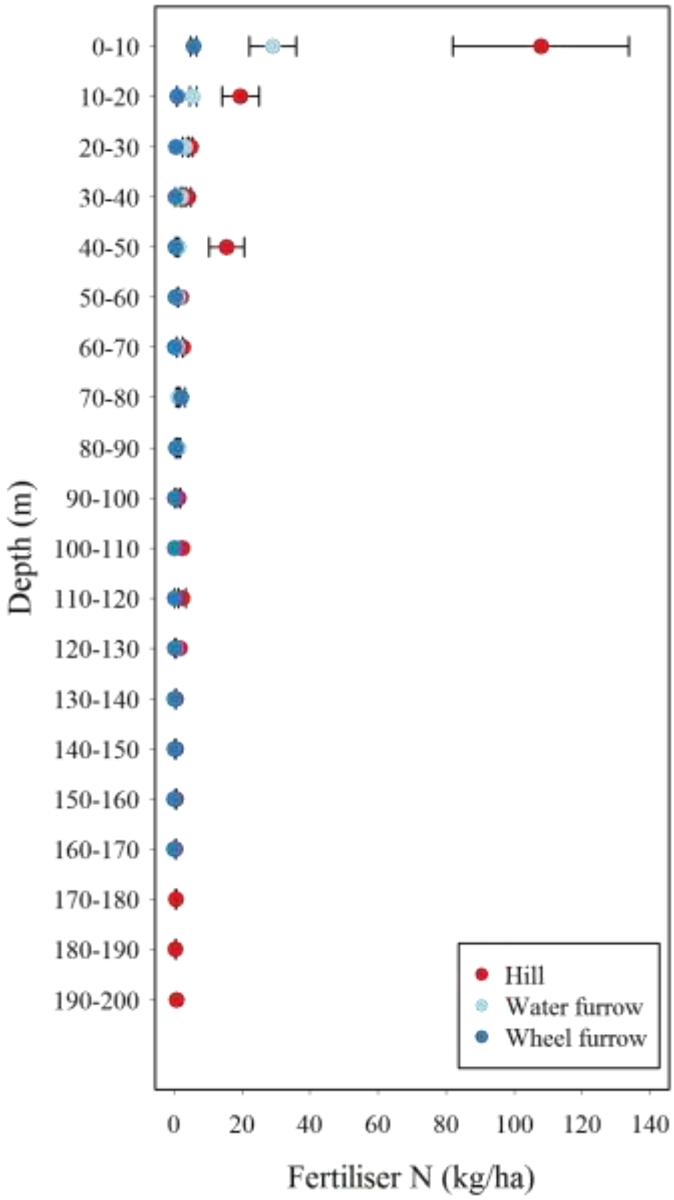

Figure 1.4. The distribution of residual fertiliser N after the harvest of the 2014-2015 cotton crop.

Grower perceptions

Roth Rural (2013) surveyed growers about the perceived fate of the fertiliser N in cotton production systems. On average, growers partitioned the applied fertiliser accordingly: 68% to the plant, 12 % to immobilization in the soil, 8% to atmospheric losses and 12% to run-off. Grower perceptions were at complete odds to this study (Figure 1.3) and other published literature (eg Constable *et al.* 1990; Fritschi *et al.* 2004; Rochester *et al.* 1993). The discrepancy between grower perceptions and research findings reflects poorly on the translation of information between the scientific community and wider industry. Improving the partnership, and specifically transfer of knowledge, between researchers and growers will lead to improved soil and crop management (White *et al.* 2006).

Soil organic N loss, plant uptake and budget

The soil organic N provided around 147 kg N ha^{-1} to the cotton plant during the growing season. The fertiliser directly contributed only 85 kg N ha^{-1} to the plant (Table 1.1). Proportion of soil N stored in different plant components was similar to distribution of fertiliser N in the different plant parts; with most N store in seed and vegetative growth, and less in the lint and dead leaves (Figure 1.5).

Similarly, more N was lost via run-off (an additional 22kg N ha^{-1}) and deep drainage than was accounted for by fertiliser N loss alone (Figure 1.5). We might expect that more N was lost to the atmosphere than the 88kg N ha^{-1} supplied by fertiliser N.

The ΔSoil N (kg N ha^{-1}) for the measured crop in 2014-2015 was -45 kg N ha^{-1} (Table 1.2). This change in soil N for this season may represent a longer term pattern of soil N decline. For example, under increasing applications of synthetic N labile Mulvaney *et al.* (2009) found that over a 50 year period, losses of labile soil N ranged between 14 and 36 kg N ha^{-1} yr^{-1} (the Morrow Plots, Mulvaney *et al.* 2009). While our study represents only a single cropping season, our calculated ΔSoil N combined with the longer term C study (Hulugalle *et al.* 2013) indicates that the soil organic N (kg N ha^{-1}) is potentially declining.

Table 1.2. Cotton crop N budget (2014-2015) ACRI Lysimeter Facility.

Type	Component	Total N (kg N ha^{-1})
Inputs +Storage	Dead leaves	28
	Vegetative	69
	Fertiliser soil N	62
	Urea fertiliser application	232
Total Inputs + Storage		**391**
Losses + Export	Soil organic N uptake	147
	Runoff	63
	Drainage	1
	Atmosphere N losses	89
	Lint	8
	Seed	127
Total Losses + Export		**436**
Δ Soil N		**-45**

The soil C stocks have been declining at the ACRI site (2002-2011) at a rate of 1.60 ±0.69 Mg C ha^{-1} $year^{-1}$ (Hulugalle *et al.* 2013). If it assumed the C:N ratio in the soil is 12:1, then the C decline reported by Hulugalle et al. (2013) would represent a change of storage and the release of 133 ± 57.5 kg N ha^{-1} $year^{-1}$. This is greater than the estimated N_2 production from the applied fertiliser in the study because it did not account for the further N2 losses sourced from the organic matter pool. The decline in soil organic N has serious implications for sustained food and fibre production (Mulvaney *et al.* 2009).

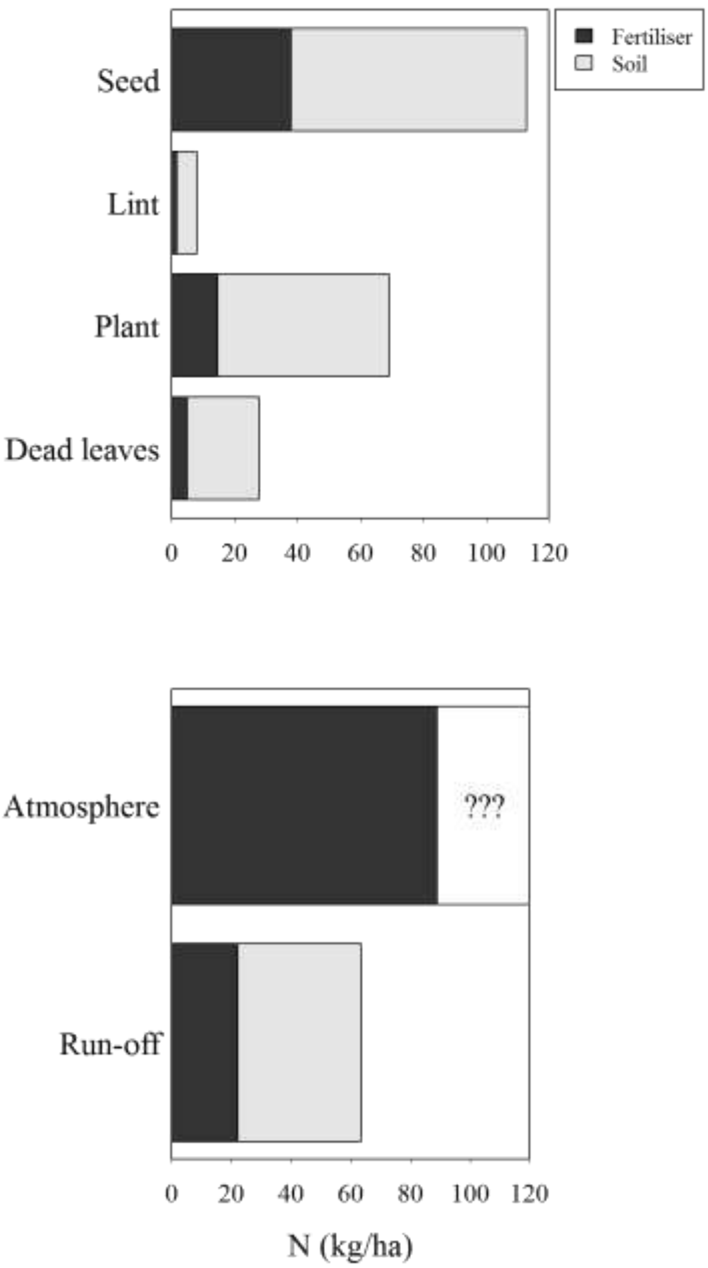

Figure 1.5. The contribution of fertiliser and soil native N to the cotton plant and the main loss pathways. The "???" represents the unknown N_2 flux from the soil organic nitrogen pool.

Timing of Losses

The ^{15}N mass balance studies showed that during the course of the season, 153 kg N ha^{-1} sourced from the soil and the fertiliser was lost from the field in atmospheric, deep drainage and run-off losses.

The bulk of atmospheric N_2O-N losses, and presumably N_2-N, from irrigated cotton occurs immediately after fertiliser application (Macdonald *et al.* 2016a; Scheer *et al.* 2013; Scheer *et al.* 2008). We presume that the 88kgN ha^{-1} lost to the atmosphere would have been lost soon after the initial urea application of 180kgN ha^{-1}. Similarly, deep drainage losses are also greatest during the start of the season (Macdonald *et al.* 2016b). The temporal distribution of run-off losses is similar to the atmospheric and deep drainage losses where the majority of N export occurs soon after fertilisation (Figure 1.6). This is reflected in the amount of N and the urea-N exported during irrigation 1 and 4, which occurred post fertiliser application, relative to the other irrigations. High N losses occur as a result of disparity between N supplied and crop N requirements early in the season, and the movement of NO_3-N and DON-N previously accumulated in the soil.

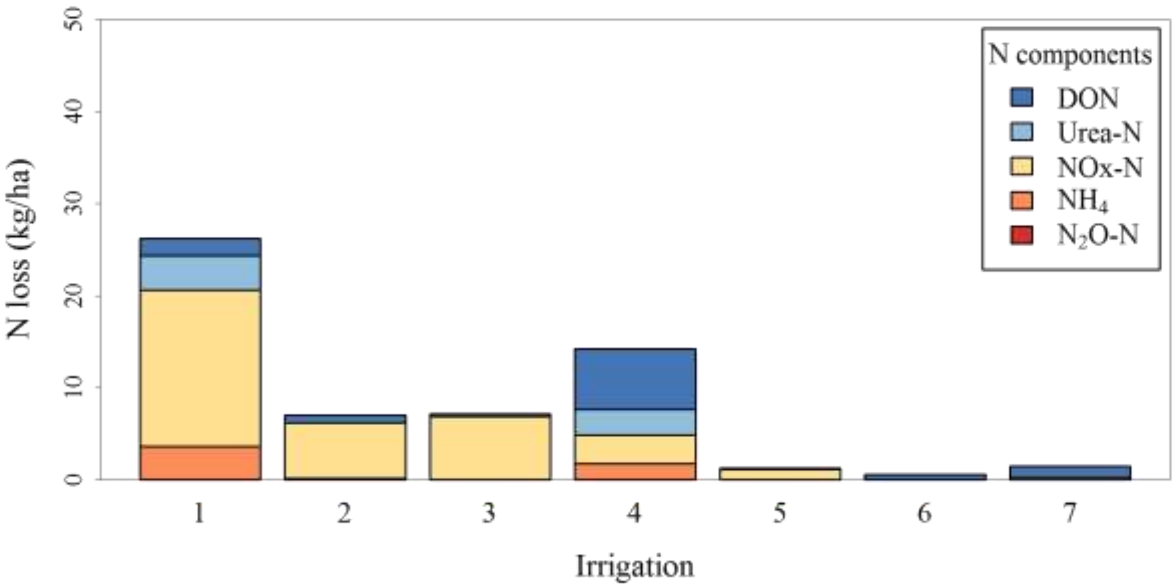

Figure 1.6. The nitrogen components (dissolved organic N not including urea (DON), urea (Urea-N), nitrous oxides (NOx-N), ammonium (NH_4-N), and nitrous oxide (N_2O-N)) in N run-off losses from each irrigation during the 2014-2015 cotton season at the lysimeter facility. Irrigations 1 to 7 occurred 12, 54, 61, 74, 96, 110, 124 and 138 days after sowing. Fertiliser was added to the field prior to irrigations 1 (180 kg N ha^{-1}) and 4 (53 kg N ha^{-1}).

Within the soil, numerous N transformations occur. The applied ^{15}N urea is rapidly converted to NH_4-N post fertilisation (Figure 1.7) and this may explain the flux of NH_4-N in the irrigation tail water (Figure 5) during irrigation 1. The ^{15}N urea is also rapidly converted to DON-N and NO_3-N during irrigation 1 and 2 which is again reflected in the export of both species (Figures 1.6 and 1.7). By irrigation 3 the labelled fertiliser has been exhausted, which is reflected in the cumulative figures (Figure 1.7) and the fertiliser is either in the plant, incorporated in the soil organic pool or lost from the system.

The export of the N species from the hill is caused by the movement of water from the irrigation furrow through the hill into the non-irrigated furrow (Macdonald *et al.* 2016a). Overall the flux of total N in the run-off water indicates that the form, placement and timing of the fertiliser does not synchronise with soil and crop N dynamics and irrigation practice. The irrigation tail water is not discharged off farm but reused to further irrigate other cotton fields (Macdonald *et al.* 2016a). Exported N is thus redistributed throughout the farm and fertigates other fields during the season.

Some of the dissolved N will be lost as an indirect emission of N_2O-N from the storages and channels (Harrison *et al.* 2003; Macdonald *et al.* 2016a). The N_2O_d-N concentrations in run-off are at the maximum (0.03 kg N_2O-N ha^{-1}) early in the season, suggesting denitrification of N in the soils, and potentially sediments and water column. Use of the IPCC EF_{5G} of 0.0025 and total N flux, 0.15 kg N_2O-N ha^{-1} cotton $season^{-1}$ would potentially be produced, which equates to 13% of the direct emissions.

Conclusions

Despite using the appropriate agronomic N split management and rate (232 kg urea-N ha^{-1}), large N losses (153 kg N ha^{-1}) via the atmospheric, deep drainage and surface run off pathways occurred. N losses predominantly occurred at the start of the season, when most of the fertiliser was applied (180 kg urea N ha^{-1}) and when crop N requirements were low. Such high losses indicate that further optimisation of fertiliser placement and timing, and type of fertiliser used, is possible.

A large amount of the fertiliser (62 kg N ha^{-1}) remains in the soil at the end of the season and will potentially mineralise during subsequent seasons. However an overall soil nitrogen deficit of 45 kg N ha^{-1} was observed, but not including the N_2 losses from the soil organic pool. This N deficit is within expected declines in soil N, based on long term declines of organic carbon at the site. Reduction of the soil organic nitrogen pool is an issue facing all cropping production systems. Further studies are required to quantify long-term nitrogen changes; and to develop management practices that build soil carbon and nitrogen stocks.

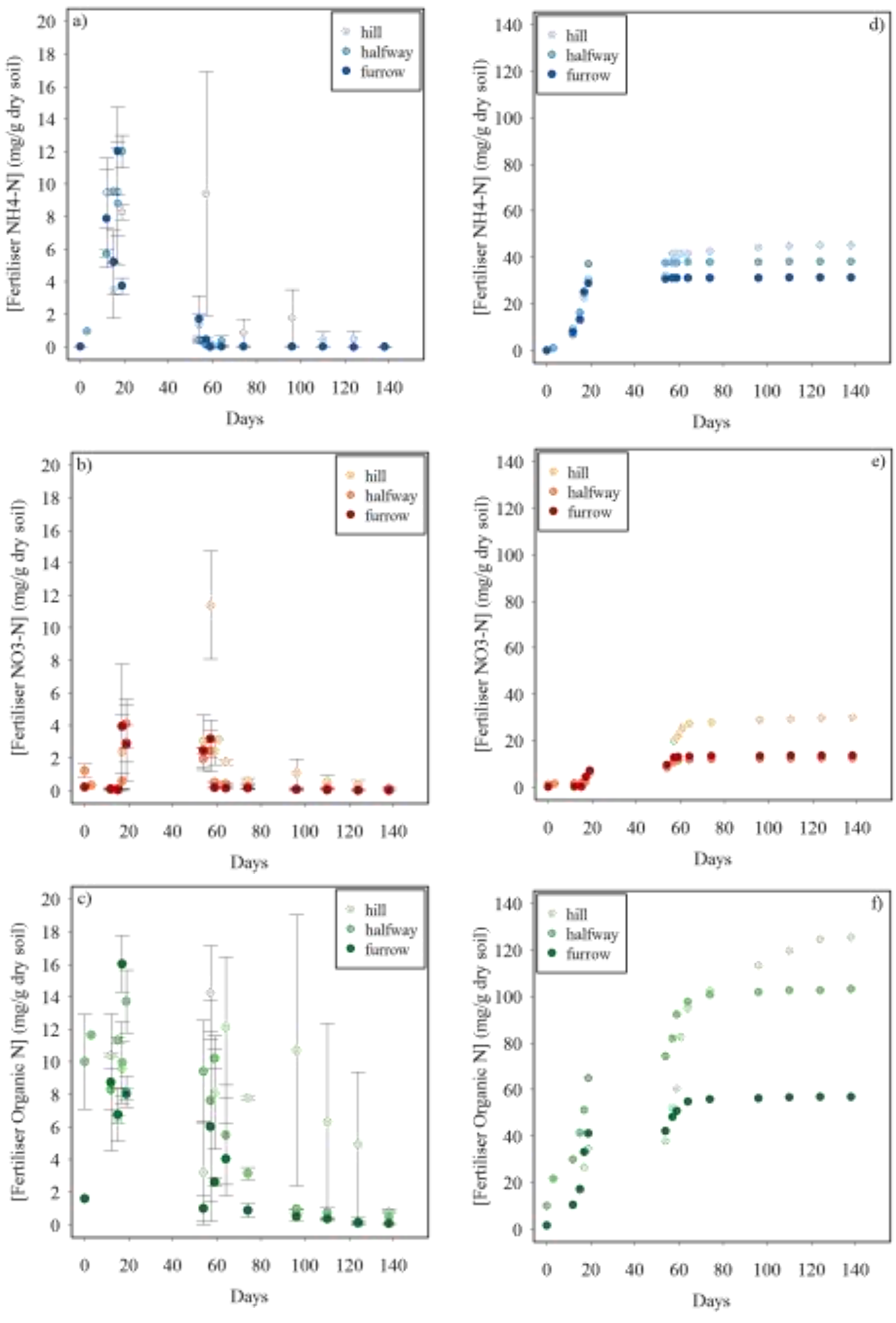

Figure 1.7. The contribution of labelled fertiliser N (180 kg ha^{-1}) to the NO_3-N, NH_4-N, and DON-N (mg g^{-1} dry soil) in the micro-plots during the 2014-2015 cotton crop. Irrigation 1 to 7 occurred 12, 54, 61, 74, 96, 110, 124 and 138 days after sowing. The graphs on the left column reflect changes in absolute concentration. The graphs on the right column reflect cumulative changes in the different N species.

Dissolved organic nitrogen contributes significantly to leaching from furrow irrigated cotton-wheat-maize rotations

Introduction

In many irrigation areas, ground water resources have become degraded due to the leaching of nitrate derived from fertilised soils (Chaudhuri *et al.* 2014; Chaudhuri *et al.* 2012). It has long been recognised, for example in the Rothamsted experiments, that soil nitrate (NO_3-N) leaching can potentially be an important portion of the soil N budget (Addiscott 1988). The amount of nitrate leached is influenced by rainfall and soil and crop management (Addiscott 1998). However, nitrate is only one component of the soil N budget, which is also comprised of ammonium (NH_4-N) and organic N pools.

All applied N fertiliser enters the organic N pool as it is transformed, which makes it the single most important and largest N soil pool (Scharf 2015). Dissolved organic nitrogen (DON-N), is composed of proteins, oligopeptides and amino acids, and is converted to simpler forms through a series of microbial mediated steps to NH_4-N and NO_3-N (Prendergast-Miller *et al.* 2015). Peptides and amino acids can be directly taken up and utilised by plants and microbes (Farrell *et al.* 2013; Farrell *et al.* 2011; Farrell *et al.* 2014; Jones *et al.* 2005; Jones *et al.* 2009) in the same manner as ammonium and nitrate. The DON-N can be sourced from the degradation of terrestrial organic material (Macdonald *et al.* 2014) and organic or synthesised urea.

In sandy soils DON deep drainage flux can be significant (Siemens *et al.* 2002) representing between 6-20% of the total N flux (16—159 kg N $ha^{-1}yr^{-1}$). In non-sandy soils, such as Vertosols, it is not clear from the literature (Hulugalle *et al.* 2010; Hulugalle *et al.* 2012a; Weaver *et al.* 2013) if DON-N an important fraction within the deep drainage N-flux. Vertosols only represent about 4% of the worlds agricultural soils and are limited predominantly to Australia, India and some southern US states.

In furrow irrigated cotton rotation systems, Kjelhdal N leaching (10-60 kg N ha^{-1}) from cracking clay soils (Vertosols) can be significant fraction of the applied N fertiliser (160 kg N ha^{-1}) during the cotton season (Hulugalle *et al.* 2010; Hulugalle *et al.* 2012a; Weaver *et al.* 2013). It is not clear from these studies when the peak NO_x-N losses occur and if DON-N is an important fraction within the deep drainage loss. There is a need to quantify the timing and composition of the drainage N losses from irrigated systems on cracking clay soils to improve our understanding of the crop-soil processes and N management.

Materials and Methods

Location and Soil

All samples were taken from the lysimeter facility at the Australian Cotton Research Institute (ACRI) near Narrabri. For a description of the site and lysimeter facility please see pages 17-19.

Electrical conductivity, dissolved organic and mineral nitrogen analysis

Electrical conductivity (dS m^{-1}) of the leachate was measured in the field using a TPS WP81 (TPS Brendale, Qld) and a k=10 GK Series Conductivity Sensor. Nitrate/Nitrite-N (NO_x-N) and Ammonium-N were analysed simultaneously on a separate channels with the cadmium reduction method (Method 4500-Nitrate E; Rice *et al.* 2012) and with the alkaline phenol method (Method 4500-Ammonia F; Rice *et al.* 2012). Total nitrogen (TN) was analysed on a duplicate sample which was first digested using the persulfate oxidation method (Method 4500-Nitrogen C; Rice *et al.* 2012) and NO_x-N concentration was subsequently determined by the cadmium reduction method (Method 4500-Nitrate E; Rice *et al.* 2012). All of the dissolved nitrogen species in the drainage water was analysed with an Alpkem Segmented Flow Analyser (Alpkem Corporation, Perstorp Analytical Company, Wilsonville, OR 97070 USA).

The DON (mg L^{-1}) in each sample was calculated according to equation 2.1.

$$\mathrm{DON} = \mathrm{TN} - [\mathrm{x} + y] \qquad \text{Eq 2.1.}$$

Where x = NO_x-NWand y = NH_4-N and all the concentrations are in mg L^{-1}. Samples were re-analysed if the calculated DON value was negative or greater than 5% of the TN value.

Instantaneous N flux per unit area

The instantaneous flux per unit area of DON, TN, NO_x -N and NH_4-N g ha^{-1} of each sample collect from individual trays was calculated according to equation 2.2.

$$\mathrm{N\ Flux\ (g\ ha^{-1})} = \frac{\mathrm{N_i\ (g)}}{\mathrm{Tray\ Area\ (ha)}} \qquad \text{Eq 2.2.}$$

$$\text{where } \mathrm{N_i\ (g) = C\ (g\ L^{-1})\ x\ V_i\ (L)} \qquad \text{Eq 2.3.}$$

Each tray has an area of 2.6 x10^{-5} ha, where i refers to the individual trays, V_i is the amount of water collected from each tray and C is the concentration of the N per unit of water.

Average flow-weighted concentrations and flux

The average flow-weighted ($\overline{\mathrm{N}}_{(\mathrm{FW})}$) concentration of drainage from the six trays was calculated from the instantaneous mass of TN, NO_x-N and NH_4-N g of each sample collected from individual trays.

$$\overline{\mathrm{N}}_{(\mathrm{FW})}\ \mathrm{mg\ L^{-1}} = \frac{\mathrm{N_t}}{\mathrm{V_t}} \qquad \text{Eq 2.4.}$$

$$\text{where } \mathrm{N}_t = \textstyle\sum_{\mathrm{i=1}}^{6} \mathrm{N_i\ (g)}\ and\ \mathrm{V}_t = \sum_{\mathrm{i=1}}^{6} \mathrm{V_i\ (L)}.$$

The average flow-weighted concentration for DON ($\overline{\mathrm{DON}}_{\mathrm{FW}}$) was calculated using

$$\overline{\mathrm{DON}}_{\mathrm{FW}} = \overline{\mathrm{TN}}_{\mathrm{FW}} - (x + \mathrm{y}) \qquad \text{Eq 2.5}$$

Where x = NO_x-N_{FW} and y = NH_4-N_{FW}

The flow-weighted flux was according to Eq 2.6.

$$\text{N Flux (g ha}^{-1}) = \frac{\text{N}_{(\text{FW})} \text{x } V_t}{\text{Lysimeter Area (ha)}} \qquad \text{Eq 2.6.}$$

The tray has an area of 2.6 x10^{-5} ha, V_t is the total volume of water collected from all tray during a sampling event and $\overline{\text{N}}_{\text{FW}}$ is the flow weighted concentration is the amount of nitrogen analyte per unit of water.

Drainage samples and infilling missing samples

During the study period 203 drainage samples were collected from the six lysimeter trays, but only 198 samples had sufficient volume for analysis of NO_3-N, 170 for analysis of NH_4-N and 168 for TN. Missing TN data (n=5) was infilled according to the following significant relationship TN_t = 1.46 NO_x-N_t + 14.8 (P<0.05; R^2=0.92). There was no significant relationship between NH_4-N_t and the other measured parameters, and due to the relatively minor average concentration (<0.09mg L^{-1}) missing values were assigned to 0.

Farm operations and cropping

This study spans five years and encompasses three cotton, two wheat and a single maize crop and two fallow periods (Table 2.1). All crops were fertilised with nitrogen, except the winter wheat in 2011, which was sprayed out. In 2011 the cropping trial was modified to include maize in the rotation and to be able to readjust the cropping calendar the winter wheat was not grown to maturity. All of the crops were grown using skip row irrigation and irrigations were triggered when the soil water deficit was approximately 65-75 mm. The cotton and other rotation crops biomass were mulched back to the field after the harvest of cotton lint or wheat/corn.

Table 2.1. Cropping calendar and fertiliser/irrigation applications during the measurement period.

Sowing	Harvest	Crop	N Fertiliser	Residue t ha^{-1}	N kg ha^{-1} residue supplied	Irrigations
09/10/2008	10/06/2009	Cotton Sicala 60 BRF	160 kg Anhydrous-N ha^{-1} 26/09/08	5.6	106	6
23/06/2009	18/11/2009	Wheat Gregory	20 kg Urea-N ha^{-1} 23/06/09 60 kg Urea-N ha^{-1} 28/08/09	1.3	22	2
18/11/2009	28/10/2010	Fallow		0	0	0
29/10/2010	29/04/2011	Cotton Sicot 71 BRF	160 kg Urea N ha^{-1} 24/11/2010	5.9	112	4
10/06/2011	16/08/2011 (sprayed out)	Wheat Crusader	No Fertiliser			1
19/09/2011	14/03/2012	Maize Pioneer 31G66	180 kg Urea N ha^{-1} 28/08/2011	0.24	4	2
15/03/2012	24/10/2012	Fallow				0
25/10/2012	09/05/2013	Cotton Sicot 71 BRF	160 kg Urea N ha^{-1} 12/12/2010	5.1	89	5

Results

Antecedent rainfall conditions and irrigation frequency.

Deep drainage measurements at the lysimeter facility began in the 2008-09 cotton season during the millennium drought (2000-2010). This drought ended in 2010, which resulted in trend of positive monthly rainfall anomalies (2010-2011; Figure 2.1). Since the end of the 2011 maize crop, monthly rainfall has been below the long term average, reflected in the negative trend in the anomaly (Figure 2.1). Overall during the measurement period there has been a dry (2008-10), wet (2010-11) and drying period (2011-2014; Figure 2.1), which has resulted in fluctuations in the number of irrigations that were required by each crop (Table 2.1).

Average flow-weighted drainage water concentrations

The average DON-N and NO_x -N concentration for the whole period of measurement are similar (7-9 mg L^{-1}; see Figure 2.2) and the average NH_4-N concentration was an order of magnitude smaller. Proportionally, the average TN was comprised of 45% DON-N and 54% NO_x -N and 1% NH_4-N. During both the wheat seasons (2009 & 2011), the cotton 2012/13 season and the 2009 fallow season NO_x -N dominates drainage (Figure 2.2, Table 2.2) and during the other seasons there was an equal DON-N/ NO_x -N or a larger DON-N concentration.

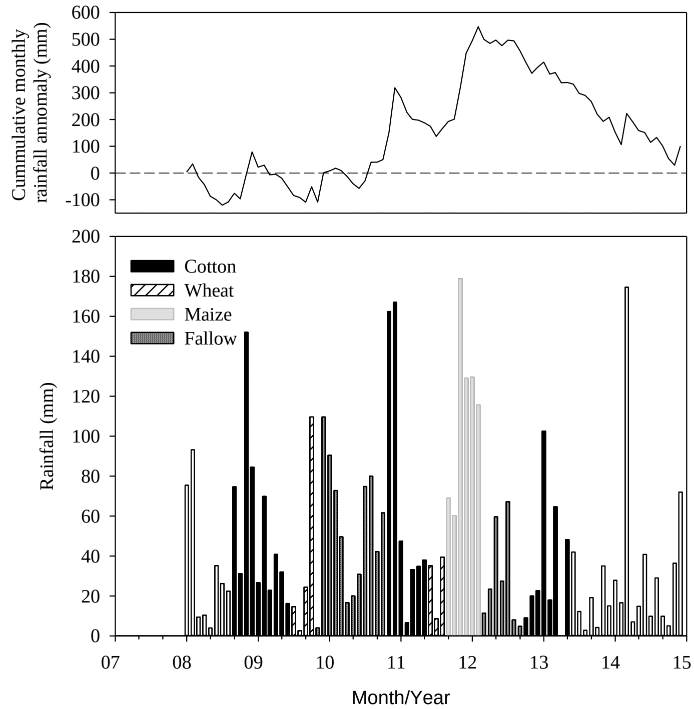

Figure 2.1. Cumulative monthly rainfall anomaly and monthly rainfall by crop during the measurement period. None filled bars are rainfall monthly totals outside the crop measurement period.

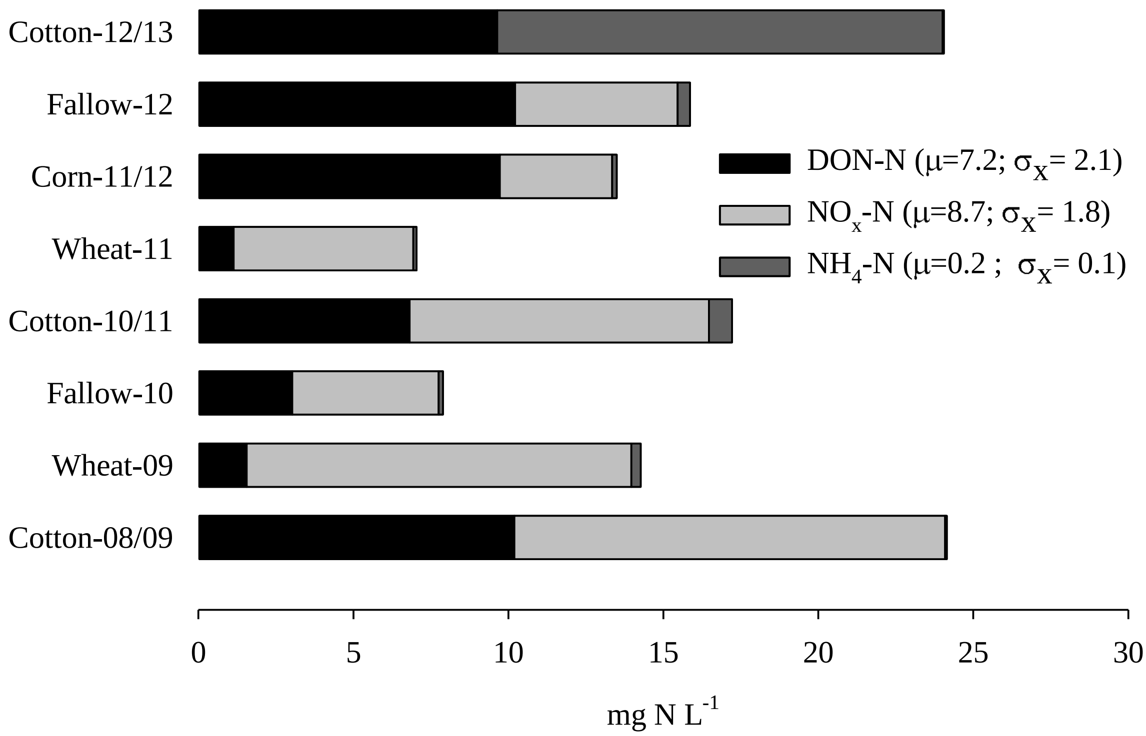

Figure 2.2. Flow-weighted DON-N, NO_x-N and NH_4-N concentration (mg L^{-1}) for each crop type. The mean and standard error for the entire period of measurement are displayed in the legend.

Table 2.2. Percentage contribution of the different nitrogen pools to the overall total nitrogen flux in the drainage water.

	Percentage of the TN flux		
Cropping Season	**DON-N**	**NO_x-N**	**NH_4-N**
Cotton-08/09	41	59	0
Wheat-09	11	87	2
Fallow-10	31	67	1
Cotton-10/11	45	54	1
Wheat-11	16	82	2
Maize-12	72	27	1
Fallow-12	64	33	3
Cotton-12/13	37	63	0
Average	**40**	**59**	**1**

Deep drainage nitrogen flux

The average measured flux of DON-N and NO_x -N was 1.1 and 1.6 kg ha^{-1} and the NH_4-N flux was an order magnitude smaller. Overall the DON-N was as equally important as the NO_x -N pool within the deep drainage measured. The majority of the DON-N and NO_x -N occurs during the measured cotton seasons and the fallow period in 2010 (Figure 3). In the maize and the fallow period of 2011 DON-N is greater than NO_x -N flux. In total over the five years 21.6 kg N ha^{-1} were lost to deep drainage, this was comprised of 59 % NO_x -N, 40 %DON-N kg ha^{-1} and < 1 % NH_4-N. This total N loss equates to 3% of the applied fertilizer (740 kg N ha^{-1}).

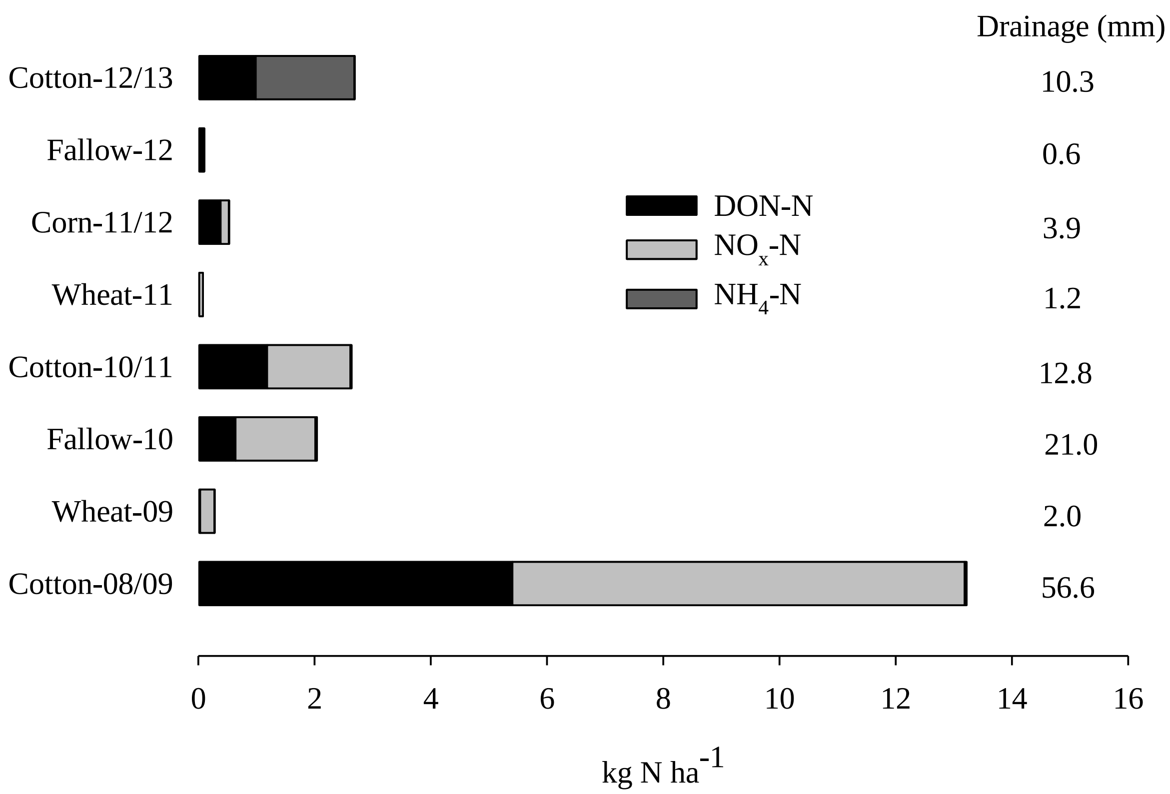

Figure 2.3. Flux of DON-N, NO_x-N and NH_4-N (kg N ha^{-1}) for each crop type. The mean and standard error for the entire period of measurement are displayed in the legend and the total drainage (mm) for each crop is displayed.

Cotton Seasons 2008-2009 and 2012-2013

NO_x -N concentration, Electrical conductivity and drainage of individual trays.

There was no clear inverse relationship between EC and NO_x -N concentration during both cotton seasons in 2010-2011 and 2012-2013 (Figure 2.4). However in 2008-2009, Tray 1 was characterised by a large EC, small drainage volume and low NOx-N concentration which contrasted with Tray 6 which appeared to have captured by-pass flow (Figure 2.4a-c). Overall average drainage in 2012-2013 was five times smaller than 2008-2009 (compare Figure 2.4c & f), but the average NO_x-N concentration for each tray was greater (compare Figure 2.4a & d) while the EC was smaller (except for Tray 6) than 2008-2009 season (compare Figure 2.4b & e).

Nitrate and DON-N individual tray flux

The key difference between the 2008-2009 and 2012-2013 seasons was the drainage was five times less, but the proportional variation between the total DON-N and NO_x -N flux is similar for both seasons (Figure 2.5). Individual tray drainage amounts and subsequently the N flux has changed between each cropping season, but the overall proportion of DON-N and NO_x -N was similar.

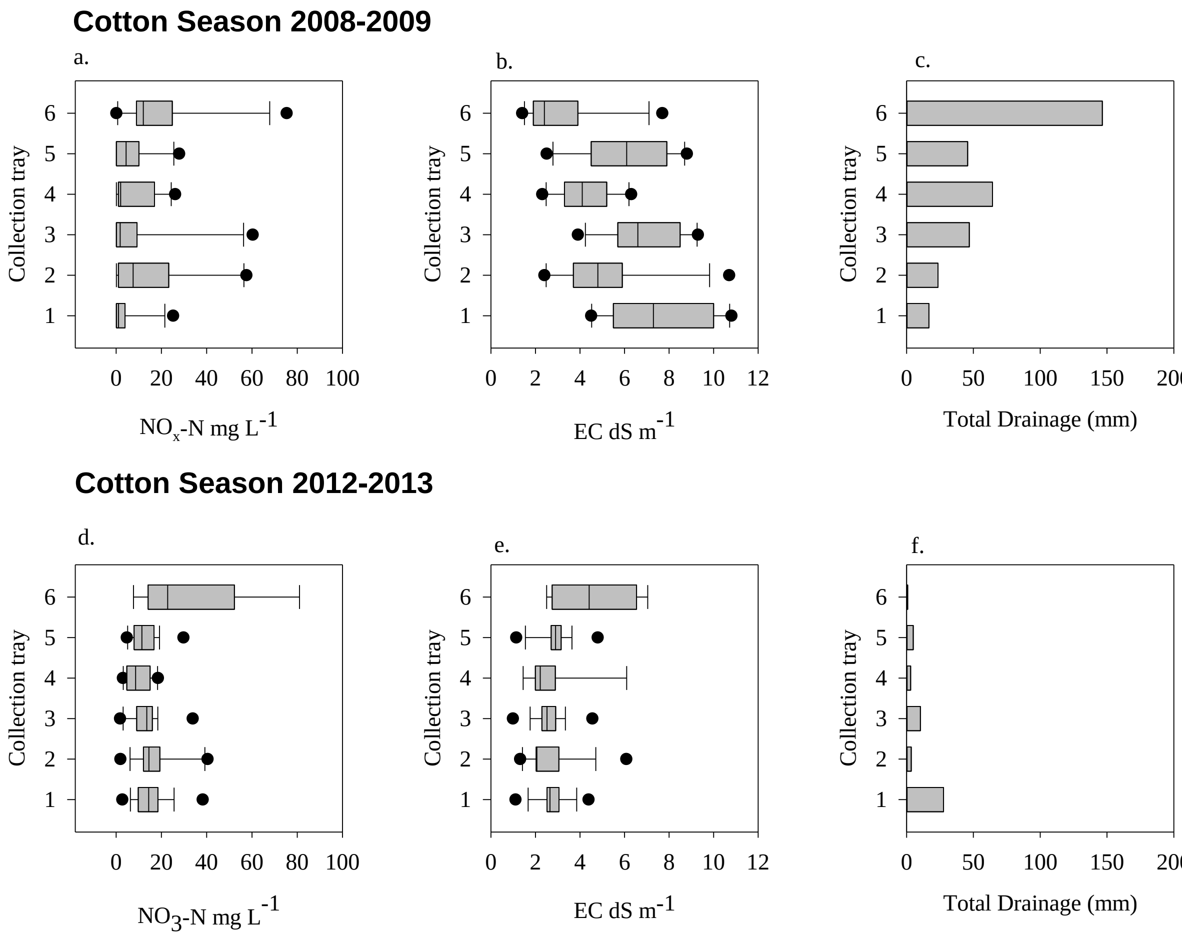

Figure 2.4. NO_x-N and EC box-plot for samples collected for individual trays and total drainage for samples collected for individual trays during 2008-2009 (a,b,c) and 2012-2013 (d,e,f) seasons.

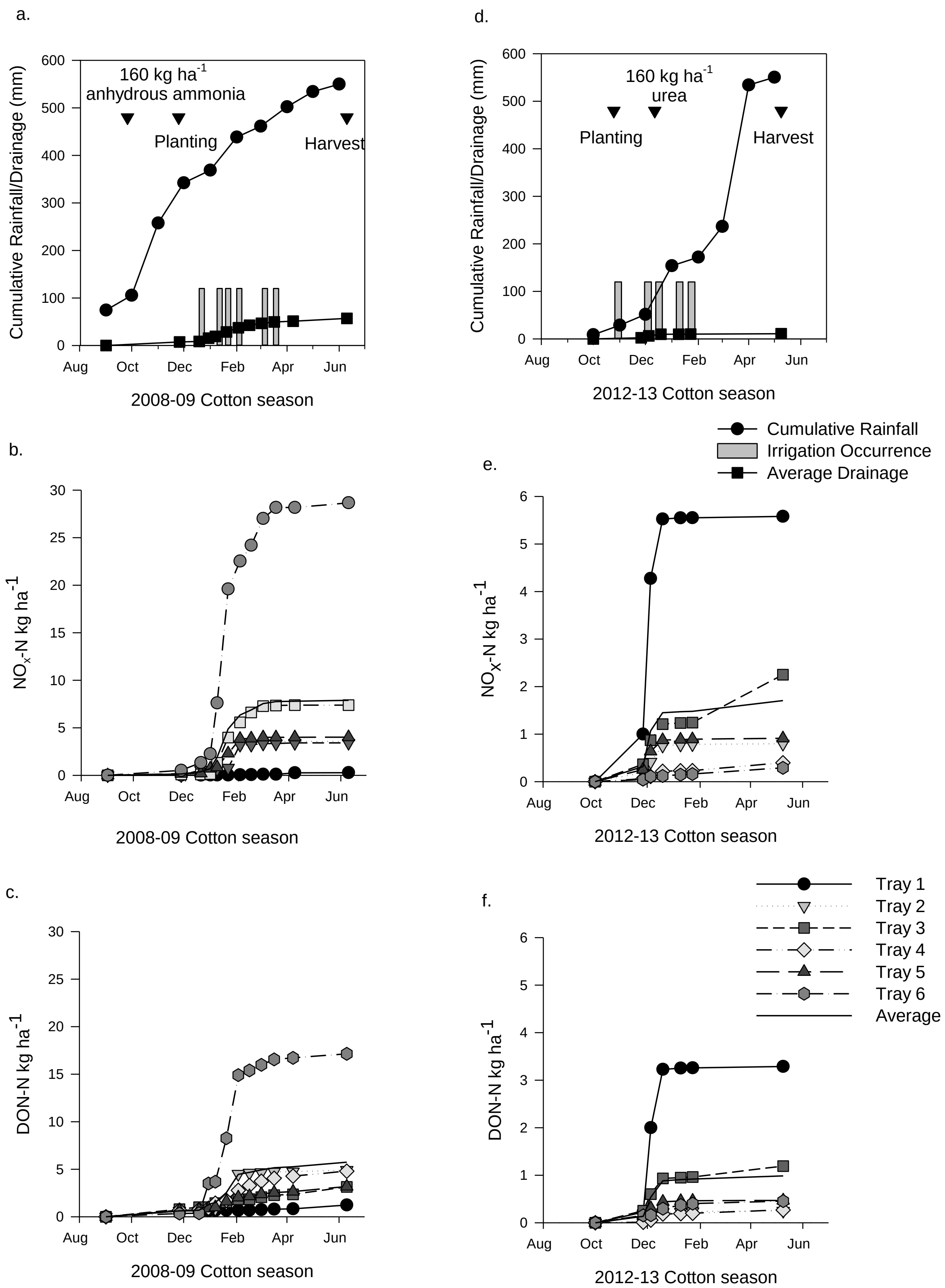

Figure 2.5. Crop operations, cumulative rainfall, drainage and irrigation, tray NO_x-N flux and tray DON N flux for the 2008-2009 (a,b,c) and 2012-2013 (d,e,f) seasons. The inverted triangles indicate the timing of farm operations during the measurement period.

Discussion

Importance of the deep N drainage losses

Only 3 % of the applied fertiliser N was lost to deep drainage, which is significantly less than the measured and estimated atmospheric denitrification losses (Macdonald *et al.* 2015; Rochester 2003). Whilst the loss is small it may have a large cumulative effect on regional aquifer systems over a long time frame. There is some possibility that the upper aquifer in the lower Namoi catchment may have had some nitrate input from irrigated agriculture (Lawrence 1983; McLean 2003) similar to the Texas Rolling Plains, USA, (Chaudhuri *et al.* 2014) and the Burdekin River delta, Australia (Thayalakumaran *et al.* 2008). In 2006 there was 44,000 ha of irrigated cotton (Powell *et al.* 2011) in the lower Namoi. Assuming all this land was managed in a similar way to the cotton crops in this experiment, 946 t N would be lost to deep drainage in the lower Namoi catchment over the five years. It is unclear what is the final fate of the deep drainage losses.

DON-N and NO_x-N flux

Many agronomy, soil and water studies focus only on mineral N despite the organic nitrogen pool being perhaps the single most important soil N pool (Neff *et al.* 2003). In this study, the DON-N flux under vertosols was an important component (40%) of the total N deep drainage flux within the irrigated cotton rotation system. During the cotton season the majority of the NO_x-N and the DON flux occurred earlier in the season; between irrigations 1 and 4, and does not appear to be influenced by fertiliser N timing or product (e.g. Figure 2.5a-b). The crop residue biomass is a significant quantity and approximately contributed 15 t ha^{-1} (Table 2.1) of organic matter, which contributed 330 kg ha^{-1} N. The decomposing residues and organic- N associated with crop residues may have contributed to DON-N fraction in deep drainage and a ^{15}N tracer study in future would quantify the contribution.

The lack of clear inverse relationship between EC, DON-N and NO_x -N, except during the first season of measurement (2008-2009), indicates that the N lost via deep drainage was not solely sourced from the soil matrix but from other sources such as the applied fertiliser and/or nitrogen contained irrigation water. The irrigation water can contain large amounts of N (Hulugalle *et al.* 2012a; Hulugalle *et al.* 2012b; Weaver *et al.* 2013) due to recycling of irrigation tail water, which can supply DON-N and NO_x-N to the drainage water. Also during the drier first season potentially greater oxidation of the soil organic matter occurred due to better aeration of the soil via deep cracking and shrinkage typical of drying cracking clays leading to more DON-N and NO_x-N. These dissolved species were then leached.

The composition of the deep drainage waters in this study were similar to many other natural and modified ecological systems where DON-N has been found to be an important ground water component of the N cycle (Hinckley *et al.* 2001; Kroeger *et al.* 2006; Lorite-Herrera *et al.* 2009) and the dominate N fraction in the soil leachate (Qualls *et al.* 1991). Thus failure to measure and account for DON-N in deep drainage and the soil profile will underestimate the losses and process understanding of the agriculture N budget and inputs into the ground water N budget (Kroeger *et al.* 2006; van Kessel *et al.* 2009).

Inter-annual and intercrop drainage and N-flux variability

The lack of spatial and temporal sampling means that is impossible to statistically examine the significance of the drainage and the flux. During the course of the measurements (2008-2013) there is a reduction in the volume of drainage that was collected by the lysimeter. At this stage it is not clear why there has been a reduction but some possibilities include; increased soil densities and reduction of deep cracking due to increased soil moisture and improved rainfall towards the end of the Millennium drought; soil compaction due to poor soil ripping around the lysimeter; and improved irrigation scheduling. It is clear that relative DON-N and NO_x-N concentrations are similar between 2008-2009 and 2012-2013 seasons but the reduction in drainage reduced the N flux by five times. Therefore irrigators may be able to reduce N loss to deep drainage by improving water use efficiency towards the end of the large scale El Ninõ droughts; when the soil is deeply cracked, large losses of N may occur (See Cotton 2008-2009 in Figure 2.3). During the measurements there was a wet and a dry fallow period (Figure 2.1 and 2.3). During the wet fallow 10 times more N was fluxed from the soil relative to the dry fallow (Figure 2.3). The use of cover crops could reduce N leaching during wet fallows (Dabney *et al.* 2001) whilst maintaining soil health and yield in cotton production systems (Rochester 2011; Rochester *et al.* 2005). In the measurement period, the cotton seasons lost the most amount of N to deep drainage relative to other crops, which indicates there is room for further refinement of fertiliser and irrigation management.

Conclusions

The deep drainage total nitrogen flux was 21.6 kg N ha^{-1} and represents only 3% of the applied N fertiliser (740 kg ha^{-1}) over the five years of measurement. The total flux was composed of 12.8 kg NO_x -N ha^{-1}, 8.7 DON-N and 0.1 NH_4-N kg ha^{-1}. DON is an important component of N lost via deep drainage from irrigated cotton production systems on Vertosols. A strong, inverse relationships between DON-N and NO_x-N concentration and EC during Millennium drought (first year of measurement), indicate that N in drainage was from the soil matrix. After the first year of measurement, the lack of relationship between EC and N concentrations suggests that N in leachate may result from by-pass flow of fertiliser carried in irrigation water, down large cracks. Deep drainage may be influenced longer term antecedent moisture conditions, where long periods of drought cause deep cracking and increased deep drainage and N flux during the irrigation season.

ESTIMATING INDIRECT N_2O EMISSIONS

Potential contributions of surface and ground water to nitrous oxide emissions from irrigated cotton production systems

Introduction

Agricultural N_2O emissions have resulted from increased N fertiliser application. The relationship between agricultural N application and direct N_2O-N flux has been widely studied (Dalal et al., 2003). In cotton production systems, under N rates of 0-320kgN ha^{-1}, between 0.5 to 10 kg N_2O-N ha^{-1} as a direct emission (Macdonald et al., 2015).

Nitrogen losses via run-off (McHugh et al., 2008) and deep drainage (Chaudhuri et al., 2012) can be large (10-20 kg N ha^{-1}). The N which is exported by the irrigation and deep drainage can be transformed into nitrous oxide and emitted to the atmosphere (Harrison and Matson, 2003; Mosier et al., 1998). Large indirect N_2O-N losses from irrigated agriculture systems may also occur as a result of increased N application (Dalal et al., 2003; Scheer et al., 2013).

In Australian cotton production systems, at least 80% of the area is irrigated using gravity surface-irrigation systems (Roth et al., 2013). Indirect N_2O-N, as opposed to directly form the soil surface, can be produced along many stages of the irrigation network (Figure 3.1) and contribute to the total greenhouse gas footprint. No current estimates of indirect emissions from surface and ground water under Australian irrigated production systems exist.

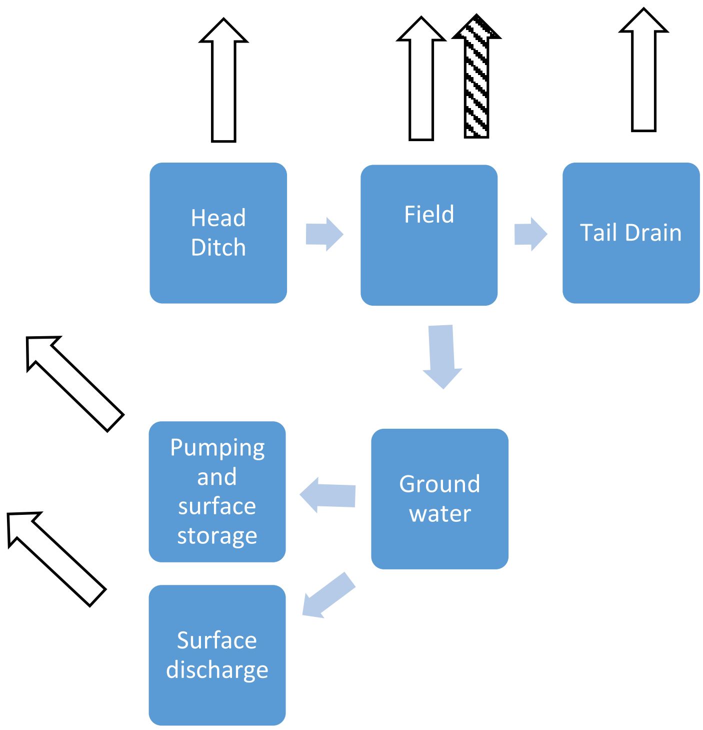

Figure 3.1. Indirect (open) and direct (patterned arrow) emissions from irrigated production systems. Blue arrows represent transfers of N with water.

Methods

Location

The Namoi River catchment, New South Wales, Australia, was used to investigate the potential contributions of surface and ground water to nitrous oxide emissions from irrigated production systems. The catchment is approximately 40,000 km^2, and the Namoi River rises in the Great Dividing Range at elevations over 1000 m, falling to 250 m. The river then flows through sedimentary slopes to the open floodplains in the west. The Namoi catchment is the second largest cotton growing region in Australia, with an average of 68,800 hectares of irrigated cotton grown annually. The Australian Cotton Research Institute (ACRI; 149°27'E 30°18'S) is located within the Namoi Catchment and the climate is semi-arid with a mild winter and a hot summer (Figure 3.2).

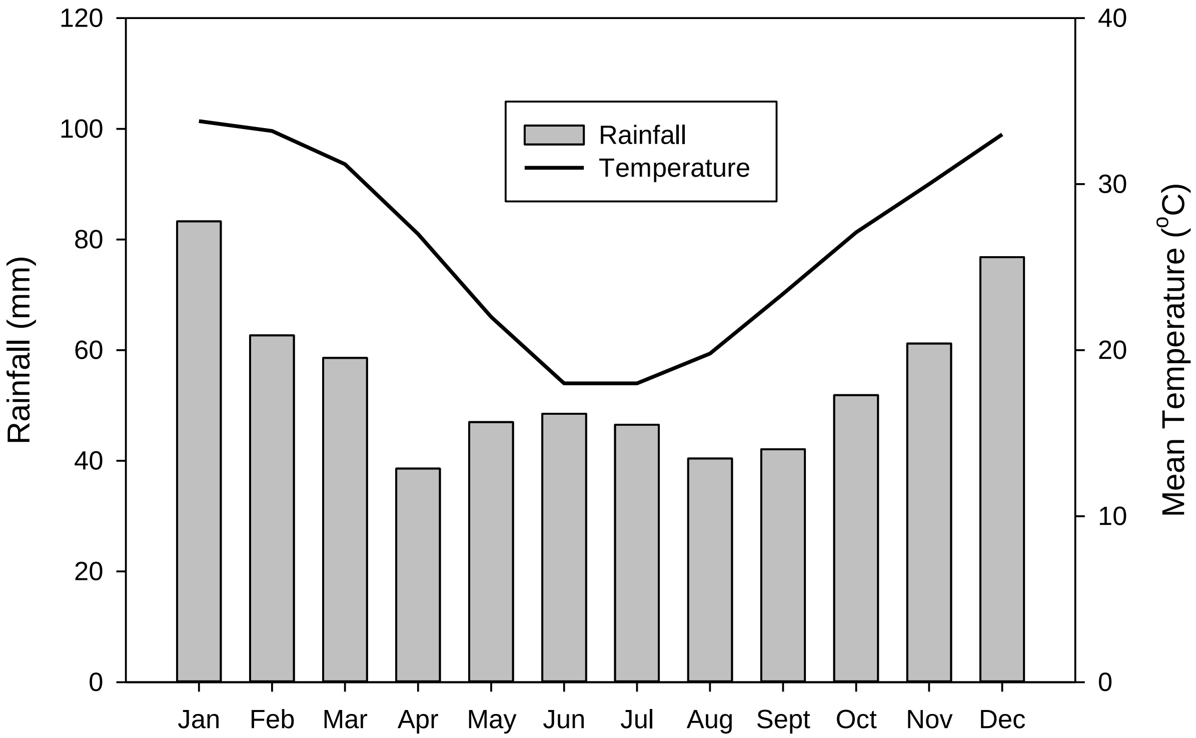

Figure 3.2. Average rainfall and temperature at Narrabri.

Climate data

The average rainfall is 646 mm and is seasonally distributed (Figure 3.2). Summers are hot and irrigation is required to maintain soil moisture and subsequent crop growth. Monthly rainfall data (2000-2010) was sourced from the Australia Bureau of Meteorology.

Ground water quality data

The average nitrate-nitrogen (NO_3-N) and ammonium-nitrogen (NH_4-N) concentration (Table 1) in the lower Namoi catchment was calculated from data collected by McLean (2003). Samples were collected by McLean (2003) after purging bore and NO_3-N (Cadmium Reduction) and NH_4-N (Nessler Method) determined in the field using a Hach DR3000 Field Spectrometer.

Table 3.1. Groundwater nitrate-nitrogen (NO_3-N) and ammonium-nitrogen (NH_4-N) concentration (mg N L^{-1}) within bores from the Namoi Catchment (McLean, 2003).

		Nitrate			Ammonium		
Aquifer	Sample number	Mean	Maximum	Minimum	Mean	Maximum	Minimum
Narrabri	84	1.74	11.62	0.00	0.32	5.12	0.00
Gunnedah	138	1.08	7.63	0.00	0.39	18.06	0.00
Cubbaroo	45	0.82	2.98	0.00	0.33	2.36	0.01

Field Experiment data from the Australian Cotton Research Institute

A series of N and water balance experiments were conducted at the ACRI between 2001-2010 (Hulugalle et al., 2012a; Hulugalle et al., 2012b; Weaver et al., 2005; Weaver et al., 2013) and the irrigation water quality, fertiliser application (Table 2 and 3) and deep drainage data from these studies was used to calculate the potential contributions of surface and ground water to N_2O-N emissions from irrigated production systems. Detailed descriptions of the experimental design, farming systems and environmental characteristic can be found in the above studies and will only be briefly described.

All of the field experiments were undertaken at ACRI. The soils at the site are a self-mulching grey vertisol and are classified as fine, thermic, montmorilonitic, Typic Haplusterts (Soil Survey Staff, 1998). A crop rotation experiment has been undertaken at this site since 1999. The data from 2000-01 and 2002-03 (Weaver et al., 2013) is from the cotton phase of the cotton-wheat rotation. The surface and soil water data from 2005 through to 2011 (Hulugalle et al., 2012a; Hulugalle et al., 2012b) is from all the experiment rotations: continuous cotton (CC), cotton-wheat (CW) cotton-vetch (CV) and cotton-wheat-vetch (CWV).

All of the rotational treatments received additional water during the growing season via furrow irrigation. At the beginning of each season, irrigation water is allocated by the New South Wales government to ACRI from the Namoi River. During the season water is pumped into farm storages and from there it is delivered to the fields by head ditches. After transiting the field, run-off water is returned to the storages via tail drains and stored until it is reused. During irrigations surface water samples were collected and soil water samples were collected at 1.5 m via suction cup samplers. The nitrate content of the irrigation, tail and soil water were measured in the ACRI laboratory using Kjeldahl method. The deep drainage was determined by the chloride mass balance method and each irrigation was applied at 1 ML ha^{-1}.

Table 3.2. Estimation of NO_3-N loading in head ditch water and the potential indirect emissions of N_2O-N from the head ditch and surface water in cotton production systems.

		Head Ditch Water		Surface Water Indirect N_2O emissions*
Data source	Year	NO_3-N (kg ha^{-1})	N_2O-N (kg ha^{-1})	N_2O-N (kg ha^{-1})
Weaver et al (2013)	2000-01	39	0.10	0.13
	2002-03	109	0.27	0.30
Hulugalle et al (2012a)	2005-06	29	0.07	0.10
	2006-07	16	0.04	0.07
	2007-08	36	0.09	0.12
	2008-09	9	0.02	0.05
	2009-10	18	0.05	0.07
	2010-11	0.04	0.00	0.03

* *Tail water nitrate loading assumed to be 11 kg NO_3-N ha^{-1} (McHugh et al., 2008) and this equates to 0.0825 N_2O-N kg ha^{-1}. Surface water indirect N_2O emissions is the sum of the head ditch emissions and 0.03 N_2O-N kg ha^{-1}.*

Tail water quality data

No tail water quality data was reported in the above studies and the only data available for furrow irrigated cotton production systems is McHugh et al. (2008). The McHugh et al. (2008) study was conducted in Emerald, Queensland Australia.

Calculation of direct N_2O-N emissions

The direct N_2O-N emissions from the published field experiments were calculated using the emission factor (Equation 1) from a study conducted at ACRI (Macdonald et al., 2015).

$$N_2O - N\ (kg\ N\ ha^{-1}) = 0.303e^{0.008x} \qquad \text{Eq 3.1.}$$

where x is the kg of N per hectare applied as fertiliser. The direct emission for each year was calculated from the applied fertiliser. This emission factor (Eq 1) is greater than the industry average emission factor calculated by Scherbak et al. (2014).

Calculation of indirect N_2O-N emissions

Land surface

Indirect land surface emissions are produced from the N supplied by the irrigation water to the field. The total land surface emissions were calculated using equation 1 where x is the amount of fertiliser and the mass of N applied in the irrigation water (volume time N concentration) to the field. The indirect land surface emissions (kg N_2O-N ha^{-1}) is the difference between the total N_2O loss and the direct N_2O emission from the fertiliser.

Surface water

Potential indirect N_2O emissions from the surface water (head ditch and tail water) nitrogen concentration within irrigated agricultural systems were calculated using the current emission factor (EF_5; De Klein et al., 2006). The IPCC emission factor for leaching and run-off (EF_5) is 0.0075, which is composed of three components, emission factor for groundwater and surface drainage (EF_{5g} = 0.0025), rivers (EF_{5r} = 0.0025) and estuaries (EF_{5e} = 0.0025) (IPCC 2006). Given water for cotton irrigation usually remains on site, EF_{5G} was used to calculate the indirect emissions. The indirect N_2O-N_{EF5} flux was calculated using the nitrogen flux (kg ha^{-1}) for irrigation and tail water. The regression relationship between rainfall and indirect emissions was determined using SigmaPlot 13.0.

Ground water

Potential ground water indirect N_2O emissions were calculated using the current EF_5 (De Klein et al., 2006) conversion after the water is pumped to the surface. We have assumed that 500 mm of ground water irrigation would be used during years when there is no surface water allocation.

Results

Direct N_2O emissions

The direct grand average annual N_2O-N emission from the applied synthetic fertiliser was 0.9 kg N_2O-N ha^{-1} yr^{-1} and the emission ranged between 0.8 to 1.3 kg N_2O-N ha^{-1} yr^{-1} for the treatments (Table 3). This represents 78% of the total (direct and indirect) average annual N_2O-N emissions. The emissions from wheat and vetch were not included in the analysis because emissions are insignificant relative to the cotton phase due to the relative amounts of the N fertiliser applied (Macdonald et al., 2015).

Indirect Emissions

The combined average indirect annual N_2O-N emission from the land and water surface potentially equates to 21% of the total annual N_2O-N emission. There is a significant relationship ($p < 0.1$) between rainfall and the total indirect emission data (Figure 3.3). This relationship is strongly influenced by the data point below 250 mm.

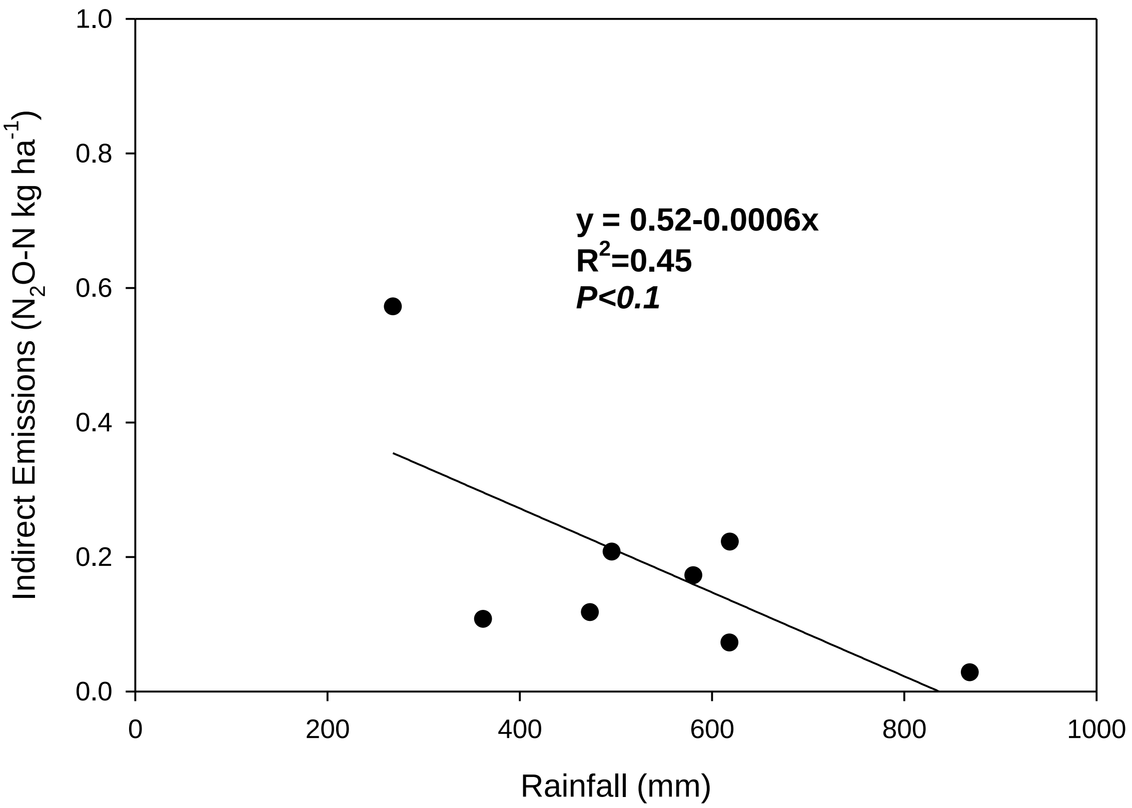

Figure 3.3. Relationship between rainfall and indirect emissions

Surface Water

The NO_3-N supplied to the field by the irrigation water varied each year (Table 3.2) and the indirect emissions from the water surface varied as a result. On average 0.08 kg N_2O-N ha^{-1} yr^{-1} was emitted from surface water within the head ditch. Tail water NO_3-N loading was assumed to be 11 kg N ha^{-1} yr^{-1} based on McHugh et al. (2008) and this equates to 0.0275 N_2O-N kg ha^{-1}. The average surface water emission represents 7.8% of the total (direct and indirect) average annual N_2O-N emissions (Figure 3.4). The McHugh et al (2008) study may not be the best analogue for estimating surface water N loading because of differences in soils and climate between the two locations. Further the use of static value does not account for the annual variation irrigation N concentration, N storage in the crop and the soil. But it is the only currently published Australian furrow irrigation cotton production system study.

Table 3.3. The N fertiliser rate and additional nitrate-nitrogen (NO_3-N) sourced from the irrigation water and the potential direct and indirect N_2O-N emissions (kg N_2O-N ha^{-1}). (CC=continuous cotton; CV=cotton vetch; CW=cotton wheat and CWV=cotton-wheat-vetch).

Season	Fertiliser Rate (kg N ha^{-1} yr^{-1})				NO_3-N sourced from irrigation water (kg N ha^{-1} yr^{-1})				Direct N_2O emissions (fertiliser N) (kg N ha^{-1} yr^{-1})				Indirect Land N_2O emissions (irrigation N) (kg N ha^{-1} yr^{-1})			
	CC	CV	CW	CWV	CC	CV	CW	CWV	CC	CV	CW	CWV	CC	CV	CW	CWV
2000-01*			140				39				0.9				0.3	
2002-03*			150				109				1.0				1.4	
2005-06+	160	80	160	0	29	29	29	29	1.1	0.7	1.1	0.5	0.3	0.1	0.3	0.1
2006-07+	240	80	240	30	16	16	16	16	2.1	0.7	2.1	0.6	0.3	0.1	0.3	0.1
2007-08+	160	100	160	60	36	36	36	36	1.1	0.9	1.1	0.8	0.4	0.2	0.4	0.2
2008-09+	160	80	160	60	9	9	9	9	1.1	0.7	1.1	0.8	0.1	0.0	0.1	0.0
2009-10+	160	120	160	70	18	18	18	18	1.1	1.0	1.1	0.8	0.2	0.1	0.2	0.1
2010-11+	180	120	180	120	0	0	0	0	1.3	1.0	1.3	1.3	0.0	0.0	0.0	0.0
Mean	177	97	169	57	18	18	27	18	1.3	0.9	1.2	0.8	0.2	0.1	0.4	0.1

* Fertiliser and N sourced from irrigation water data based on *Weaver et al. (2005; 2013) and + Hulugalle et al (2012a; 2012b)

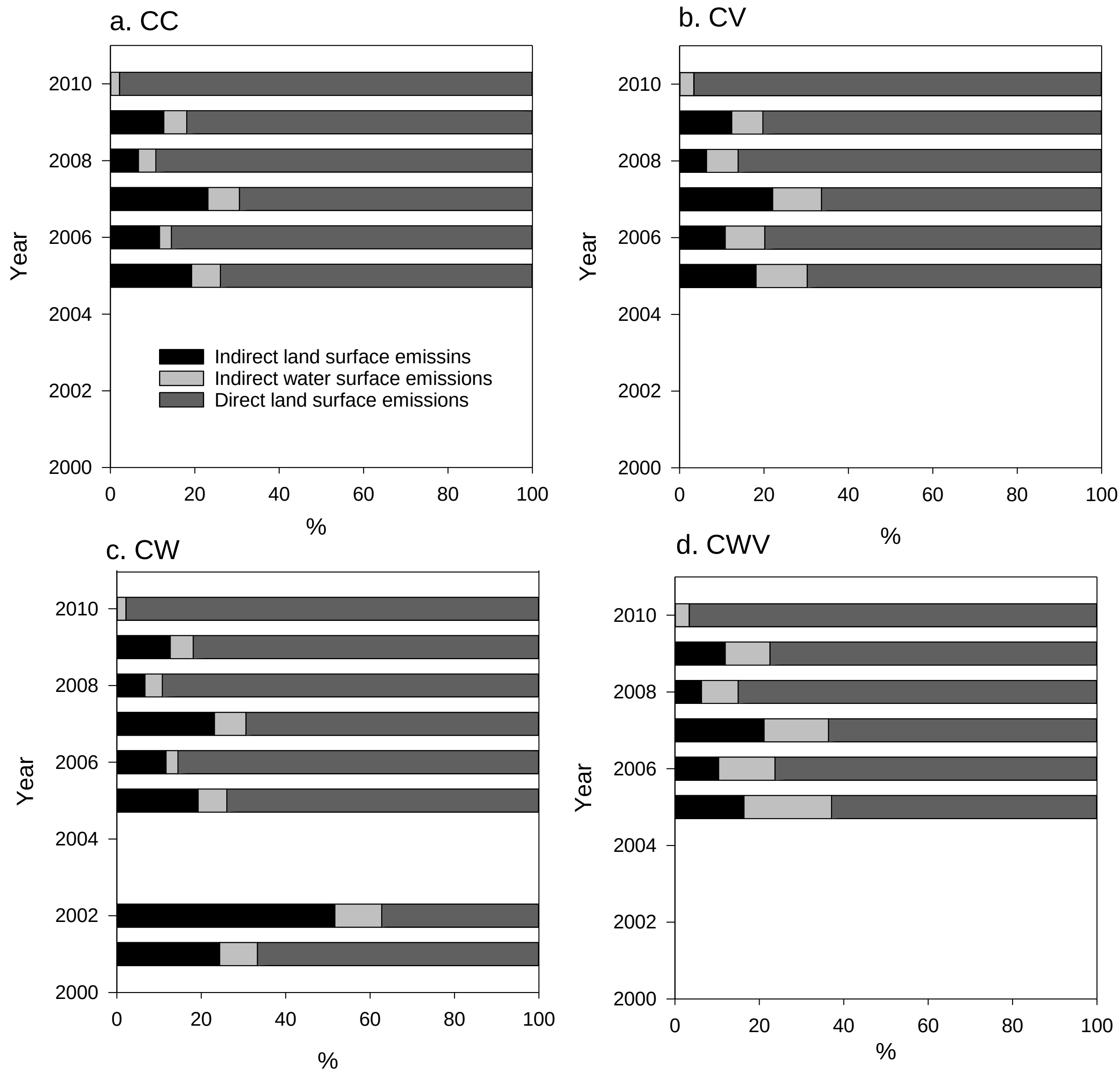

Figure 3.4. The proportional contribution of indirect and direct emission to the total N_2O oxide flux. (CC=continuous cotton; CV=cotton vetch; CW=cotton wheat and CWV=cotton-wheat-vetch).

Land surface

The upper bound indirect average annual N_2O-N emission was 0.18 kg N_2O-N ha^{-1} yr^{-1} and the treatment average ranged between 0.1 to 0.4 kg N_2O-N ha^{-1} yr^{-1} (Table 3.3). The average indirect land surface emission represents 13% of the total (direct and indirect) average annual N_2O-N emissions (Figure 3.4). The lower bound indirect emission calculated by the N remaining in the field (irrigation water N – tail water N kg N ha^{-1}) was 0.1 kg N_2O-N ha^{-1} yr^{-1} and the treatment average ranged between 0.03 to 0.24 kg N_2O-N ha^{-1} yr^{-1}. The average lower bound indirect land surface emission represents 7% of the total (direct and indirect) average annual N_2O-N emissions (Figure 3.4).

Deep drainage and ground water

The deep drainage loss of NO_3-N to below 1.2 m during the 2000-01 season was 61 kg NO_3-N ha^{-1} (Weaver et al., 2005; Weaver et al., 2013). The total NO_3-N deep drainage loss below 1.2 m during from 2004 to 2008 was 31 kg NO_3-N ha^{-1} (Hulugalle et al., 2012a; Hulugalle et al., 2012b). The average annual NO_3-N loss for irrigated cropping production was 20 kg NO_3-N ha^{-1} yr^{-1}, which is approximately 10% of the applied fertiliser. The groundwater bores used in the study were located within the lower Namoi catchment and had an average NO_3-N concentration of 1.2 mg N L^{-1} varying between 0 and 11.62 mg N L^{-1} and an average NH_4-N of 0.3 mg N L^{-1} and varying between 0 and 18.06 mg N L^{-1} (Table 3.1). The indirect N_2O emission of groundwater that has been pumped to the surface can be estimated using EF_5. The potential emissions of the Namoi ground water once it was pump to the surface are 0.004 kg N_2O-N ha^{-1} ML^{-1}.

Discussion

Potential contribution of indirect surface water N_2O-N emissions

The direct emissions accounted for 75-82% of the average total yearly emissions (Figure 3.4). Indirect potential emissions derived from surface waters could contribute on 17-24% of the total N_2O-N kg ha^{-1}. Recent research suggests that the current EF_5 can underestimate indirect emissions by 9-fold (Turner et al., 2015) and there is a degree of uncertainty in regard to this emission factor (Outram and Hiscock, 2012). It is apparent that irrigation industry may contribute N_2O-N kg ha^{-1} yr^{-1} than previously reported (Macdonald et al., 2015). Further measurements are required to quantify indirect emissions spatially and temporally within irrigation production systems. A key limitation is the lack of tail water N concentration data, the water residence times and N_2O production rate. There is a negative relationship between rainfall and indirect emissions (Figure 3.3). During periods when rainfall is within the lower 10 percentile of annual rainfall measured (460 mm) the indirect emissions increase. This relationship is strongly influenced by the data point below 250 mm, but further measurement is required to understand the causation of indirect emissions during such events. During periods of drought similar to this, the allocation of river water to irrigation is reduced. Groundwater, with potentially higher concentrations of N than surface waters may be used to augment water supply which may exacerbate N_2O-N emissions (Table 2; 2002-2003).

Potential contribution of indirect groundwater N_2O-N emissions

Cotton production system during 2001-2010 lost 20 kg NO_3-N ha^{-1} below 1.2m due to deep drainage. It is unclear how much of this NO_3-N reaches the production aquifer but certainly irrigated cropping systems can significantly increase the NO_3-N concentration in the deep unsaturated zone (Silburn et al., 2013) and in the groundwater (Korbel et al., 2013). There is no recorded systematic monitoring of the NO_3-N and total N concentration of the ground water resources within the Namoi Catchment. It is therefore impossible to quantify if the groundwater resource has changed over time due to NO_3-N leaching from irrigated agriculture. Over the last decade there has been improvements in water use efficiency that would have reduced NO_3-N leaching (Silburn et al., 2013). Further reductions in NO_3-N leaching could be achieved by increased nitrogen use efficiency within the cotton production system.

The 2011 cotton grower survey (Roth, 2011) found that irrigated cotton growers applied on average 217 kg N ha^{-1}, which ranged between 30-530 kg N ha^{-1}. Rochester (2011) has shown internal nitrogen use efficiency should be optimised at N fertiliser rate of 220 kg N ha^{-1} and potentially N loss via leaching could be reduced without penalising yield.

The average total concentration of the groundwater is 1.5 mg L^{-1} and if 5 ML of this water is used for irrigation then potentially 0.02 kg N_2O-N ha^{-1} of indirect emission could be produced during storage prior to irrigation. This alone is 2 % of the direct average annual land surface emission (Table 3) and 1.5 % of the total N_2O emission. This is greater than the published rates for natural seepage (<1%, Hiscock et al., 2003) due to the volume of water that is extracted.

Potential Emissions at the ACRI Farm scale

On a typical irrigated farm, the area of land under crops is greater than the water surface area (drains, storages, delivery network). At ACRI there is 188 ha of cropping lands and 13 ha of irrigation system; this ratio would be greater on commercial farms. However on this farm, the average direct and indirect N_2O-N emissions at the farm scale (188 + 13 ha) were 169 kg N_2O-N direct; 56 kg N_2O-N indirect emissions from the land surface; 1 kg N_2O-N from the head ditch; 0.4 kg N_2O-N from the tail drain. In total 26 % of the emissions would be emitted via the indirect pathway at the farm scale. If groundwater with a concentration of (1.3 mg -N L^{-1}) was used to irrigate the crop then a total ~<1% of the emissions would be emitted via the indirect pathway at the farm scale.

Conclusion

Indirect emission, estimated from EF_5, from irrigated agriculture could potentially account for approximately 26 % of the total annual N_2O-N emissions on a per hectare basis. Further measurements are required to refine this estimate. The contribution from indirect emission will be smaller on a farm scale basis due to the larger cropping to irrigation network surface area ratio found on commercial farms. Nitrate loading of the irrigation water and the tail water is a key cause of the indirect emissions. Irrigated cotton production systems also lost 20 kg NO_3-N ha^{-1} yr^{-1} below the crop rooting depth. But due to lack of temporal and spatial groundwater N monitoring it is not possible to determine the fate of the leached N. It is clear for this study that the use of NO_3-N rich groundwater could potentially increase farm indirect emissions on a per hectare basis. Along with improved monitoring of N in groundwater sources, further monitoring and evaluation of field N losses via deep drainage and run-off is required to develop systems to mitigate losses. Direct measurement of the N_2O-N water surface emissions are required to validate the IPCC calculated values.

QUANTIFYING INDIRECT N_2O EMISSIONS

The contribution of the cotton irrigation network to farm nitrous oxide emissions

Introduction

Excess N may be lost from the field via leaching (Benjamin et al. 1998) or run-off into the irrigation system (McHugh et al. 2008). A study from furrow irrigated cotton in Emerald QLD Australia, with 250 kg N ha^{-1} applied, showed average N run-off to be 18.8 and 11.3 kg N ha^{-1} for 2001/2 and 2002/3, respectively (McHugh et al. 2008). In furrow irrigated corn production systems in Iran, NO_3^- run-off ranged from 26-70 N ha^{-1} after application of 60 kg N ha^{-1} (Ebrahimian et al., 2012). Nitrogen species lost via run-off may subsequently undergo denitrification to form N_2O in the water column or drain sediments. Harrison and Matson (2003) have shown with direct measurement average emissions of 0.04 N_2O-N kg ha^{-1} d^{-1} can occur within furrow irrigated wheat production in Mexico.

Indirect N_2O emissions may be a significant component of the total N_2O emissions for Australian cotton systems. Current estimates of indirect N_2O emissions rely on emission factors (EFs), which are based on a bottom-up approach (see Project Background, pages 14-16, for more detail). Based on the NO_3-N losses reported by McHugh et al. (2008) and use of the IPCC EF_{5G}, we might estimate that approximately 0.028 to 0.047 kg N_2O-N ha^{-1} would be produced from furrow irrigated cotton via indirect emissions. The accuracy and precision of these estimates is unknown. Indirect N_2O fluxes from agriculture have not been measured in Australia.

The aim of this study is to 1) quantify indirect N_2O losses and 2) compare indirect to direct N_2O emissions, under an Australian furrow-irrigated cotton farming system.

Methods

Site Description and Sampling Regime

The research was conducted at the Australian Cotton Research Institute (ACRI) located at Narrabri Australia (30° 19′ S 149° 46′ E). The Institute is located at the geographic centre of cotton production in Australia. The soil at this site is a high shrink-swell medium grey clay overlying brown clay and is classified as a fine, thermic, montmorillonitic Typic Haplustert (Soil Survey Staff 2010). Cotton is grown at the ACRI using furrow irrigation and on average the irrigation network contains water for 100 days per year. The irrigation network comprises of storage ponds, supply channels, head (supply) and tail ditches for each field, furrows through the field, main tail drains and return channels (which return water to the storage ponds) (Figure 4.1). Prior to the irrigation season, water is transferred from the river or ground water source to supply channels, and then to head ditches. Water is then supplied to the irrigation furrows via siphon from the head ditches. Once the water has transited the field it empties into the tail ditch and runs off into the main tail drains. The return channel takes the water back to a pump that lifts the water either into the storage ponds or back into the head ditch. The cycling of water around the irrigation network occurs within a 12 hr period, the return water is stored until required for a subsequent irrigation.

Water sampling and measurements were made at the ACRI during the 2013/14 Australian cotton season. Samples were taken over one week periods in October, November and December of 2013. The first three months coincide with land preparation, sowing and fertilising, active growth phase and complete uptake of the fertiliser N by cotton crop and the final crop irrigation. The blocks, field drains, channels and storage ponds throughout the irrigation network, were sampled in triplicate on an ad hoc basis coinciding with the farm irrigation schedule for the sampling period (Figure 4.1).

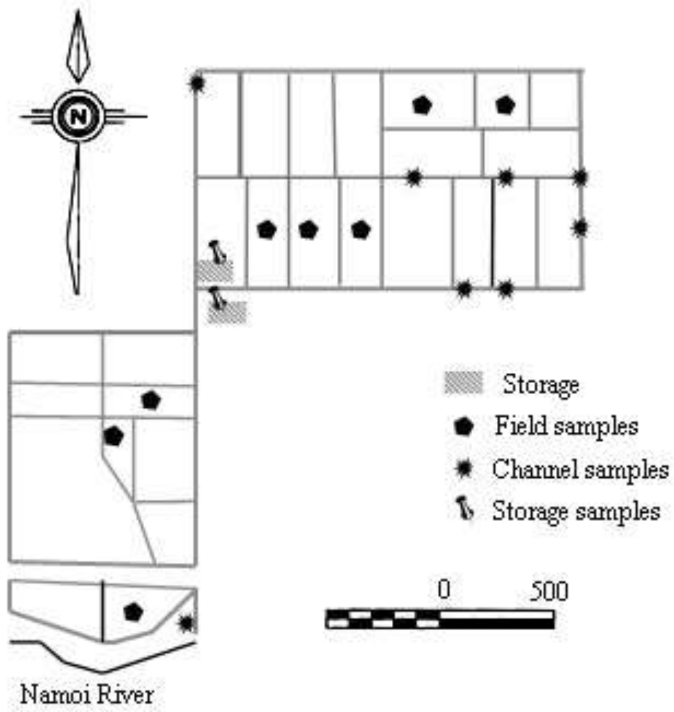

Figure 4.1. The location of water samples (taken throughout the cotton farm irrigation system of the Australian Cotton Research Institute, Myall Vale, NSW, during the first three months of the 2013/14 cotton season. Field water samples were collected at both the tail and head ditches of each field.

Dissolved nitrate, organic nitrogen and nitrous oxide in the irrigation network

In situ electrical conductivity (EC), pH and temperature of the water were measured using a TPS WP-81 field meter. Samples were filtered (0.45 µm) and analysed for nitrate (NO_3-N), total ammonia nitrogen (TAN), total dissolved nitrogen (DTN). Total nitrogen (TN) was determined on unfiltered samples, N>45 equates to TN-DTN. Nitrate-N and TAN were measured using the cadmium reduction method (Method 4500 Nitrate) and automated phenate method (Method 4500 Ammonia G), respectively (Rice et al. 2012). TN and DTN samples were digested using the persulphate method (Method 4500-N) and the NO_3-N concentration in the digest was measured using the cadmium reduction method (Rice et al. 2012). Dissolved organic nitrogen (DON) was determined by subtracting mineral N (NO_3-N and TAN) from the TDN. The calculated DON values, except for 6 samples (mean= -0.2; S.E=0.03) were always greater than 0. After sampling, water samples were stored at 4°C, and analysed within 4-7 days of collection. The detection limit of the NO_3-N and TAN analysis was 0.02 mg N L^{-1}

Dissolved N_2O-N_d concentrations were determined using the headspace equilibrium technique (Weiss & Price 1980; Roper et al. 2013). Briefly, during field sample collection 6 mL of unfiltered sample water was injected into an evacuated 12 mL Exetainer and stored between 2-4°C, returned and analysed in the laboratory within 4-7 days of collection. It has been shown that after 12-48 hours (Harrison and Matson 2003) that there is limited consumption or production of N_2O. However at the longer storage times used in this study there may have been some consumption or production of N_2O but it is expected to be limited because at temperatures below <4°C de-nitrification is limited (Nowicki 1994). Prior to analysis, samples were allowed to warm to room temperature (~ 25°C) and 10 mL of He was injected into each Exetainer. The N_2O concentration of the headspace was then measured using a Shimadzu 2014-GC fitted with an ECD. The temperature of the lab was recorded during sample analysis using an EL-USB-2 data logger and used to calculate the N_2O-N_d concentration in the analysed water sample using the approach of Weiss & Price (1980) and Roper et al. (2013).

Nitrous Oxide Emissions: Direct (terrestrial cropping area) and indirect (irrigation network) N_2O emissions

To enable the comparison of the direct and indirect emissions the report fluxes are relative to the source. Thus the direct emissions are the function of the hectares of land surface and the indirect emissions are in terms of the hectares of irrigation network.

Direct (terrestrial cropping area) N_2O emissions

Direct (or terrestrial) N_2O emissions were calculated from the equation of Macdonald et al. (2015).

$$\mathrm{N_2O - N\ (kg\ N_2O\ ha^{-1}) = 0.891 * e^{(0.005x)}} \qquad \text{Eq 4.1}$$

where x is the fertiliser rate and in this case the average rate was 200 kg N ha^{-1}.

Indirect (irrigation network) N_2O emissions

The N_2O flux from the irrigation network surface (13 ha) was calculated using a) dissolved N_2O concentrations (Cole & Caraco 2001; Clough et al. 2007) and b) IPCC emission factors (IPCC 2006).

a) Dissolved N_2O method (N_2O-N_d):

Indirect nitrous oxide fluxes were estimated from dissolved N_2O-N_d concentrations according to equation 4.2:

$$\mathrm{N_2O - N_{df}}\quad (\mathrm{\mu mole\ m^{-2} d^{-1}}) = k_{\mathrm{total}} * \left(\mathrm{N_2O - N_{d_{(water)}} - N_2O - N_{d_{(eq)}}}\right) \qquad \text{Eq 4.2}$$

Where N_2O-$N_{d(water)}$ (µmol m^{-3}) is the measured concentration of N_2O in the water, N_2O-$N_{d(eq)}$ (µmol m^{-3}) is the concentration the water would have if it were in equilibrium with the atmosphere N_2O concentration and *k* is the gas transfer coefficient (m s^{-1}) (Cole & Caraco 2001; Clough et al. 2007).

The gas transfer coefficient, k_{total} (m s^{-1}) was calculated as the sum of the transfer velocities attributed to wind (k_{wind} m s^{-1}) and water (k_{water} m s^{-1}) speed; and were calculated using equations 4.3 and 4.4 (Clough et al. 2007; Wanninkhof 1992).

$$k_{wind} = 0.31{u_{10}}^2 \left(\frac{Sc}{660}\right)^{0.5} \quad 4.3 \quad \text{and} \quad k_{water} = \sqrt{\frac{DU}{h}} \quad 4.4$$

Where u_{10} (m $^{s-1}$) is the windspeed at 10 m above the height of the water body, *Sc* is the Schmidt number for N_2O (dimensionless), *D* is the temperature and salinity dependent diffusion coefficient of N_2O in water (m^2 s^{-1}), *U* is the velocity of water (m s^{-1}) which was measured using OTT Flow meter and *h* is the average depth of the water body (m). Where water speed was unavailable, k_{wind} was used instead of $k_{total.}$

The wind speed at 10 m height was calculated from measured wind speeds (ACRI weather station) using the logarithmic wind profile law (equation 5):

$$\frac{U_1}{U_2} = \ln\left(\frac{Z_1}{Z_2}\right) \div \ln\left(\frac{Z_2}{Z_0}\right) \quad 4.5$$

where Z_0 is the 'effective roughness height', here assumed to be 0.001m, and U_1 and U_2 are the respective wind speeds (m s^{-1}) at heights Z_1 and Z_2, respectively (Kubik et al. 2011). *Sc* and *D* were calculated in R, using the package 'marelac' from measured water salinity and temperature and atmospheric pressure (R Core Team 2014; Soetaert et al. 2014).

The average daily N_2O-N_{df} flux (kg N_2O-N m^{-1} ha^{-1}) was calculated using equation 4.2. During the irrigation season the number of days the irrigation network contains tail water is approximately 15 days.

b) IPCC EF_5 method (N_2O-N_{EF5g}):

The default IPCC emission factors for leaching and run-off (EF_5) of 0.0075, which is composed of three components, emission factor for groundwater and surface drainage (EF_{5g} = 0.0025), rivers (EF_{5r} = 0.0025) and estuaries (EF_{5e} = 0.0025) (IPCC 2006). Given that water for cotton irrigation usually remains on site, the EF_{5g} was used to calculate the indirect emissions using equation (7). Where $\overline{TN}$ is the average concentration of total N in the tail and main tail drain water during each of the first four irrigations (mg L^{-1}), v is the volume of water discharging the field per irrigation (assumed to be 250 000 L ha^{-1} which is 25% efficiency of a 100 mm application), n is the number of irrigations within the month, EF is the emission factor, and A the surface area of the irrigation network (here, 13 ha) and B irrigation area (here, 188 ha).

$$N_2O - N_{EF5g}\, kg\, N_2O - N\, ha^{-1} = \overline{TN} \times v \times n \times EF_5 \div A * B \quad 4.7.$$

All indirect losses are reported on water surface area and the direct emissions on land surface area.

Data analysis

All analyses were performed in R (R Core Team 2014). ANOVAs were used to examine influenced by location and sampling time on the measured parameters (EC, pH, TN, NO_3, and dissolved N_2O-N) using the following model

$$\text{Water chemistry} = \text{Location} + \text{Sampling Time}$$

Linear regression was used to determine a) the relationship between N_2O concentration and the other water chemistry parameters, and b) the relationship between the two different methods used to calculate indirect N_2O emissions. Where data did not meet assumptions of equal variance, generalised least squares procedures (using the 'nlme' package) were used as an alternative (Hay-Jahans 2011; Pinheiro et al. 2015).

Results

Water chemistry: EC, pH and nitrogen species in the irrigation network

There was a significant effect of location and month on the distribution of EC, pH, TN and NO_3-N of the water sampled (Table 4.1-4) Values of EC, TN, NO_3-N, DTN, N>45μm all increased after the irrigation water transited through the field. Conversely the pH of the water decreased during the transit (Table 4.1). Throughout the season the concentrations of the different N species followed a similar pattern with EC, TN, NO_3-N, DTN and DON peaking during December. The water chemistry of the tail water shows that the concentration of N in the DON fractions is often as large as the NO_3-N fraction (Tables 4.1 and 4.2; Figure 4.2). There was a positive correlation between EC and nitrate concentration of the discharge water ($p<0.001$ $r^2=0.51$).

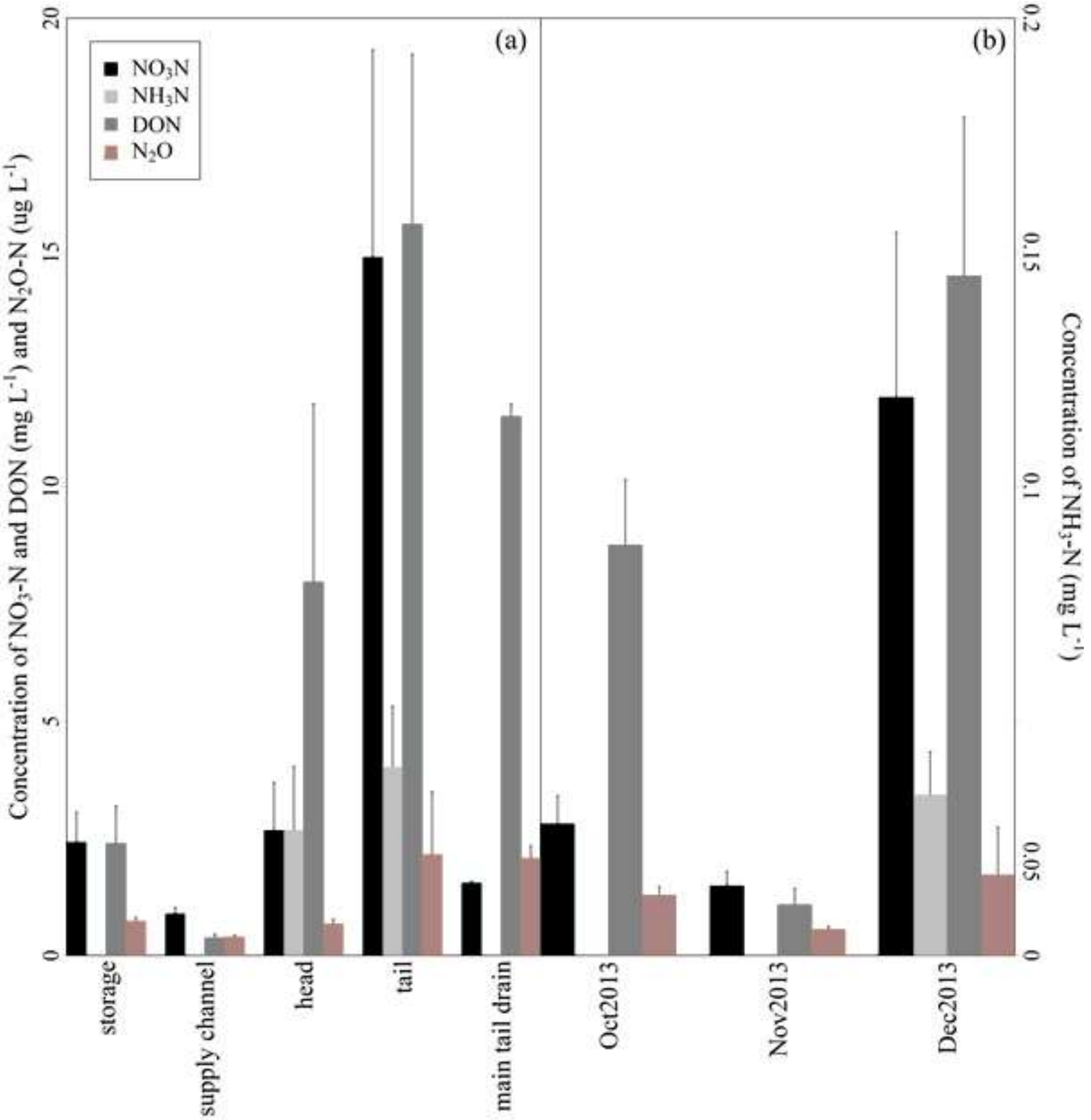

Figure 4.2. The concentration of various nitrogen components throughout (a) the irrigation system, and (b) at different time periods throughout the 2013/14 Australian cotton season, Australian Cotton Research Institute, Myall Vale, NSW. NH_3-N data was unavailable for the months of Oct and Nov 2013, and from the storages, supply channel and main tail drain locations.

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*Table 4.1. The pH, EC (µS cm^{-1}), and concentrations of various nitrogen species (mg L^{-1}) and dissolved N_2O (µg L^{-1}) (reported as mean and standard error) in water samples collected at different locations throughout a cotton farm irrigation system at the Australian Cotton Research Institute, Myall Vale, NSW, during the 2013/14 cotton season. * indicates where chemistry significantly differed between location of sampling. No analysis was undertaken for NH_3*

	***EC (µS cm^{-1})**	***pH**	***Total N (mg L^{-1})**	***NO_3^--N (mg L^{-1})**	**NH_3-N (µg L^{-1})**	***DTN (mg L^{-1})**	***DON (mg L^{-1})**	***N>45um (mg L^{-1})**	***Dissolved N2O-N (µg L^{-1})**
Storage	622 ± 40.5 (n=7)	8.67 ± 0.152 (n=7)	4.82 ± 0.272 (n=6)	2.42 ± 0.635 (n=6)	-	4.19 ± 0.179 (n=6)	2.39 ± 0.8 (n=6)	0.625 ± 0.132 (n=6)	0.73 ± 7.73e-02 (n=6)
Supply Channel	479 ± 24.9 (n=10)	8.74 ± 0.078 (n=10)	1.15 ± 0.121 (n=9)	0.895 ± 0.124 (n=10)	-	1.12 ± 0.149 (n=9)	0.373 ± 0.0821 (n=9)	0.133 ± 0.0492 (n=9)	0.395 ± 4.53e-02 (n=8)
Head	494 ± 19.9 (n=17)	8.6 ± 0.041 (n=17)	10.6 ± 4.14 (n=16)	2.67 ± 1.02 (n=16)	26.7 ± 13.6 (n=13)	9.83 ± 4.43 (n=13)	7.97 ± 3.8 (n=16)	2.57 ± 0.881 (n=16)	0.672 ± 9.5e-02 (n=16)
Tail	847 ± 94.9 (n=22)	8.28 ± 0.0368 (n=22)	30.4 ± 7.47 (n=22)	14.9 ± 4.42 (n=22)	40.1 ± 13.1 (n=16)	28.3 ± 7.33 (n=19)	15.6 ± 3.63 (n=22)	5.85 ± 1.29 (n=22)	2.15 ± 1.34 (n=22)
Main Tail Drain	718 ± 20.8 (n=3)	8.1 ± 0.04 (n=3)	13.1 ± 0.251 (n=2)	1.55 ± 0.0408 (n=3)	-	-	11.5 ± 0.265 (n=2)	12.5 ± 0.24 (n=2)	2.07 ± 0.267 (n=2)

*Table 4.2. The pH, EC (µS cm^{-1}) and concentration of various nitrogen species (mg L^{-1}) and dissolved N_2O (µg L^{-1}) in water samples collected at different sampling times across the cotton farm irrigation system at the Australian Cotton Research Institute, Myall Vale, NSW, during the 2013/14 cotton season. * indicates where chemistry significantly differed between time of sampling. No analysis was undertaken for NH_3.*

	***EC (µS cm^{-1})**	***pH**	***Total N (mg L^{-1})**	***NO_3^--N (mg L^{-1})**	**NH_3-N (µg L^{-1})**	***DTN (mg L^{-1})**	***DON (mg L^{-1})**	***N>45um (mg L^{-1})**	***Dissolved N_2O-N (µg L^{-1})**
Oct-13	656 ± 25.2 (n=11)	8.32 ± 0.0881 (n=11)	11.9 ± 1.56 (n=8)	2.81 ± 0.593 (n=10)	-	-	8.76 ± 1.39 (n=8)	11.3 ± 1.48 (n=8)	1.29 ± 0.183 (n=8)
Nov-13	546 ± 24.4 (n=18)	8.73 ± 0.0647 (n=18)	2.44 ± 0.423 (n=18)	1.49 ± 0.3 (n=18)	-	2.17 ± 0.359 (n=18)	1.08 ± 0.347 (n=18)	0.319 ± 0.0722 (n=18)	0.556 ± 5.85e-02 (n=17)
Dec-13	709 ± 78.9 (n=30)	8.4 ± 0.04 (n=30)	26.4 ± 6.17 (n=29)	11.9 ± 3.53 (n=29)	34.1 ± 9.36 (n=29)	22.8 ± 5.3 (n=29)	14.5 ± 3.39 (n=29)	3.57 ± 0.867 (n=29)	1.72 ± 1.02 (n=29)

Table 4.3. Pair-wise comparisons, using Tukey HSD, for water chemistry components between each of the different irrigation network locations sampled at Australian Cotton Research Institute, Myall Vale, NSW. Water chemistry components shown are significantly different between each pair of locations. DTN measurements were not available for the main tail drain.

Location	Storage	Supply Channel	Head	Tail
Supply Channel	TN, DTN, N45	-	-	-
Head	N45	N45	-	-
Tail	TN, DTN, DON, N45	EC, pH, TN, NO3N, DTN, DON, N45	pH, EC, N45	-
Main Tail Drain	TN, DON, N45	EC, pH, TN, NO3N, DON, N45	pH, EC, N45	N45

Table 4.4. Pair-wise comparisons, using Tukey HSD, for water chemistry components between each of the different sampling times at Australian Cotton Research Institute, Myall Vale, NSW. Water chemistry components shown are significantly different between each pair of sampling times. DTN measurements were only available for Nov-13 and Dec-13 sampling events.

Time	Oct-13	Nov-13	Dec-13
Oct-13	-	-	-
Nov-13	EC, pH, TN, DON, N45, N_2O	-	-
Dec-13	TN, NO3N, N45	EC, pH, TN, NO3N, DTN, DON, N45	-

Dissolved N_2O-N Concentration

Dissolved N_2O-N_d concentrations followed a similar pattern to that of the other N species, with time of different sampling and locations, but concentrations were highly variable. Differences in N_2O-N_d concentration due to location or sampling time were not significant (Tables 1-3) despite dissolved N_2O-N concentrations tending to increase in the tail ditch and the main tail drain. Average concentrations of dissolved N_2O-N_d ranged from 0.395 ± 0.045 µg L^{-1} (supply channel) to 2.15 ± 1.34 µg L^{-1} (tail drain) in the irrigation network for the three months of measurement.

Indirect N_2O Emissions

N_2O-N_d: The cumulative N_2O-N loss 0.503 ± 0.338 kg ha^{-1} from irrigation water surface during the first four irrigations between October and December 2013 0.503 ± 0.338 kg ha^{-1} (Table 5).

N_2O-N_{EF5}: Average total N concentrations for water sourced from tail ditches and main tail drains over the 4 irrigation was 28.96 ± 6.903 mg L^{-1}. This corresponded to a cumulative N_2O-N emission of 0.843 ± 0.022 kg ha^{-1} from the irrigation water surface and represents a field leaching loss of 23.31 ± 0.61 kg N ha^{-1} during the first four irrigations between October and December 2013 (Table 5).

There was a strong, positive linear relationship between monthly N_2O flux calculated using the IPCC EF_{5g} and dissolved N_2O methods ($p<0.05$, $R^2=0.99$). However, the disparity between the two methods increased with higher N_2O emissions; and total N_2O emissions estimated using the IPCC method was 46% higher than under the dissolved method.

Land surface direct N_2O-N emissions

During the cotton season, direct emissions of N_2O-N from the land surface were (on average) 16 g N_2O-N ha^{-1} d^{-1} (Macdonald et al. 2015). The cumulative direct N_2O-N emission off the entire cotton farm, over the season (150 days), was 2.42 kg N_2O-N ha^{-1}. During the period of indirect measurements (90 days) the direct N_2O-N emissions off the cotton farm were 1.45 kg ha^{-1}.

Discussion

EC, pH, dissolved nitrate, organic nitrogen in the irrigation network

The water chemistry of irrigation water was modified during its transit through the cotton field (Table 4.1). Nitrate and DON were the main components of total N present in the irrigation water (Figure 4.2), and both N species were lost from the cotton field (Table 4.1). The measured NO_3^-N concentrations are similar to studies within the Australian cotton industry (McHugh *et al.* 2008; Weaver *et al.* 2013) and other irrigated cropping systems (Harrison *et al.* 2005). Salt and other nutrients accumulate as a result of evaporation from the furrow surface (Noborio & McInnes 1996), and are remobilised during the first flush at the beginning of an irrigation. Irrigated furrows were less saline than non-irrigated furrows; suggesting that movement of water from irrigated to skip furrows transits through the adjacent hill removing salts and N, which are then lost via run-off (Figure 4.3). The differences in the N concentrations between the sampling events (Table 4.2) are likely due to the mineralisation or organic N within the hill releasing ammonium and NO_3^--N which can be mobilised by the irrigation water.

Further, we observed that there was significant variation in the water N concentration during irrigation and between irrigations. The soil physical and moisture characteristics also vary within each furrow and mound and as a result the irrigation water and dissolved N compounds will transit through the soil at different rates. It is evident from the measured concentrations that the flux of DON pool must be as important as the NO_3^--N in the measured furrow irrigated system (Table 4.1 and 4.2). The DON is being sourced from the mound as the water passes through from the irrigated furrow to the skip furrow. DON like NO_3-N can undergo transformation and conversion into N_2O-N_d in the water column and on the sediment surfaces (Nevison 2000; Tiedje et al., 1982). All N species lost into the irrigation system can potentially undergo subsequent transformations to form N_2O-N_d within the water column and drain sediments (Nevison 2000; Harrison & Matson 2003).

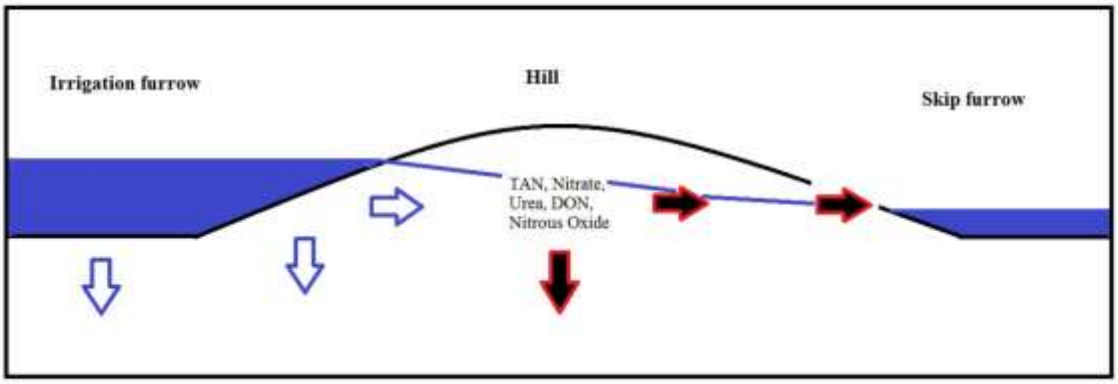


Figure 4.3. A schematic showing the movement of water without (white fill) and with fertiliser nitrogen (black fill) compounds from the hill to the skip furrow.

Dissolved N_2O-N_d

The dissolved N_2O-N_d in irrigation water may be sourced from N_2O produced within the field, or from subsequent denitrification or nitrification reactions in the water column. Irrigated cotton fields provide optimal conditions for denitrification including microbial available carbon, nitrate and anaerobic environment. The much lower dissolved N_2O-N_d concentrations in our study compared to other studies (Harrison et al., 2005; Outram & Hiscock, 2012) are likely due to the fact that the fields are irrigated when there is a 75 mm water deficit in the soil profile. At such water contents the formation of N_2O in the surface soil would be negligible (Weier et al., 1993; Davidson et al., 2000) and the measured terrestrial atmospheric flux rates in cotton systems at these soil moistures are small relative to after emissions that occur after the irrigation has ceased (Mahmood et al., 2008; Scheer et al., 2013;). There is no pool of N_2O-N to move from the soil during the irrigation and typically denitrification and N_2O-N emissions occurs 1 or 2 days are the irrigation has ceased. Further our site is located in a semi-arid irrigated cropping region of Australia whereas many of the other indirect emissions studies were conducted in areas of higher rainfall (Outram and Hiscock 2012; Risk et al., 2013; Kaushal et al., 2014) which are more conducive to shallow ground water fluxes of dissolved N_2O-N_d.

There was no relationship between dissolved N_2O-N_d and the other N components. This is in contrast to a number of studies that have demonstrated a relationship between N_2O-N_d and NO_3-N concentrations (Beaulieu & Arango 2009; Beaulieu et al. 2011; Harrison & Matson 2003; Reay et al. 2005; Warneke et al. 2011), and NH_4^+-N concentrations (Xia et al. 2013). Water in the cotton irrigation system is transient, with water only retained for a short period of time, due to the cessation of irrigation once mounds are "wet up" and short field lengths (less than 500 m). There is also no lateral ground water discharge into the canals.

Run-off from the cotton field at the ACRI experimental farm is negligible within 12 hours of the start of the irrigation, however on commercial farms, field irrigations occur over longer time frames due to the field length exceeding 1000 m. Increasing contact time between water and the soil surface could maximise N_2O-N_d production from total N in the irrigation tail water. Further indirect N_2O emissions, resulting from N loading in the irrigation water, may continue downstream (e.g. in storage ponds) and as the irrigation networks dry down, neither of which were measured in this study.

Indirect N_2O-N Emissions: N_2O-N_{df} and N_2O-N_{EF5G}

There was a strong positive relationship between the two methods used to calculated monthly N_2O flux. Whilst both methods gave estimates of N_2O emissions within the same order of magnitude, the IPCC method returned an emission rate 65% greater than that calculated using the dissolved N_2O-N_d method. Differences between the dissolved N_2O and IPCC methods may have occurred due to the N_2O-N_d method underestimating amounts of N_2O-N produced from the water surface. Alternatively, there are uncertainties associated with the current IPCC EFs for indirect emissions. Although the current EFs have been reduced from previous estimates, due to large discrepancies between measured and IPCC estimated fluxes (Clough et al. 2007; Reay et al. 2005; Nevison 2000), the range of uncertainty for EF_5 is still large, from 0.0005 to 0.025 (IPCC 2006).

European measurements form much of the basis for the IPCC EFs (Reay et al. 2012). Use of local emission factors, or models which account for local climatic conditions, soil characteristics and land management, will then reduce the uncertainty in flux estimates (Reay et al. 2012). A definite need exists to better quantify and understand the processes controlling indirect N_2O emissions within the Australian cotton industry. This in turn will provide a better platform for policy decisions and discussions for potential mitigation strategies.

Magnitude of indirect emissions

The irrigation network area relative to the cropping area on a typical irrigated cotton farm may only represent 6.5% of the farm area. Despite a comparable flux rate on the hectare basis relative to the direct land surface emissions, at the farm scale the indirect emissions are a minor component of the N_2O inventory. The indirect emissions estimated by both methods, from the whole farm, were approximately 2.4-4 % the magnitude of direct land surface emissions and less that 0.02% of the applied fertiliser (260 kg ha^{-1}) to the farm. These are similar to the values reported by Harrison et al. (2005) for furrow irrigated wheat production in Mexico.

Sampling and measurement of indirect emissions

A key issue in determining the indirect emissions on a per hectare basis is the accurate quantification of the fate of the water within the irrigation network. The tail water in semi-arid irrigated cotton systems is typically recirculated and re-used on-farm. Tail water is returned to the farm storage, stored briefly (24 hrs) and mixed with river or ground water and returned to the fields for the next field irrigation. The duration and location of the tail water storage will change during each day of the irrigation period due to farm watering requirements. We have assumed that the indirect emission is mainly sourced from the tail water due to the N loading from the field and is equally spread across the irrigation network.

In this study, point measurements of N components and N_2O only occurred during the time frame for an irrigation (<12 hrs), and were concentrated at the cotton field. During this time N that has been leached from the fields may be transformed into N_2O, NO_x or N_2 in the storage ponds and either emitted or assimilated in the water column or in the drain sediments. Secondly, whilst many indirect emission studies have focused on the emissions of N_2O from the water surface, there may also be significant amounts of N_2O emissions from the sediments once the canals are drained. It has been shown that sediments can sequester NO_3^--N from the water column (García-García & Gómez 2009), which could lead to significantly greater indirect emissions, if irrigation water is allowed to pond and is not re-used. The complexity of these biogeochemical pathways would explain the large uncertainties associated with estimating N_2O emissions using dissolved N_2O-N_d concentrations.

Reducing indirect N_2O emissions

The key to reducing indirect N_2O-N emissions from cotton irrigation networks is to control the N supply to the irrigation water. Improvements in water and N use efficiency would reduce the export of total N and hence lower the potential for indirect and N_2 emissions.

Indirect N_2O-N emissions may be reduced by maximising the use of plant available N already present in the water. The tail water contains large amounts of dissolved N which could be used to fertilise adjacent fields. Reducing water return times to the field is likely to increase the amounts of N that can be re-used, however a better understanding of the rates of transformation is required for optimisation of N recycling in the cotton irrigation network.

Conclusions

Estimates of N_2O emissions from the surface waters of a cotton irrigation network are now possible. The N concentrations of N_2O-N_d and N_2O-N_{EF5g} are 0.503 ± 0.338 and 0.843 ± 0.022 kg ha^{-1} irrigation surface, respectively over 90 days. Overall the indirect emissions from the surface of the irrigation network are not a significant component of the N_2O inventory for Australian cotton systems because the irrigation network covers only a small area relative to the entire land surface of the farm. The measurement of indirect emissions from irrigated cotton production is not straight forward due to the ad-hoc re-use and storage of water. Additional N_2O emissions are likely to occur downstream of the field within storages and main tail drains, during the irrigation season and as the channels dry down. Nitrogen fertilisation due to the re-use of drainage water and subsequent field N_2O-N emission could also contribute to indirect emissions. Overall the EF_{5g} and the N_2O-N_d indirect flux estimation method were in agreement and the EF_{5g} could be used to estimate indirect fluxes provided local calibration was undertaken. The irrigation network is a prime mitigation target for minimising losses of dissolved N components via denitrification. Rapid re-use of N enriched tail water, reducing N loss via run-off, and improving water and N use efficiency are potential methods to reduce N losses.

Estimating indirect nitrous oxide emissions from stored irrigation water

INTRODUCTION

We previously found that whilst concentration of dissolved inorganic nitrogen (DIN) in the irrigation water from tail drains was high, concentrations of dissolved N_2O-N remained low. (see pages 52-64). N_2O present in the water may originate from dissolved N_2O produced in field soils (Reay et al. 2004b) or from production within the sediments or water column of the irrigation network. Therefore measurements of dissolved N_2O, and estimated flux from waterbodies with a short residence time, (e.g. tail drains) are unlikely to correlate to water chemistry parameters associated with N_2O production. Production of N_2O0N from other N species could occur downstream in storage dams and the main channel. We thus decided to focus our measurements on N_2O emissions on from water storages. Whilst the amount of water within the storage changes, and movement in and out of the storages occurs regularly throughout the season, the storage never dries-down.

The aims of this study were to:

1. Quantify the magnitude of indirect N_2O emissions from irrigated cotton agriculture. In our previous study we based estimates of indirect N_2O emissions on the dissolved N_2O methods (see pages 52-64). Another method commonly used to measure indirect emissions is floating chambers. In this study we used both methods to measure N_2O flux rates.

2. Compare measured emissions to those estimated using current IPCC methodology.

3. Examine the relationship between N_2O emission rates and various physicochemical parameters associated with N_2O production.

MATERIAL AND METHODS

Site Description

We undertook the research at the Australian Cotton Research Institute (ACRI), Narrabri NSW Australia (30° 19′ S 149° 46′ E). A description of the site can be found in the previous section (pages 52-64).

Cotton production and irrigation

Nitrogen application occurred over two intervals. The first, and greatest, application of urea occurs just prior to sowing in October. Urea may be drilled or broadcast. The second application of urea is applied mid-season, around January, and is applied by broadcasting pellets. Nitrogen application rates were approximately 200 $kgNha^{-1}$.

Sources of irrigation water come from river and/or groundwater allocations. During the 2015/16 season all irrigation water was groundwater. Water from the bore or storage dams reaches the plot via a network of supply channels. The water is supplied to the plot furrows via siphons and transits down the plot until it is discharged at the tail end. Tail water is then returned to the storages via a network of return channels. Movement of water through the whole irrigation system occurs within a 12 hour period. Water in plots is transient, but within the storages and main channels, water is allowed to sit until the next irrigation.

Around 7 to 10 irrigations may be applied to each plot during the cotton season, depending on water availability. The total area of the irrigation system at ACRI is 13ha.

Water Sampling and Analysis

Water Sampling

Irrigation water was sampled from the tail drains and main channels using a sampling pole and container. At the storage dams, water was sampled using a drop line and bottle and/or a sampling system which consisted of a 12V pump (KNF pump model NMP830KNDCB, KNF Neuberger Inc., USA) and battery (12V/7Ah sealed lead acid), which was connected to two 250 mL collection bottles via a plastic sample tube.

Water Chemistry

In situ electrical conductivity (EC), pH, temperature, redox potential and percentage O_2 saturation was measured using a TPS 90-FLMV field meter (TPS, Australia). Nitrate concentrations were analysed *in situ* using nitrate test strips (Nitrate Test RQeasy®, reflectometric 5-250mgL^{-1} NO_3^- Reflectroquant® method, Merck Millipore).

Water samples were filtered through a 0.45 μm filter (MS SF35GPS045, Micro Analytics Pty Ltd) before analysing for dissolved total nitrogen (DTN), ammonia (TAN) and nitrate (NO_3-N). Samples were stored at 4^{o}C before analysis. Where samples were unable to be analysed within 4-7 of days of collection, samples were frozen and stored.

A preservative, phenylmercuric acetate was added to samples set aside for urea analysis. Nitrate-N and TAN were measured using the cadmium reduction method (Method 4500 Nitrate) and automated phenate method (Method 4500 Ammonia G), respectively (Rice et al., 2012). DTN samples were digested using the persulphate method (Method 4500-N) and the NO_3-N concentration in the digest was measured using the cadmium reduction method (Rice et al., 2012). The detection limit of the NO_3-N and TAN analysis was 0.02 mg N L^{-1}. Urea-N concentration in the water samples was determined using the modified diacetyl monoxime method (Mulvaney and Bremner, 1979) and measured with Shimadzu UV 2700 Spectrophotometer (Shimadzu, Kyoto, Japan). Dissolved organic nitrogen (DON) was determined by subtracting mineral N (NO_3-N and TAN) and urea from the TDN. Samples were re-analysed if the calculated DON value was negative or greater than 5% of the TN value. All of the dissolved nitrogen species in the surface water was analysed with an OI Flow Solution 3700 (OI Analytical, College Station, TX, USA).

Seasonal Indirect Nitrous Oxide Emissions

Floating Chamber N_2O-N Flux

Cylindrical floating chambers (diameter 410 mm, height 200 mm) attached to an inflated inner tube were constructed from 1.6mm thick 304 stainless steel (Figure 5.1). The skirt of the chamber was flush with the bottom of the tyre; when the chamber was floated on water the skirt protruded 35mm below the water surface. The two air openings on the chambers were connected to a sampling unit by 20m of nylon tubing (6mm outer diameter and 4mm inner diameter) with SMC connectors (SMC KQ2LE06 bulkhead union elbow, SMC KQ2T06 union tee). The sampling unit consisted of a 12V pump (KNF pump model NMP830KNDCB, KNF Neuberger Inc., USA) and battery (12V/7Ah sealed lead acid), a flow regulator (flow rate 4Lmin^{-1}) and a metal sampling port (1 union tee SS-600-3, and 2 reducers SS-6M0-R-6, Swagelok), fitted with a rubber septum. The rubber septa were obtained from evacuated containers (12mL Exetainer®, Labco Ltd, High Wycombe, UK), and facilitated gas sampling. The final headspace volume of the chambers and connecting tubing was 15.551 L.

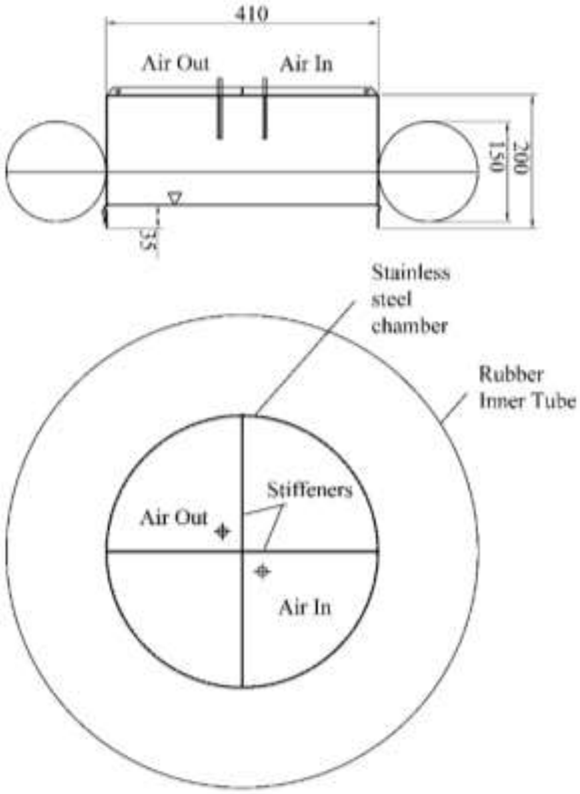


Figure 5.1. Schematic of floating chamber apparatus used to measure indirect nitrous oxide emissions. The diagram shows the dimensions (mm) of the cylindrical floating chambers.

Floating chambers (n=3) were deployed onto the water surface of one of the storages or on the main channel. 30mL of headspace gas was sampled straight after the chamber hit the water surface. 10mL of the gas sample was purged and the remaining 20 mL injected into a pre-evacuated 12 mL exetainer which was fitted with a rubber septum and screw cap lid (Exetainer ®, Labco Ltd, High Wycombe, UK). Headspace gas samples were then taken every 10 minutes for a total of 60 minutes. The temperature and relative humidity within each of the chambers was logged every minute using iButton data loggers (TL-TH ThermoLogger, Thermodata). Ambient gas samples were also taken at each of the locations where the floating chambers were deployed.

Gas samples were analysed using a gas chromatograph (Shimadzu 2014-GC) fitted with an ECD. Concentration of the gas samples was adjusted to account for the changing water vapour pressure within the floating chamber. Water vapour pressure at each sample date and time was calculated using the logged chamber temperature and relative humidity (Webb et al., 1980).

Rates of nitrous oxide accumulation within the chambers was calculated from the slope of the concentration of nitrous oxide over time, using linear regression. Where the relationship between concentration and time was poor ($p>0.2$ and $R^2<0.5$) flux was considered to be 0. Nitrous oxide emission rates were then calculated using the following equation, as described in McMahon and Dennehy (1999).

$$flux = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \frac{P}{RT} \times 1000 \qquad \text{Eq 5.1}$$

Where flux = gas flux ($molm^{-1}s^{-1}$), ($\Delta c/\Delta t$) = change in [N_2O-N] over time ($ppmv.s^{-1}$), V = volume of chamber (m^3), A = surface area enclosed within chamber (m^2), P = pressure (atm), R = universal gas constant of 0.0821 ($LatmK^{-1}mol^{-1}$), and T = air temperature (K).

Dissolved N_2O-N Flux

A theoretical N_2O-N flux was calculated using concentrations of dissolved nitrous oxide in the irrigation water. Details of water sampling, measurements of dissolved nitrous oxide and flux estimations using dissolved nitrous oxide concentrations in the water are described in Macdonald, Chang, and Warneke (2016) and in the previous section (see pages 51-63).

Estimating total seasonal emissions

1. *Dissolved N_2O-N and floating chamber estimates*

Seasonal indirect emissions were estimated using the following equation.

$$N_2O - N\ emission = \sum_{1\ to\ n}^{i} \left(F_i \times d_{(F_i - F_{i+1})}\right) \times A \qquad \text{Eq 5.2}$$

Where, N_2O-N emission = total N_2O-N lost as indirect emissions during the cotton season (kg), F_i = N_2O-N flux ($kgha^{-1}d^{-1}$), $d_{(Fi-Fi+1)}$ = days between two flux measurements (days), and A = area of cotton irrigation system (13 ha). We assumed that the season continued for approximately 192 days after the end of the first irrigation. Using both the floating chamber and dissolved N_2O-N derived flux, we estimated losses of N_2O-N via indirect emissions were 0.17 and 0.87 kg N_2O-N, respectively.

2. *IPCC estimates*

We used the default IPCC emission factor for runoff/leaching ($EF5_g$) of 0.0025 to estimate indirect nitrous oxide emissions from concentrations of TN (IPCC, 2006).

An estimate of TN lost from the plot was calculated by multiplying the average concentration of TN measured in runoff water for each irrigation by the amount of runoff water lost. The volume of runoff water per irrigation during the season ranged between 23 to 63mm, with irrigation efficiency ranging between 50 to 76% (unpublished data). On average, 19.5 kg DIN ha^{-1} was lost under a continuous cotton rotation (Macdonald et al., submitted). During the 2015/16 cotton season, 59.75 ha of cotton was planted at ACRI. We therefore estimate that a total of 1314.5 kg TN was moved from the field into the cotton irrigation system over the course of the entire season. Using the IPCC methodology, we estimated that 3.28kg N_2O-N was produced as an indirect emission over the season.

Data Analysis

All data was analysed in R (RCoreTeam, 2014). Changes in water chemistry over the season were analysed using a linear regression, with the function 'lm'. Our data did not meet requirements for normality or homogeneity of variance. The relationship between the different water chemistry parameters and measured N_2O-N flux was analysed using Kendall's Rank Correlation using the 'cor' function. Correlations with a p-value less than 0.05 were not considered to be significant. We also explored non-linear relationships between N_2O-N flux and nitrogen and dissolved N_2O-N concentrations using the 'nls' function to derive nonlinear least-squares estimates of the model parameters.

RESULTS & DISCUSSION

Water chemistry

Irrigation water pH ranged between 7.56 and 11.18 and increased slightly as the season progressed ($p<0.01$, $R^2 = 0.28$) (Table 1). Electrical conductivity ranged between 210 to 592 $uScm^{-1}$, and decreased as the season progressed ($p \approx 0$, $R^2 = 0.62$). Similarly, DTN and DIN decreased throughout the season ($p \approx 0$, $R^2 = 0.45$ and $p \approx 0$, $R^2 = 48$, respectively). DTN concentrations ranged between 0.1 to 10.56 mgL^{-1} and DIN concentrations ranged between 0 and 12.62 mgL^{-1}.

Table 5.1. Water chemistry measured in irrigation water left in storage dams and the main channel. Samples taken from the two storages and the main channel at the Australian Cotton Research Institute, Narrabri NSW.

Component	Range	Average
pH	7.56 – 11.18	8.56
EC (uS/cm)	210 – 592	475
Oxygen Saturation (%)	47 – 100	82
Redox potential (mV)	112 – 251	168
Dissolved N_2O-N (ugL^{-1})	0 – 7.11	0.92
Dissolved inorganic nitrogen (DIN) (mgL^{-1})	0 – 12.62	2.62
Dissolved total nitrogen (mgL^{-1})	0.1 – 10.56	2.81

There were strong positive relationships between EC and both DTN and DIN concentrations ($p \approx 0$, $\tau = 0.69$ and $p \approx 0$, $\tau = 0.7$, respectively) (Figure 5.2). In contrast, there were weak negative relationships between pH and EC ($p<0.05$, $\tau = -0.35$), DIN ($p<0.05$, $\tau = -0.33$) and DTN ($p<0.05$, $\tau = -0.31$) (Figure 5.2). *In situ* NO_3-N measurements also declined as the season progressed (Figure 5.S1); however rates of decline during the first 7 days after the first irrigation, where water remained static within the storages and main channel, were insignificant ($p>0.05$).

Dissolved N_2O-N concentrations ranged between 0 to 7.11 ugL^{-1} and did not change significantly over time. There was no relationship between the concentration of dissolved N_2O-N and other nitrogen species (DIN or DTN) (Figure 2). Whilst rates of denitrification generally increase with increased nitrate concentrations (see Table 1. in Beaulieu et al., 2011 for a summary), production of N_2O may be limited by other factors, such as NPOC, pH and oxygen saturation (for a brief summary see Table 1. Baulch et al., 2011, see also Eichner, 1990, Hu et al., 2015).

There was a weak negative relationship between dissolved N_2O-N and O_2 saturation ($p<0.05$, $\tau = -0.39$) (Figure 5.2). The relationship between O_2 and dissolved N_2O was similar to that observed by Rosamond et al. (2012), who found that greatest emissions occurred during hypoxic conditions and with higher night time temperatures. Under low O_2, facultative anaerobic microbes may switch from oxic respiration to denitrification, leading to increased production of N_2O (Rosamond et al., 2012).

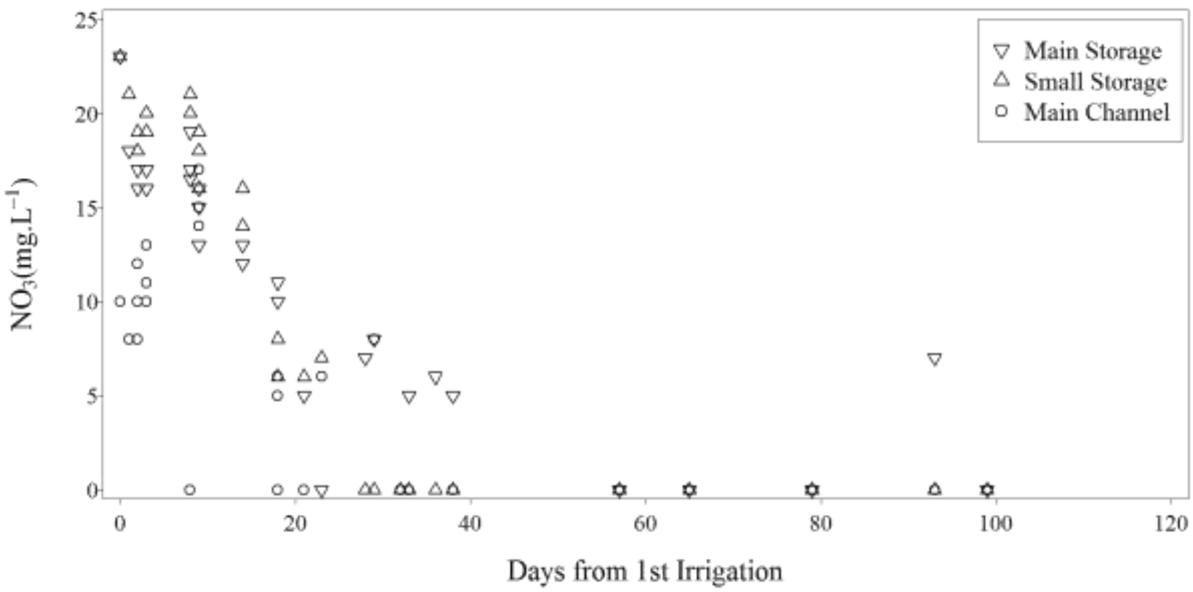


Figure 5.S1. Changes in nitrate concentration in a cotton irrigation network during the first 120 days after the first irrigation. Measurements were made in situ using nitrate test RQeasy® test strips. Samples taken from the two storages and the main channel at the Australian Cotton Research Institute, Narrabri NSW.

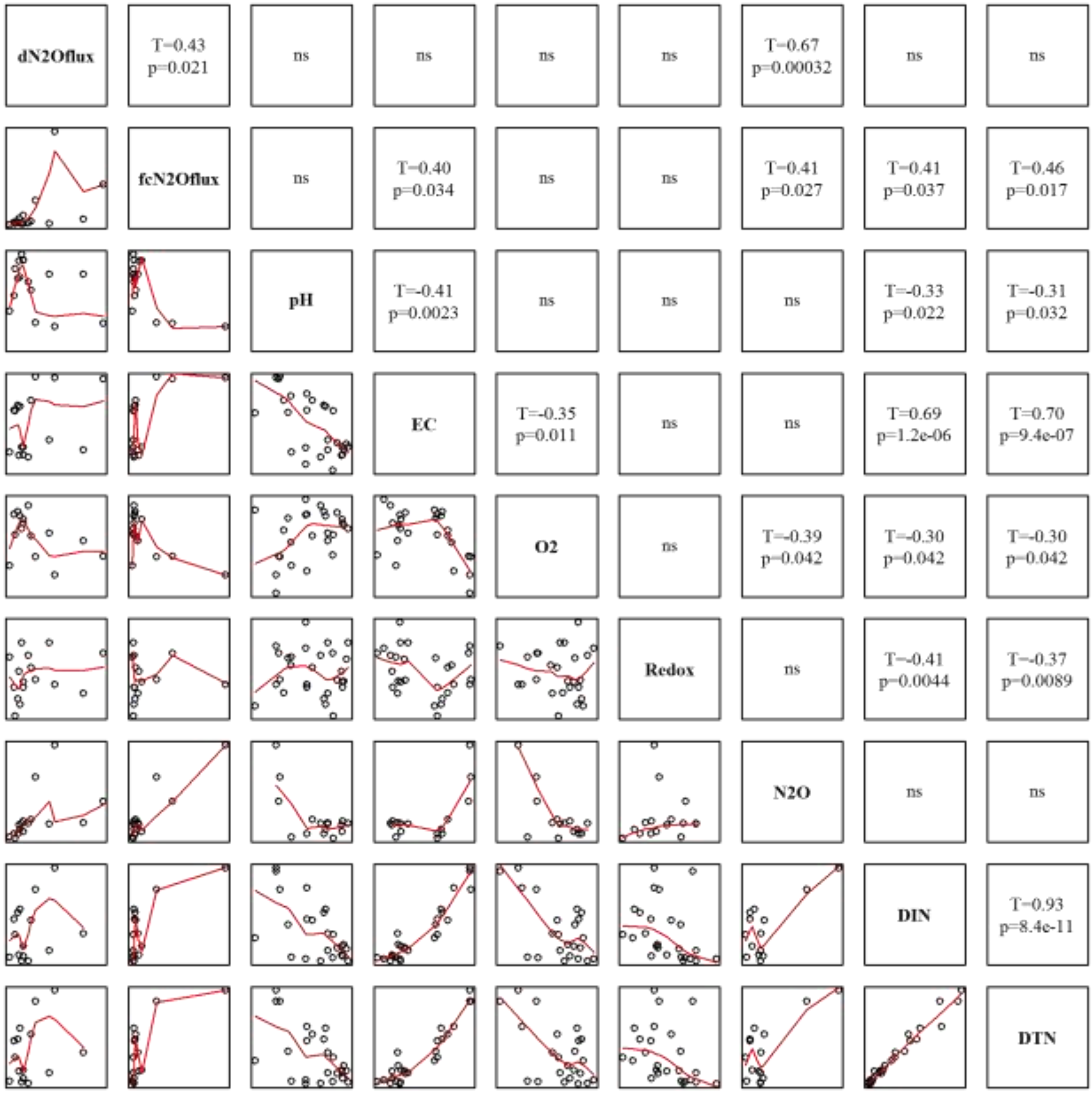


Figure 5.2. Relationship between indirect nitrous oxide emissions measured using floating chambers (fcN2ONflux) and estimated from dissolved nitrous oxide concentrations (dN2ONflux), and various water chemistry parameters. Water samples and flux measurements were taken from the two storages and/or the main channel at the Australian Cotton Research Institute, Narrabri NSW. During the first 7 days, farm irrigations ceased, and water remained stagnant within the storages and main channel. Indirect emissions were calculated using both the floating chamber and dissolved nitrous oxide methods. The relationship between the different parameters was analysed using Kendall's Rank Correlation; correlations were performed on complete pairs only, and were only considered significant if p<0.05. The lower panels on the left show plots of untransformed data fitted with a LOESS curve. The top panels on the right give Kendall's tau and p-values for each of the correlation relationships that were found to be significant.

Estimations of N_2O-N Flux

Floating chamber N_2O-N flux

Highest rates of N_2O-N flux occurred at the start of the season and we measured a maximum rate of 0.163 ugN_2O-N $m^{-2}min^{-1}$, four days after the end of the first irrigations of the season, N_2O-N flux rates then dropped over time (Figure 5.S2). An estimated 0.17 kg N_2O-N was lost as an indirect emission throughout the cotton season; this was 0.052 times the magnitude of IPCC estimated indirect N_2O-N losses.

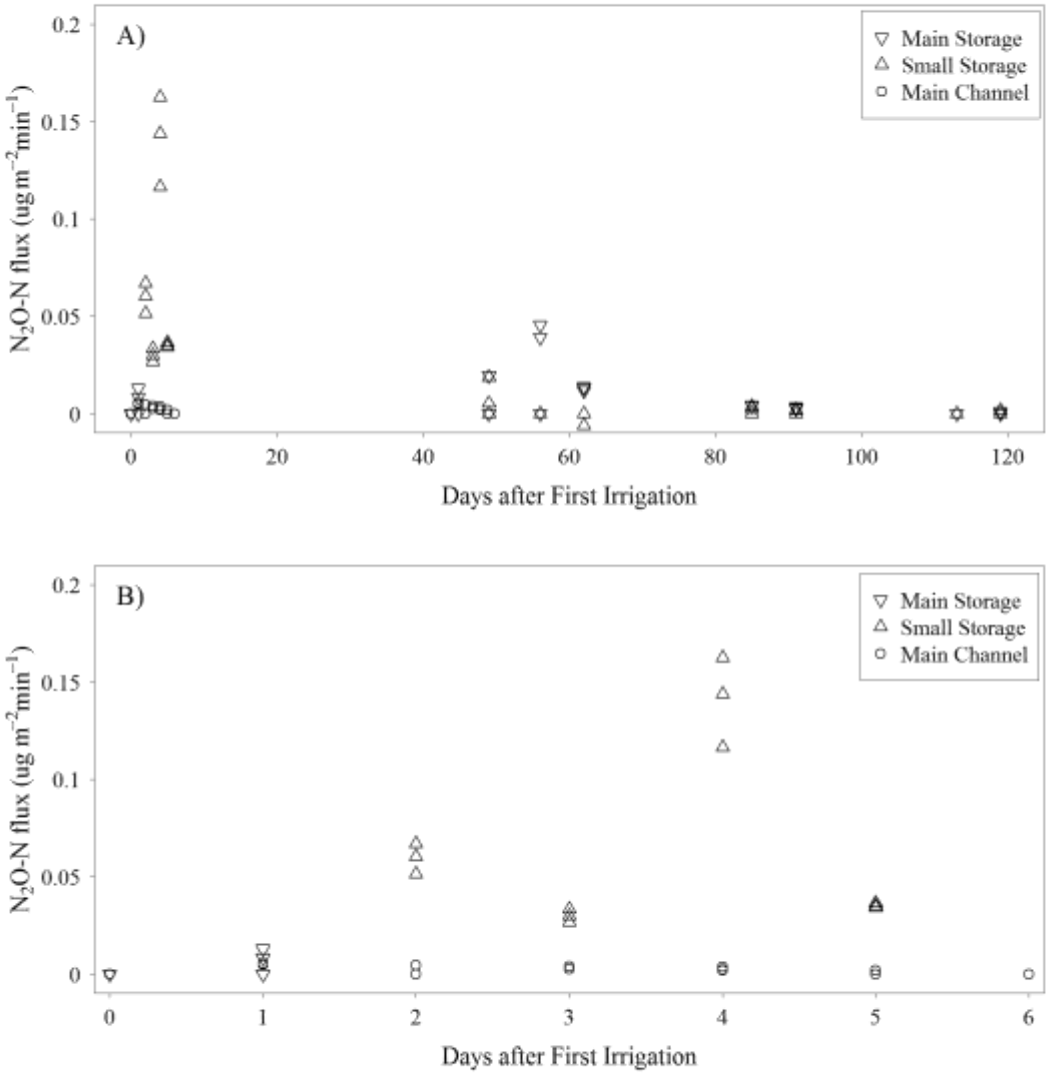


Figure 5.S2. A) Indirect nitrous oxide emissions in a cotton irrigation network during the first 120 days after the first irrigation. B) Indirect nitrous oxide emissions in a cotton irrigation network during the first 7 days after the first irrigation. During the first 7 days, farm irrigations ceased, and water remained stagnant within the storages and main channel. Indirect emissions were calculated using the floating chamber method. Measurements were taken from the two storages and/or the main channel at the Australian Cotton Research Institute, Narrabri NSW

Dissolved N_2O-N flux

Calculated rates of N_2O-N flux ranged between -0.042 and 0.27 ug N_2O-N $m^{-2}min^{-1}$. There appeared to be no change in rates as the season progressed. Approximately, 0.87 kg N_2O-N was estimated to be lost as an indirect emission throughout the cotton season; this was 0.27 times the magnitude of indirect N_2O-N losses estimated using the IPCC methodology.

Comparison of floating chamber and dissolved N_2O-N methodologies

Estimates of N_2O-N flux using, both the floating chamber and dissolved N_2O-N concentration, were within the same order of magnitude (Figure 5.3). There was a weak correlation between N_2O-N flux derived from the floating chamber and dissolved N_2O methodologies ($p<0.05$, $\tau = 0.43$) (Figure 5.3).

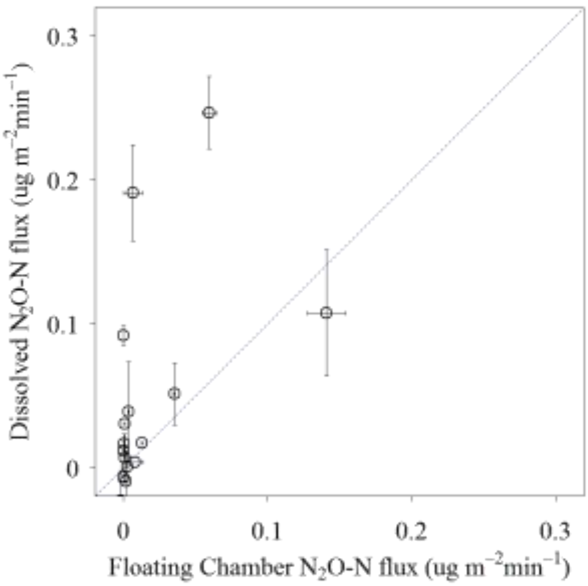


Figure 5.3. Comparison of nitrous oxide flux rates ($ugm^{-2}min^{-1}$) estimated using both the floating chamber and dissolved nitrous oxide methods. The dotted line shows the 1:1 relationship between flux measurements.

The relationship between floating chamber and dissolved N_2O-N methods for flux estimation were poor (Figure 5.3). As a result, seasonal estimations of N_2O-N differed by a factor of 5 between the two methods. Such poor correlations between the two methods have also been demonstrated by Clough et al. (2006) and Clough et al. (2007), who attributed these differences to boundary layer effects.

Indirect N_2O emissions result from a combination of two events: production of N_2O within sediments and the water column, and outgassing of N_2O from the water body. Outgassing describes the diffusion or ebullition of gas from water into the atmosphere. It is dependent on the gas concentration gradient between the water and atmosphere. Rates of N_2O outgassing aren't controlled by rates of production, but rather turbulence between the air-water interfaces (Beaulieu et al., 2011, Reay et al., 2004b).

The floating chamber methodology measures changes in N_2O concentration at a fixed location above the water surface. Chamber measured N_2O flux is a function of both both N_2O production and outgassing. However, rates of outgassing under the chamber are likely to be quite different compared to those measured adjacent to and outside the chamber. Procedural effects of the chamber alter the wind-water boundary. Under high wind speeds the presence of the floating chamber could increase turbulence of the water-air boundary and result in higher flux values (Clough et al., 2006, Clough et al., 2007). Under low to moderate wind speeds, the chamber may block vertical and horizontal movement of air over the isolated water surface, reducing the magnitude of the air-water concentration gradient. Flux derived from chamber measurements may be lower or higher than actual flux rates.

In contrast, the dissolved N_2O method relies on single point measurements of concentration and therefore only provides an estimate of N_2O outgassing. Production and outgassing of N_2O may not correlate (Beaulieu et al., 2011). If production rates of N_2O decrease, outgassing rates are likely to decrease too, and vice versa. More frequent measurements of dissolved N_2O concentrations might help increase precision of flux estimates based on the dissolved gas method.

Discrepancies between the floating chamber and dissolver N_2O flux methods may be explained by the different assumptions and procedural effects associated with both methodologies. Numerous studies have estimated rates of N_2O-N emission using only the dissolved N_2O method (e.g. Beaulieu et al., 2011, Cole and Caraco, 2001, Rosamond et al., 2012). Given the discrepancies that exist between the two field-based methods used to estimate N_2O estimations, we suggest that estimates of indirect emissions may require the use of both methods.

Relationship between measured N_2O-N Flux and nitrogen species

Bottom-up estimates of N_2O flux rely on the assumed relationship between DIN and N_2O (Firestone and Davidson, 1989, Hu et al., 2015). In some situations, these relationships are clear and increasing concentrations of nitrate have led to increased N_2O emissions (e.g. Baulch et al., 2011, Beaulieu et al., 2011, Reay et al., 2003, Silvennoinen et al., 2008).

We found moderate, positive relationships between floating chamber flux measurements and DTN ($p<0.05$, $\tau = 0.46$), DIN ($p<0.05$, $\tau = 0.41$), EC ($p<0.05$, $\tau = 0.40$) and dissolved N_2O-N concentration ($p<0.05$, $\tau = 0.41$) (Figures 5.2 and 5.4). However the linear relationship between N_2O-N flux and DTN and DIN were weak ($R^2 = 0.43$ and 0.47, respectively). Instead exponential relationships between floating chamber N_2O-N flux and DTN or DIN were a better fit ($R^2>0.9$) (Figure 5.5).

Dissolved N_2O flux estimates were not related to any of the water chemistry parameters measured, apart from dissolved N_2O concentrations (Figure5.2).

Total emissions are a function of both N_2O production and outgassing rates. Production and outgassing may also operate independently. Concentrations of nitrate or dissolved N_2O may be independent of total N_2O emissions (Beaulieu et al., 2011, Holl et al., 2005, Reay et al., 2004a). As discussed in the section above, the flux measurements from the floating chambers in this study are likely to be more representative of N_2O production rates rather than outgassing compared to the dissolved N_2O method. The production component of N_2O emissions may partly be explained from bottom-up principles. The different assumptions behind the floating chamber and dissolved N_2O methods may explain why the differences in the magnitude of flux estimated, and the differing relationship between N_2O flux and measured components of water chemistry.

Predictions of total N_2O emissions are complex because of the complexity of both the production and outgassing processes. It is therefore unsurprising that we, and other studies, have found poor relationships between dissolved N_2O measures of flux, which provide estimates of outgassing rates, and DIN or DTN concentrations (e.g. Clough et al., 2006, Rosamond et al., 2012). A better understanding of the two processes of N_2O production and outgassing is required if we are to better understand the controls on N_2O emissions.

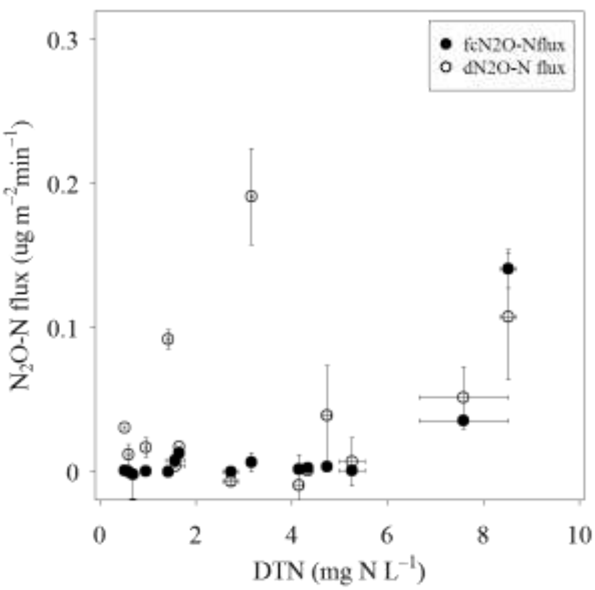


Figure 5.4. Relationship between N_2O-N flux rates ($ugm^{-2}min^{-1}$) calculated, using both the floating chamber and dissolved N_2O-N methods, and dissolved total nitrogen (DTN) concentration (mgL^{-1}).

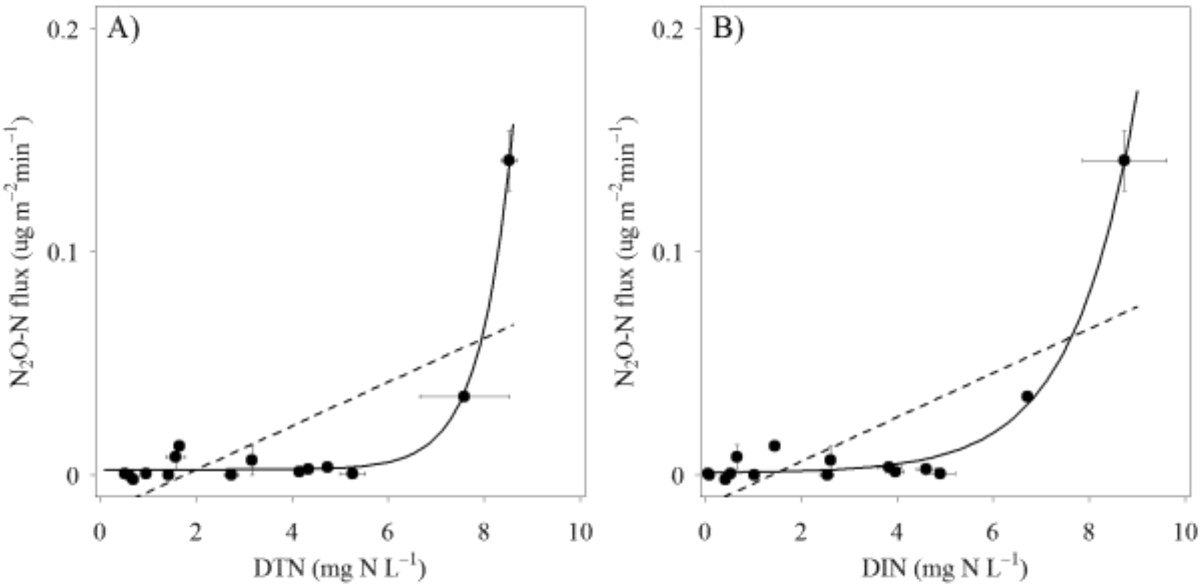


Figure 5.5.

A) Relationship between N_2O-N flux rate (ugm^{-2}min^{-2}) measured using floating chambers, and dissolved total nitrogen (DTN) concentration (mgL^{-1}). The fitted lines show modelled relationships between DTN concentration and flux. The dashed line (----) represents the linear relationship (y = 0.00985x – 0.0174) (p<0.01, R^2 = 0.43), and the solid line (——) represents the exponential relationship (y = exp$^{(1.476x - 14.54)}$) (p $\approx$ 0, R^2 = 0.99).

B) *Relationship between N_2O-N flux rate (ugm^{-2}min^{-2}) measured using floating chambers, and dissolved inorganic nitrogen (DIN) concentration (mgL^{-1}). The fitted lines show modelled relationships between DIN concentration and flux. The dashed line (----) represents the linear relationship (y = 0.0099x – 0.0139) (p<0.01, R^2 = 0.47), and the solid line (——) represents the exponential relationship (y = exp$^{(0.752x - 8.525)}$) (p* $\approx$ 0, R^2 = 0.98).

Implications for estimating indirect N_2O emissions

Simple but accurate predictions of N_2O emissions are needed to enable better accounting of greenhouse gas emissions; and the relationship between N_2O emissions and DIN concentrations, derived from a bottom-up approach, provide this simplicity. However, both field-based methods we used to estimate N_2O emissions produced estimates much lower than those estimated using the IPCC methodology. Our findings, and those made by others, demonstrate clear differences in IPCC estimates and top down measurements of N_2O emissions from a broad range of systems (e.g. Clough et al., 2006, Rosamond et al., 2012, Turner et al., 2015). Use of universal IPCC estimates are not ideal.

Production of N_2O from nitrate via denitrification is highly variable. No simple rules explain the ratio of N_2O and N_2 produced from nitrate and other nitrous oxides (Hu et al., 2015). For example a measure of the proportion of N converted to N_2O in riverine systems ranged between 0 to 90% (Beaulieu et al., 2011).

In this study, we also demonstrate that linear relationships between chamber flux and DIN or DTN is poor, though may be explained with a non-exponential model (Figure 5.5). A similar non-linear relationship has also been demonstrated between fertiliser N rates and direct surface emissions observed both globally (Shcherbak et al., 2014) and specifically within the irrigated cotton system we studied (Macdonald et al., 2015). Secondly, whilst denitrification is traditionally considered to be the largest contributor to N_2O, a substantial proportion of N_2O may be produced via nitrification (Arango and Tank, 2008, Beaulieu et al., 2011). In riverine systems, nitrification could contribute up to 52% of indirect N_2O (Beaulieu et al., 2011). Both nitrification and denitrification may occur simultaneously, and have opposing effects on nitrate concentration. For this reason alone, it should be clear that simple relationships between nitrate and N_2O emissions do not exist.

The relationship between N_2O emissions and nitrate concentrations are clearly more complex than might be initially expected from the IPCC methodology. The use of IPCC emission factors relies heavily on the assumption that the relationship between indirect N_2O emissions are linearly related to N availability. We found no evidence for such a relationship. Our findings not only call for a reduction in the emission factor used, but also suggest alternate methods of estimate N_2O emissions that do not rely on the assumption of a linear relationship between N_2O emissions and N concentrations. A better understanding of the controls on the rates of N_2O production and degassing is required if we are to develop better bottom-up models of N_2O emissions.

Conclusion

Use of universal IPCC estimates suggest that indirect emissions from the water surface can contribute up to 7 % percent of total annual N_2O emissions from irrigated cotton farms (Macdonald et al., 2016). However, estimates based on field-measurements from this study and the previous study (see pages 52-54 or Macdonald et al. (in press)) demonstrate that these IPCC estimates overestimated indirect emissions from irrigated cotton. We suggest improved accuracy of indirect emissions within irrigated cotton may be achieved through a downward revision of the current EF_5 used. Our findings also demonstrate the limitations associated with the use of EFs; and suggest that unless the controls on N_2O emissions are better understood use of EFs will rarely be accurate or precise.

MANAGING N LOSSES

Modifying fertiliser placement to reduce nitrogen run-off losses in furrow irrigated agriculture

Introduction

Export of nitrogen (N) from agricultural fields has negative consequences for water quality and ecological impacts (Beman et al. 2005). Run-off losses of N also indicate low nitrogen use efficiency (NUE) (Rochester et al. 1993), and an increased greenhouse gas production via indirect N_2O emissions (Macdonald et al. 2016, Turner et al. 2015).

In 2008, the global average riverine flux of N was estimated at 34.5 Tg N yr^{-1} (Schlesinger 2009). This increased N flux represents 23 % of the applied N to agriculture fields which has been lost to river flow (Schlesinger 2009). In cotton (*Gossypium hirsutum* L.) production systems, detailed studies about nitrogen run-off are limited. In Australia, 7% of applied fertiliser was lost under furrow-irrigated cotton (McHugh et al. 2008). Internationally, Ebrahimian et al. (2012) in a fertigation trial reports run-off nitrate (NO_3-N) losses of 19 kg N ha^{-1} and 26 kg N ha^{-1} during two fertigation events in an furrow irrigated cotton field, which represents 26 and 32 % of the inflow fertiliser, similar to the global average N loss. In our study we found that 63 kg N ha^{-1} was lost from the field via runoff. Of this 63kg N ha^{-1}, 22kgN ha^{-1}, or approximately 10% of the fertiliser applied, was derived from fertiliser N applied at the start of the cotton season (see pages 18-31 for more detail).

Variation in fertilisation application practices can reduce N run-off losses. For example, McHugh et al. (2008) found in a two year study, where 250 kg N ha^{-1} fertiliser was surface applied, that N export was significantly greater for furrow (15.1 kg N ha^{-1}) relative to subsurface drip irrigation (2.9 kg N ha^{-1}). Whilst drip irrigation may reduce N run-off losses, installation costs are currently prohibitive. Alternative and more cost-effective practices are needed to mitigate N run-off losses.

Changing the placement of fertiliser is a less capital intensive option than modification of the irrigation system. A number of studies in irrigated maize production systems have indicated reduced N losses through removing the fertiliser from the wheel track and irrigation furrow (Silburn et al. 2009), N banding or basal application near the plant line (Siyal et al. 2012), or by disconnecting irrigation water from the fertiliser bed (Benjamin et al. 1998; Lehrsch et al. 2000; Lehrsch et al. 2001).

In this study, we examine the effect of changing the placement of the urea-N fertiliser application from split broadcast to a split drilled practice. Further, there is a growing recognition in the literature that dissolved organic N (DON), urea-N, NO_3-N and an ammonium N (NH_4-N) are equally important components in agriculture production waters and soils (Davis et al. 2016; Mulvaney et al. 1979; van Kessel et al. 2009). The study also examined the effect of the placement of the N composition and flux.

Methods

Field Site

The experiment was conducted in a long term tillage-crop rotation experiment located at the Australian Cotton Research Institute (ACRI) near Narrabri in northern New South Wales (149°27’E 30°18’S). For further details about the site see pages 18-19.

Trial experimental design

The experiment was conducted in a split plot design. The difference between treatments was based on tillage, crop rotation, and historical management. The experiment, which had been on-going since 1985 (Constable et al., 1992), consisted of three initial or historic treatments:

1. MXT-CC: conventional tillage (disc-ploughing to 0.2 m depth, chisel ploughing to 0.3 m depth followed by ridging every year) with cotton sown in October every year.

2. MNT-CC: minimum tillage (after harvest the cotton plants are slashed; this is followed by a root cutter and disc-hiller) with cotton sown in October every year.

3. MNT-CW: a cotton–winter wheat (T. aestivum L.)–summer (bare) fallow–cotton sequence where cotton was sown with minimum tillage and wheat was sown with no-tillage.

The experiment was re-designed in 2011 such that all plots were split by either sowing a corn crop during the summer following cotton (with respect to the cotton-wheat, this involved sowing corn immediately after wheat but before the next cotton crop) or retaining the historical cropping system as a control. Within the split plot design, tillage/rotation system was designated as the main plot treatments and +/- corn as sub-plot treatment, replicated four times in plots 190 m long and 8-24 rows. The runoff flumes and automatic water samplers (described in this section below) were installed in first replication.

Cotton is usually planted (seed rate of 18 kg ha^{-1}) in October every year as per treatment schedule. In 2015 var. Sicot71 BRF® was planted and in 2014, Liberty link® Sicot 70 BL was planted. Cotton received fertiliser N as urea surface applied as two splits (180 kg N ha^{-1} at planting and 80 kg N ha^{-1}, 2.5 months after planting) in 2014-15 season. In 2015 season, Urea was drilled (180 kg N ha^{-1}) into bed (10 cm deep) before sowing on either side of the planting row. An additional 80 kg N ha^{-1} of urea was broadcasted to cotton in mid Jan 2016. Cotton plants were defoliated late march to early when at least 60% of bolls were opened. Picking of cotton occurs in April or early May every year using mechanical four row cotton picker.

Maize seeds (Var Pioneer P1467) were planted at 6-7 seeds m^{-2} or 20 kg ha^{-1} as per treatment schedule. Maize treatments received fertiliser N as urea surface applied at 260 kg N ha^{-1}. Maize crop was irrigated at an average rate of 1 ML ha^{-1} subject to water, rainfall and soil water content.

Wheat (Var Crusader) is planted in 2015 winter. Urea was applied to wheat before sowing at a rate of 20 kg N ha^{-1}, and 60 kg N ha^{-1} subsequently during later July or early August. The wheat was harvested in Nov 2015 and maize was planted over wheat standing stubble. The other wheat fallow cotton treatment was left fallow from Nov/Dec 2015.

Irrigation management

Cotton and Maize crops were irrigated at an average rate of 1 ML ha^{-1} subject to water, rainfall and soil water content. The total irrigation volumes (mm) across all the treatments are presented in Table 6.1. The first irrigation for cotton/maize was done immediately after planting. The subsequent irrigations were scheduled 5-6 weeks after first irrigation for cotton and subsequent irrigations were done every two weeks subject to rainfall.

Table 6.1. Timing and placement of fertiliser during the 2014-2015 cotton rotation and the 2015-2016 cotton and maize rotations.

Season		**First Application**			**Second Application**		
		Date	**Rate (kgha^{-1})**	**Placement & subsequent irrigation date**	**Date**	**Rate (kgha^{-1})**	**Placement & subsequent irrigation date**
2014-2015	Cotton	21/10/14	180	Urea broadcast top dressed. 22/10/14	13/01/15	80	Urea broadcast top dressed. 14/01/15
2015-2016	Cotton	30/09/15	180	Urea drilled 10 cm deep both sides of planting row. 21/10/15	14/01/16	80	Urea broadcast top dressed. 19/01/16
	Maize	21/12/15	260	Urea broadcast top dressed. 30/12/15			

Runoff and irrigation water sampling

San Dimas flumes (200 mm) (Wilm et al. 1936) were used to measure the runoff volume from each treatment. The galvanized steel flumes were manufactured as per standard specifications outlined by Walkowiak (2008). Two flumes were installed in head end of the field and six flumes were installed in the tail end of the cotton/maize rows (Figure 6.1), outside the actual cropping area. Runoff water from four inter-rows were directed into the flume for flow measurement and sample collection. The standard flow calibration equation for converting flow height into flow discharge for a 200 mm San Dimas flume is:

$$Q\ (L\ s^{-1}) = 0.053 * h^{1.34} \qquad \text{(Eq 6.1)}$$

Where Q is discharge and h is water height in the flume (mm). The flow height is measured using a Teledyne ISCO 730 bubbler module connected to a Teledyne ISCO 6712 standard portable water sampler which logs the flow height in minute intervals. The module uses a differential pressure transducer and a flow of bubbles to measure liquid levels to determine flow height. The samplers were programmed to flow weighted-based sampling module to capture the representative sample of entire runoff or irrigation event. After each runoff event samples were collected and transported to lab next day morning.

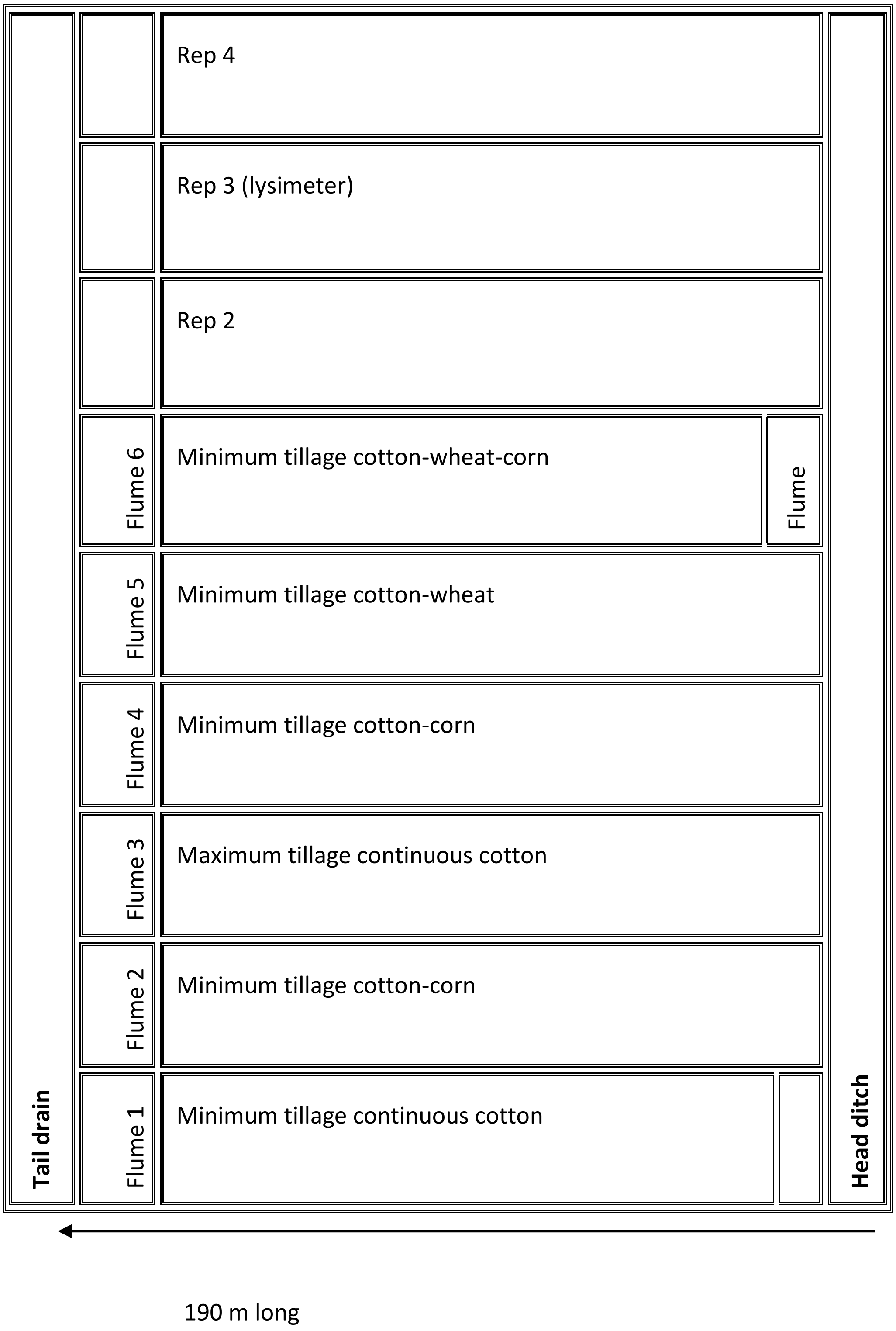


Figure 6.1. Field layout and flume locations (rep 2, 3 and 4 has six plots each similar to rep1 and does not reflect the scale used in the layout).

Electrical conductivity, dissolved organic and mineral nitrogen analysis

We measured the following water chemistry parameters: electrical conductivity, pH, and concentration of various nitrogen species (total nitrogen (TN), urea, nitrate, ammonium, and dissolved TN). For a full description of the methods see page 66.

The DON (mg L-1) in each sample was calculated according to equation 2.

$$\mathrm{DON} = \mathrm{TN} - [\mathrm{x} + y + z] \qquad \text{(Eq 6.2)}$$

Where x = NO_x-N, y = NH_4-N, z = Urea-N and all the concentrations are in mg L^{-1}. Samples were re-analysed if the calculated DON value was negative or greater than 5% of the TN value.

Salt and nitrogen flux calculations

Hem (1985) found, for a variety of natural waters in the United States, that a simple approximation relating total dissolved solids (TDS) to EC was useful for particular ranges of salt concentration and a fixed suite of dissolved salt species:

$$\mathrm{TDS} = \mathrm{Z} * \mathrm{EC}\ (\mu\mathrm{m\ cm}^{-1}) \qquad \text{(Eq 6.3)}$$

In equation (2), TDS or [X] are in mg/L, EC is the measured EC (µS/cm) corrected to 25°C and Z is a 0.64. The solute flux of the irrigation to and run-off water from the field during each irrigation and rainfall event S, (kg ha^{-1})

$$\mathrm{S_n} = \mathrm{X_n} * \mathrm{Q_n} \qquad \text{(Eq 6.4)}$$

where X is the solute concentration (mg L^{-1}), Q is the discharge (L ha^{-1}) and n is either the irrigation water (H) or the run-off water (T).

The quantity of solutes from the soil in the run water was calculated using equation (6.5),

$$\mathrm{Soil} = \mathrm{S_T} - \mathrm{S_H} \qquad \text{(Eq 6.5)}$$

Where S_H is the mass of solutes supplied by the irrigation water and S_T is the mass of solutes that was lost in the tail water. Negative values indicate that the irrigation water supplied solutes to the soil. It is assumed that the solutes that enter the field either transit the field or fertigate the field (ie with Eq 5 is negative) and there is no interaction or substitution with the soil solutes.

Infiltration was calculated in a similar manner using equation (Eq 6.6),

$$\mathrm{Infiltration} = Q_T - Q_H \qquad \text{(Eq 6.6)}$$

Where Q_H is the volume of irrigation water (L ha^{-1}) and Q_F is volume of the tail water (L ha^{-1}).

Atmospheric losses

Potential indirect N_2O emissions from the surface run-off water nitrogen concentration from the lysimeter plot were calculated using the current emission factor (EF_{5G}) (De Klein et al. 2006, IPCC 2006). The potential amount of N_2 produced and lost in the storage was estimate using a conversion factor range of EF_{N2}=0.07-0.35 (Seitzinger 1988).

Results and Discussion

Yield, Irrigation and salt flux

The fertiliser placement did not have significant effect on cotton yield. In 2014-15, the cotton yield in maximum and minimum tillage were 2127 and 2067 kg ha^{-1} with surface urea application. In 2015-16 the same treatments yielded 2147 and 2113 kg ha^{-1} with subsurface drilling of fertiliser N. This suggest, the subsurface drilling could minimise runoff N losses without compromising the cotton yield, although seasonal variation in yield may be larger than the effect of N application method. Over both seasons, the cotton yield was slightly lower than industry average yield of 2258 kg ha^{-1} in 2013-14 (Cotton Australia, 2016).

During both the 2014-2015 and the 2015-2016 seasons the irrigation efficiency in the cotton crops was above 66 % (66 and 67 % respectively), but less than the 75% efficiency target (Table 6.2). Unfortunately during irrigation 1 in the 2014-2015 season run-off measurements were unreliable due to settling issues. The irrigation efficiency was only 43% in the maize treatments in 2015-2016 and 268 mm run-off ha^{-1} (including rainfall generated run-off) occurred during the season. During 2014-2015, seven irrigations were measured in the cotton phase which produced 232 mm run-off ha^{-1}. During 2015-2016 seven irrigations measured in the continuous cotton treatments, which produced 302 mm run-off ha^{-1} (including rainfall generated run-off). Over the course of the irrigation season 1.5 t TDS ha^{-1} 2014-2015 and 0.5 t TDS ha^{-1} 2015-2016 were added to the field.

Total seasonal N flux

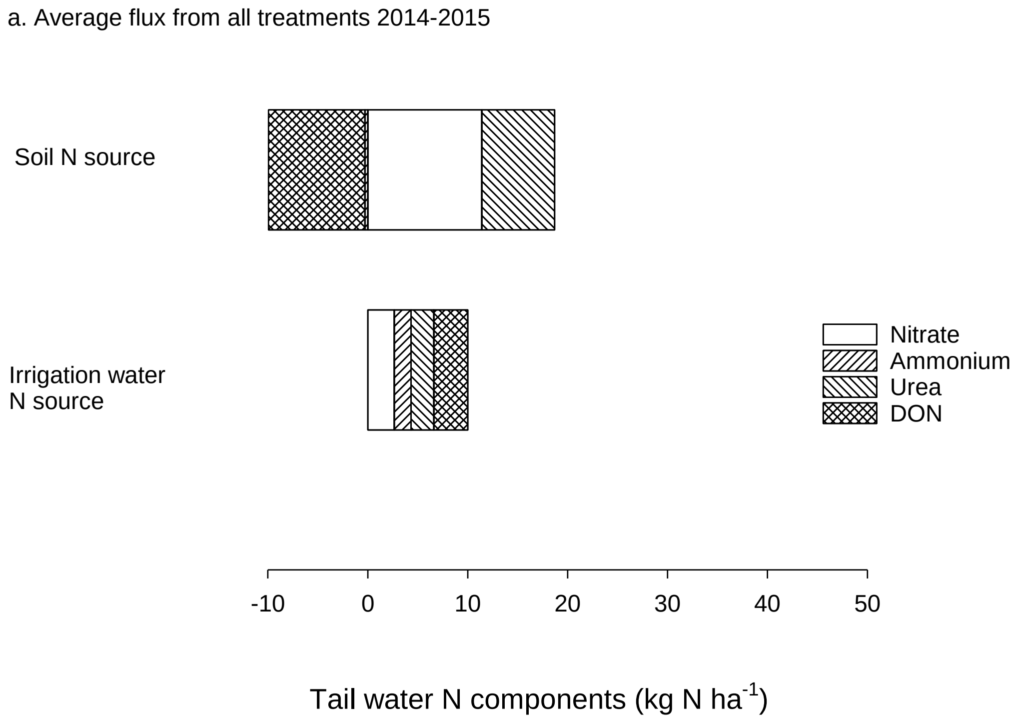
Changing the fertiliser placement from surface broadcast to subsurface banding of urea reduced the soil sourced N loss from the continuous cotton treatments by 50% (Figure 6.2). When the fertiliser was applied as a surface broadcast (2014-2015) 8% of the N was lost to run-off compared to only 4% N in the subsurface banding method (2015-2016). A similar effect has been significantly proven in fallow short term rainfall simulator and fertiliser placement experiments in grain production systems (Baker et al. 1982; Mostaghimi et al. 1991). The N loss in the subsurface banding application method was similar whereas the surface broadcast application is greater to the loss measured in the drip irrigation study by McHugh et al. (2008); but both are lower than the global N run-off lost estimate (Schlesinger 2008). The N run-off efficiency factor however may not be constant and will change at different fertiliser rates or environmental conditions. There was no evidence of increased N flux after the midseason broadcast N application in the cotton cropping systems during either measurement year (Figure 6.3 and 6.4). This may be due to the reduced rate relative to the early season application or because crop demand for N is higher later in the season (Table 6.1).

Table 6.2. The applied irrigation, infiltration and total dissolved salt (TDS) added to the soil storage by the irrigation water.

		2014-2015				2015-2016		
Irrigation Water								
		TDS kg ha^{-1}	**Irrigation (mm)**			**TDS kg ha^{-1}**	**Irrigation (mm)**	
	Average H1&H6	2343	788		**H1**	1940	767	
					H6	1264	515	
Soil								
Treatments	**Crop**	**TDS Soil Storage (kg ha^{-1})**	**Run-off (mm)**	**Infiltration (mm)**	**Crop**	**TDS Soil Storage (kg ha^{-1})**	**Run-off (mm)**	**Infiltration (mm)**
Min Till CC	Cotton	1420	265	521	Cotton	886	385	382
Min Till MC	Cotton	1559	245	541	Maize	152	366	149
Max Till CC	Cotton	1623	200	586	Cotton	792	220	547
Max Till MC	Cotton	1703	196	590	Maize	212	268	247
Min Till WC	Cotton	1329	327	459	Fallow			
Min Till MC	Cotton	1944	149	637	Maize	527	172	343

Despite having the same application method as the continuous cotton (2014-2015), the loss of N from the maize treatments (2015-2016) was 1.4 kg N ha^{-1} compared to 22 kg N ha^{-1}. In case of the continuous cotton (2014-2015) the fertiliser was broadcast the day before a 100 mm irrigation event, with the aim of reducing the ammonia loss by washing the fertiliser into the soil. The maize fertiliser application (2015-2016) occurred on the morning 21/12/2015 and on the 23/12/2015 3.6 mm rainfall occurred which delayed the irrigation. Further rain occurred on the 25/12/2015 (7.2 mm) and 27/12/2015 (15.4 mm) before a 100 mm irrigation on the 31/12/2015 (ACRI weather station http://www.weather.cottassist.com.au/). The N fertiliser was probably leached into the surface soil by the rainfall before the irrigation, which then deeply penetrated the N into the profile. Despite the reduction in N losses via the run-off atmospheric losses would have occurred. It is estimated using the decision support system of Fillery et al. (2016) that over this 10 day period 30 kg NH_3-N ha^{-1} was fluxed to the atmosphere. The NH_3-N loss should cease once the 25 mm of infiltration has occurred and this was most certainly the case after the irrigation of the 31/12/2015. There would have also been significant denitrification losses over the 10 days when the soil was moist (Scheer et al. 2013).

The apparent rainfall, tillage, and placement effects are evident in the flux (Figure 6.3) for both the 2014-2015 and the 2015-2016 years relative to the continuous cotton (Figure 6.4). The results indicate that the use of broadcast urea in sprinkler irrigation systems is a suitable fertiliser application option. However, the grower needs to manage the irrigation to provide water immediately after fertiliser and at a sufficient volume to prevent NH_3-N losses but not to induce run-off by exceeding the infiltration rate.



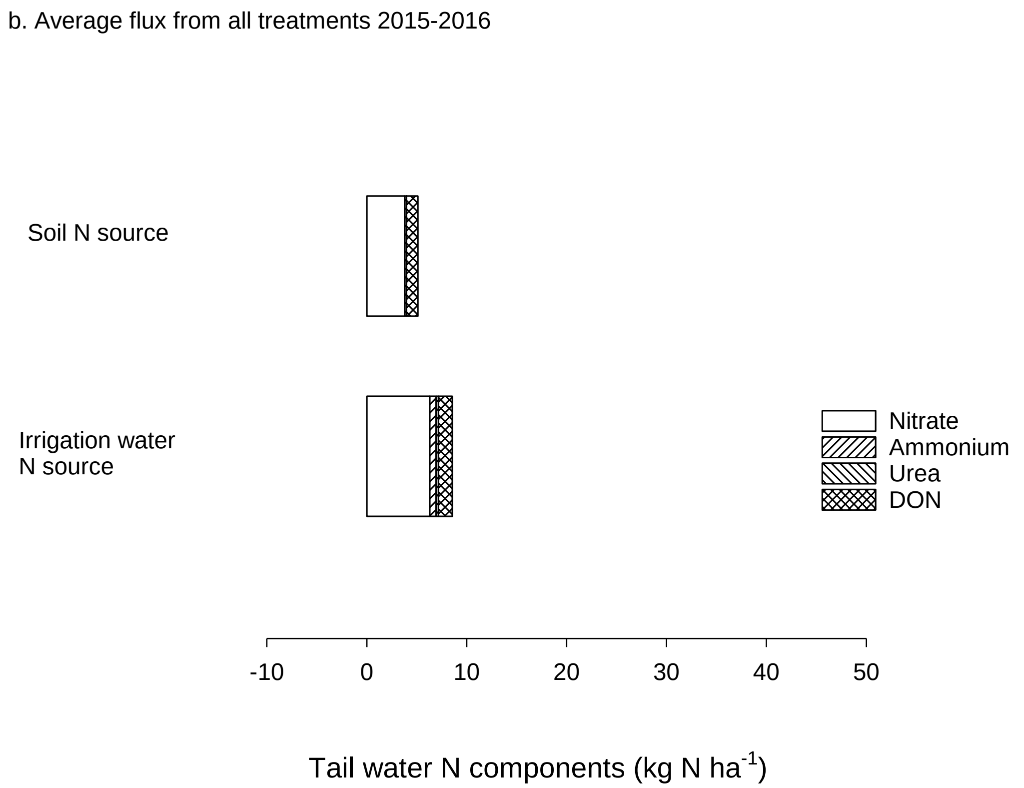


Figure 6.2. The contribution of the soil and the irrigation water to the average tail water N losses for the minimum and maximum tillage continuous cotton treatments. Negative values indicate soil storage and positive values indicate soil export. A. Surface applied urea 2014-2015. B. Subsurface banded urea 2015-2016.

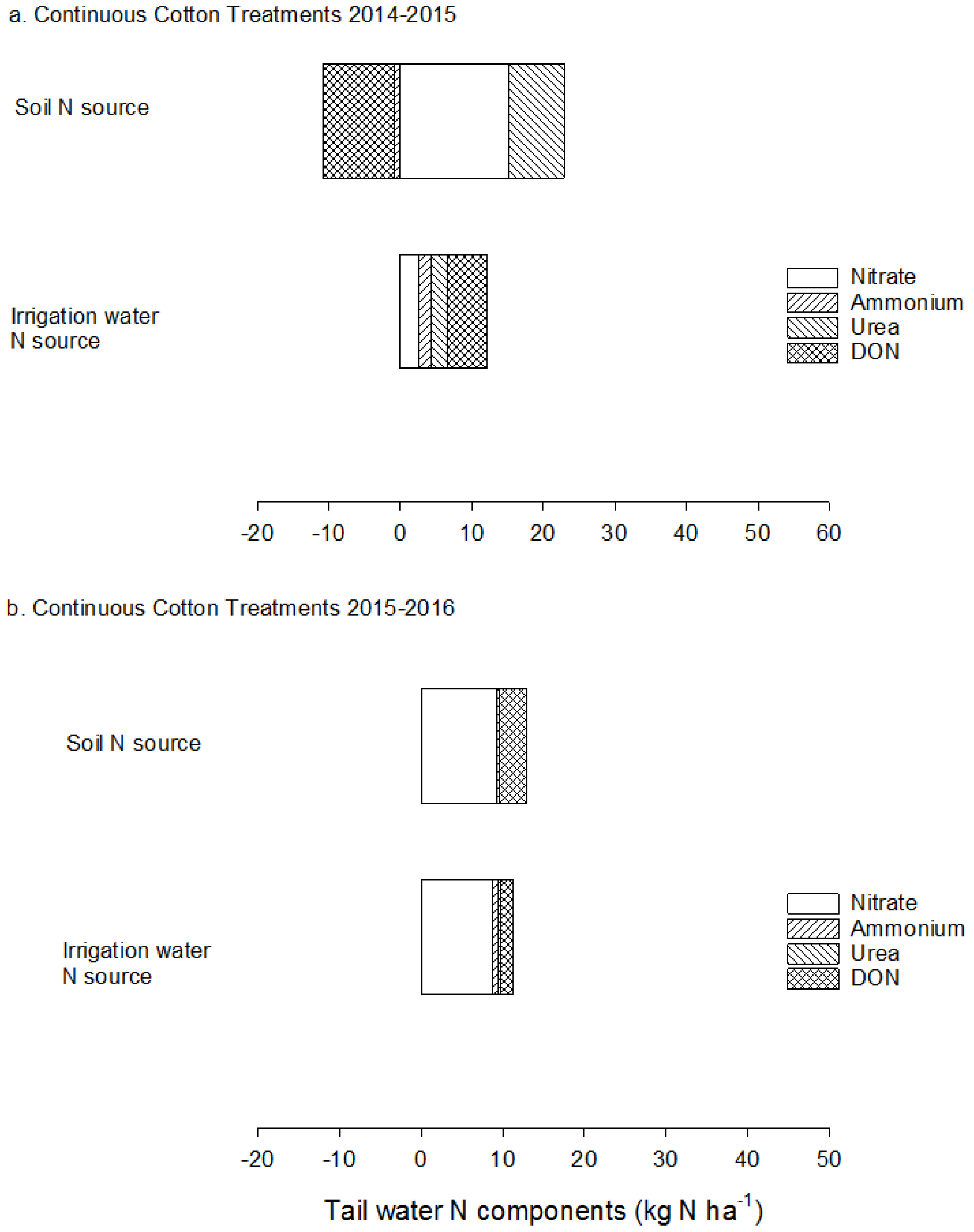


Figure 6.3. The contribution of the soil and the irrigation water to the average tail water N losses for all treatments. Negative values indicate soil storage and positive values indicate soil export. A. Surface applied urea 2014-2015. B. Subsurface banded 2015-2016.

There are annual differences in the N content of the irrigation water, 22 and 11 kg N ha^{-1} entered the field in 2014-2015 and 2015-2016 respectively. During the 2014-15 season the irrigation water supplied 12 kg DON-N ha^{-1} to the field over the season. In 2015-16 the irrigation water did not supply any N to the field. There may be variations in N loading in the irrigation water due to number of causes, the 2015-2016 irrigation water was source from groundwater, whereas the preceding season Namoi River was the source. Water restrictions in 2015-2016 reduced the farm water allocation and subsequently the planting area was also reduced at the research station. This resulted in less N use on the farm and hence less fertiliser N and soil DON was lost from the fields in the run-off water.

Seasonal N composition and timing

During the 2014-2015 cotton season where the fertiliser was broadcast the urea-N and DON-N flux was as important as the NO_3-N flux (Figure 6.2-3). The average of all the measured tillage treatments shows that the urea loss is large in surface broadcast fertiliser (Figure 6.3). Urea-N and NO_3-N flux are similar between the field average and the continuous cotton treatments. The urea-N fertiliser during the first irrigation was on the surface and was able to be dissolved and a proportion flushed out of the field as urea (Figure 6.4). In systems, like this one were the fertiliser is in contact with the irrigation water N movement and losses have been shown to occur (Lehrsch et al. 2000; Lehrsch et al. 2001). During subsequent irrigation the urea-N flux (Figure 6.4f) returns to background whilst the NO_3-N flux returns to back by the third irrigation (Figure 6.4e). Again the N composition varies between each irrigation, and these composition changes are an integration of the whole-of-farm operations. Irrigation 1 occurs early in the season when there is an excess of field N post fertilisation is washed into the irrigation network. During transit and storage the N present in the tail water is utilised by microbes and converted to organic N and NO_3-N, which is then is present in the measured irrigation water (Figure 6.4 b and 6.5 b). The DON-N present in the first irrigation tail water is from the decomposing cotton or maize or wheat residues and conversion of the urea N and DON production by microbial in the water column. In 2014-2015 the irrigation water supplied 12 kg DON-N ha-1 to the soil in irrigations 1 and 2 where in 2015-2016 the irrigation water did contribute to the net soil nitrogen balance at the end of the season.

The subsurface banding of the urea into the soil not only reduced the amount but altered the composition of the N exported (Figure 6.4-6). There was a 60% reduction in the flux of NO_3-N due to the burial of urea which a similar finding to Lembi et al. (1985) who found that the deeper placement of N fertiliser greatly reduced the flux on NO_3-N. In the 2015-2016 continuous cotton plots the NO_3-N flux was the largest component of the overall N loss and urea-N was a very small component. The urea-N flux (0.1 kg N ha-1) was an order of magnitude less than the urea-N flux (8 kg N ha-1) in 2014-2015 (Figure 6.2). The urea flux from the maize was 0 kg N ha-1 (Figure 6.6) due to the rainfall dissolving the fertiliser and it subsequent conversion to DON, NH_4-N and NO_3-N. Over the course of the season NO_3-N is exported from mid-November 2015 through to late February 2016 and this probably reflects the production via mineralisation of soil NO_3-N from the subsurface banding of urea.

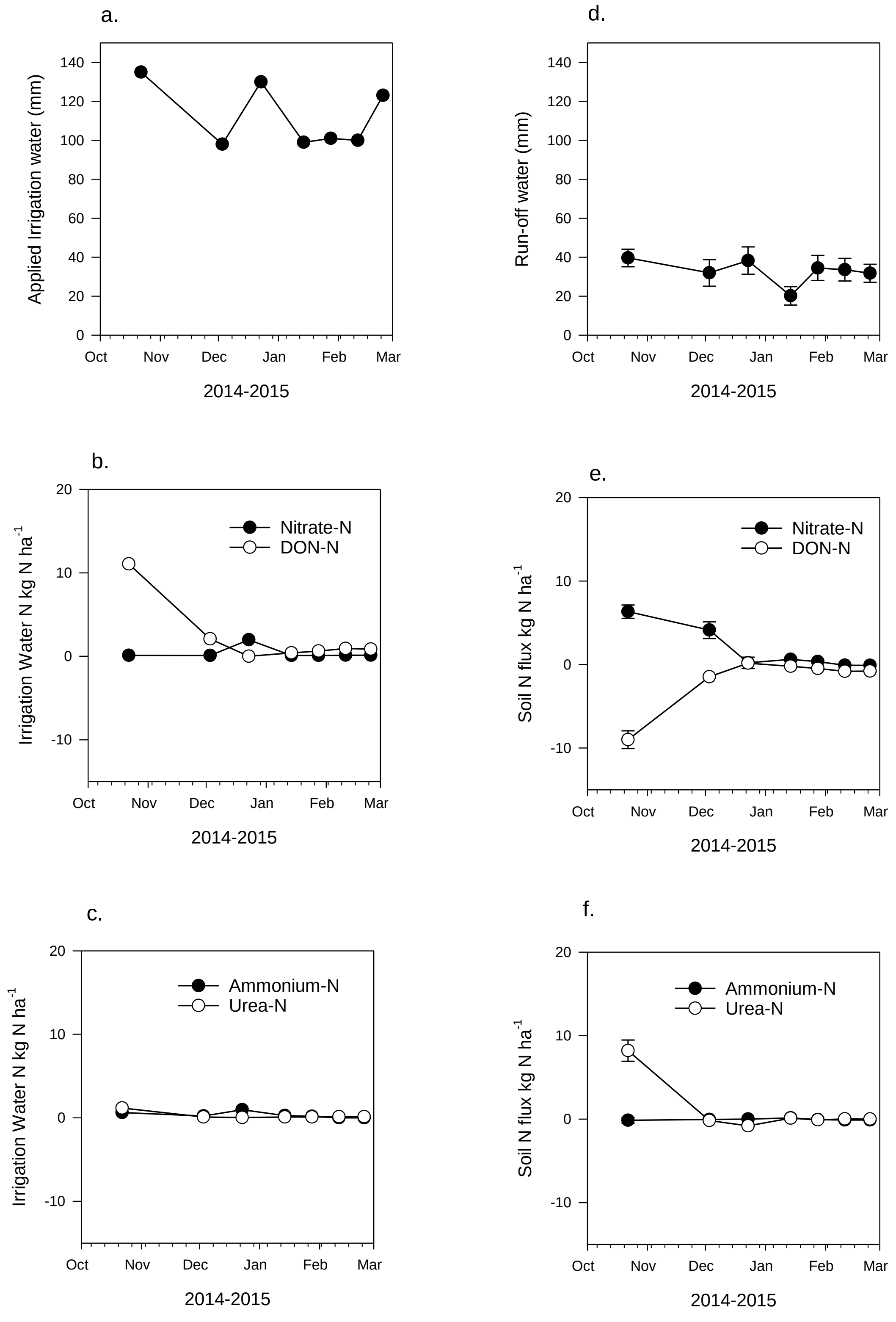


Figure 6.4. Mean irrigation, run-off, irrigation water N input and the contribution of the soil to the average tail water N losses for the cotton crops during the 2014-2015 season where the urea was broadcast.

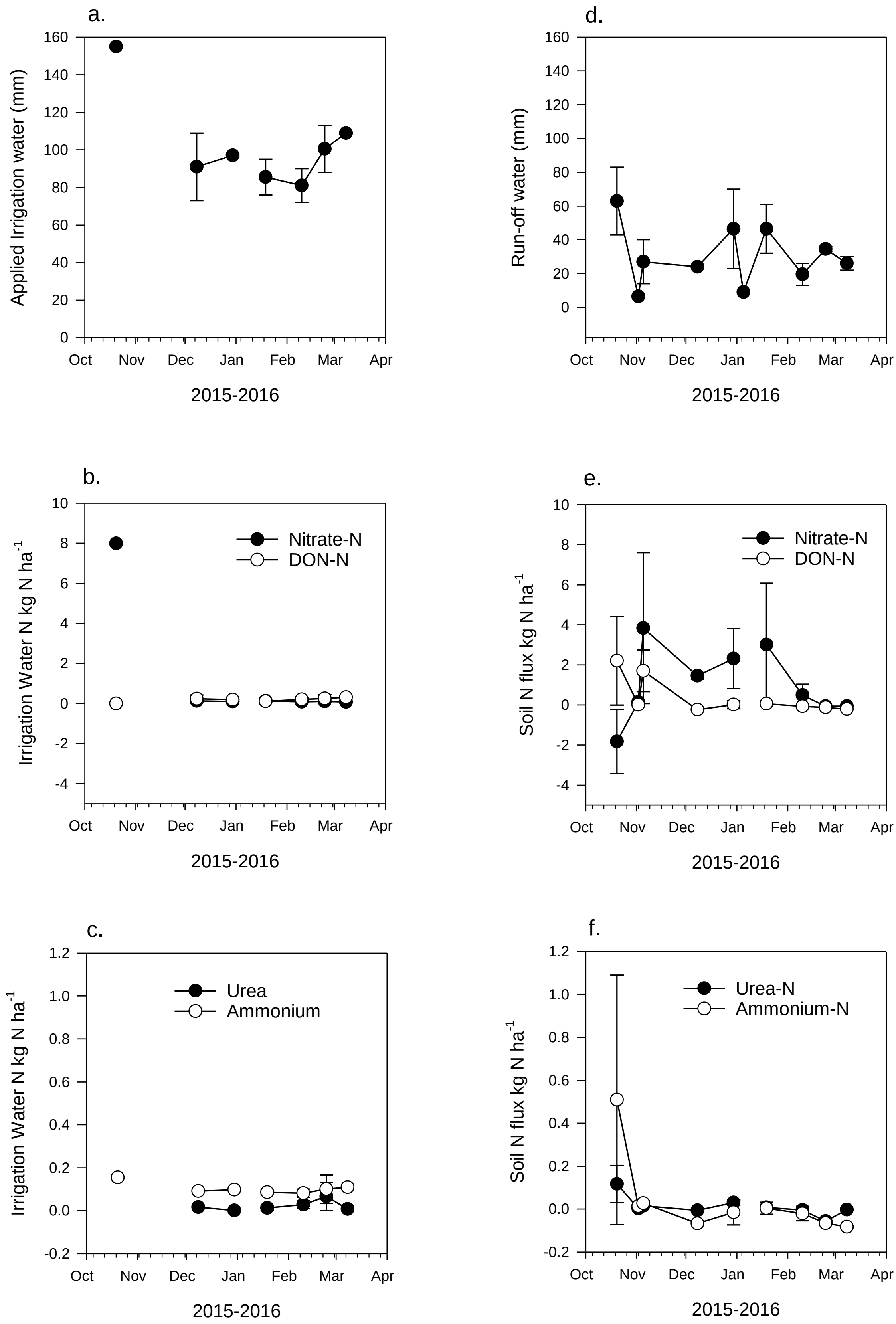


Figure 6.5. Mean irrigation, run-off, irrigation water N input and the contribution of the soil to the average tail water N losses for the continuous cotton crops during the 2015-2016 season where the urea was subsurface banded.

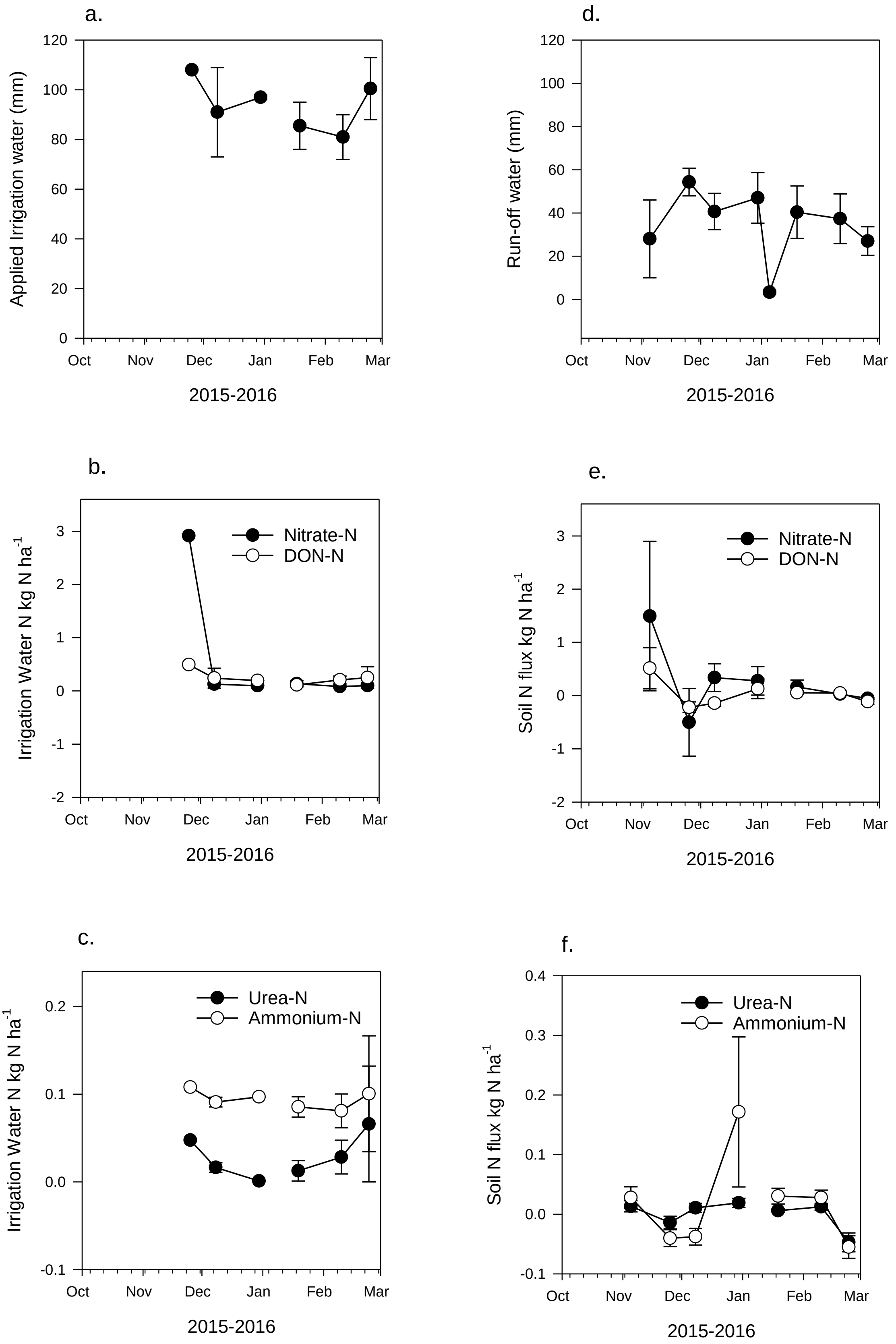


Figure 6.6. Mean irrigation, run-off, irrigation water N input and the contribution of the soil to the average tail water N losses for the maize crops during the 2015-2016 season where the urea was broadcast.

Losses from the water storages

The N enriched run-off from the continuous cotton treatments in 2014-15 and 2015-2016 could potentially produce indirect N_2O-N emissions of 0.15 and 0.09 kg N_2O-N ha_{-1} and N_2-N losses of 3-13 and 1-5 kg N_2-N. The N_2O-N produced is a small fraction of the potential gas atmospheric losses the production of N_2-N via denitrification would greatly reduce the N content in the water. Denitrification losses from the water bodies are particularly amplified during the warmer summer months when the cotton is growing. There are many unknowns with the potential denitrification losses from irrigation tail water and the future research work outlined by Seitzinger (1988) for lakes is still required for agricultural systems. Briefly this includes the effect of the amount and type of N input and sediment and oxygen content on denitrification and in situ measurement of denitrification. There are many additional knowledge gaps in cotton irrigation system N cycle, in particular the rate of sediment N uptake and the potential denitrification losses from the sediments that would occur when the system is empty. Fertigation is becoming a common practice in irrigated cotton systems and the denitrification rate and the system efficiency is unknown.

Conclusion

Subsurface banding of urea-N fertiliser in the soil resulted in a 50% reduction in the soil N losses via the run-off water compared to the broadcast urea. In 2014-2015 season where the fertiliser was broadcast 8% was lost as run-off and 2015-2016 only 4% was lost via this pathway once the fertiliser was drilled deeper into the soil profile. Similar efficiency improvements were observed once the broadcast fertiliser was washed into the soil by rainfall before the irrigation in the maize cropping treatments. However it was estimated that 14% of the applied fertiliser was lost as NH_3-N. In all years NO_3-N was the main component in the irrigation and tail water but DON-N and urea-N at times were important. In future water studies these components should be measured. Modification of the fertiliser placement also changed the N composition of the tail water; the urea-N flux was reduce to zero and DON-N and NO_3-N was also reduced in the subsurface fertiliser relative to the broadcast treatments. In Australian cotton production systems the tail water is recycled and used to irrigate other fields. Tail water nitrogen can be converted via denitrification to N_2O-N and N_2-N gas whilst in transit or storage and it is estimated that this equates to 0.09 and 0.03 kg N_2O-N ha-1 and 4-13 and 1-5 kg N_2-N ha^{-1} losses respectively in 2014-15 and 2015-2016. Further studies are required to quantify these denitrification loses and the rate that N is being cycled and stored in the irrigation system.

Identifying practical solutions to optimise NUE and WUE in cotton production

INTRODUCTION

The loss of nitrogen from the field in the tail water run-off during an irrigation is root cause of indirect emissions. The elimination or reduction of N in the run-off water will directly reduce the production of indirect N_2O-N from the water surface. Improving both nitrogen and water use efficiency (NUE and WUE, respectively) would reduce N run-off losses. Improved WUE and NUE can be achieved through modifying N placement with respect to movement of irrigation water. This study examines practical solutions that could be utilised by growers immediately to reduce N run-off whilst not reducing yield.

METHODOLOGY

Two irrigation systems experiments were set up to investigate the influence irrigation management has on reducing N loss via tail water run-off. Both experiments were situated at Ruvigne Farm, Gunnedah (150.3°E, 31°S) within the Upper Namoi Valley of New South Wales, during the 2015/16 cotton season. The site contained a uniform vertosol profile that was heavy grey clay (NSW Office of Environment, 1991).

Experimental Set Up & Sample Collection

Experiment One investigated different irrigation techniques to mitigate N loss from the process of irrigation. Treatments used (I-1, I-2 and I-3) are shown in Table 7.1 and Figure 7.1. Treatment I-2 is most similar to that used in the wider industry.

Experiment Two investigated the impacts varied irrigation and N rates have on N loss from a cotton system. Treatments are shown in Table 7.1. The experiment plot lengths were length of the field (320 m) and 8 m wide. Experiment Two was set up using a split plot design.

Table 7.1. Experimental treatments used in this study.

Treatment	N Rate (kg N ha^{-1})	Irrigation Deficit (mm)	N Placement
Experiment 1			
I-1 (n=4)	250	NA	I-1
I-2 (n=4)	250	NA	I-2
I-3 (n=4)	250	NA	I-3
Experiment 2			
T1 (n=3)	0	50	I-1
T2 (n=3)	150	50	I-1
T3 (n=3)	250	50	I-1
T4 (n=3)	350	50	I-1
T5 (n=3)	0	70	I-1
T6 (n=3)	150	70	I-1
T7 (n=3)	250	70	I-1
T8 (n=3)	350	70	I-1

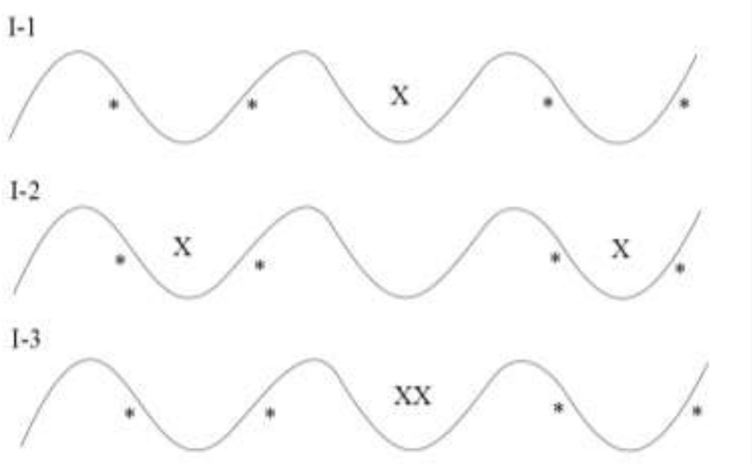


*Figure 7.1. Cross section of the field denoting the irrigation treatments used. The tops of the curves represent hills and the troughs, furrows. A * denotes where fertilizer was placed, a 'X' denotes the irrigation furrow where water was run, and a 'XX' denotes where double the amount of water, relative to the other treatments, was used.*

To alleviate in-crop operations all the N was applied prior to planting in the form of anhydrous ammonia, except for 30 kgN ha^{-1} which was applied by fertigation. The cotton cultivar grown was CSD Sicot 74BRF, sown at 150,000 seeds per ha and planted on 1 m hills.

Irrigation was delivered by 50 mm diameter siphons from a supply channel. The outflow from the siphons initially flowed down every second furrow in the field (typical of a siphon-flood furrow irrigation system). Irrigation was ceased when irrigation water had reached the tail drains. Whilst I-3 treatments had twice the amount of water volume passing from the head ditch into the field, this meant that total irrigation time for I-3 was half that of the other treatments.

N losses were measured by collecting the run-off tail water from each plot at the base of the field, from the furrow that the irrigation water was applied and the adjacent non-irrigated furrow, which ran water because of sideways absorption of the irrigation water. Collection points were ten metres up from the tail drain to ensure no contamination of run-off water from adjacent plots.

Water Chemistry

The electrical conductivity, pH and total N concentration was analysed for each sample. For more detailed descriptions of the analyses see pages 54 to 55.

Application and Measurement of Irrigation Water

Irrimate Flow meters were installed onto the siphons delivering the water to the field. The flow meters calculated the total amount of water delivered to the experiment. Neutron Moisture Meters (NMM) access tubes were installed 50 m in from the head ditch and tail drain of the field. NMM were used to measure the soil water balance of the treatments.

Scheduling of Experiment Two for the two irrigation rates (50 and 70 mm) was conducted by the calculation of plant available water using NMM data. Tail water run-off was calculated from the volume applied onto the field, minus the absorption of water into the soil profile. Recorded total N loss was calculated as the run-off water volume multiplied by the N concentration in the tail water.

Plant Sampling & Analysis

Crop maturity plant mapping and above ground biomass was conducted at approximately 30 % open bolls and two weeks before chemical defoliation. One metre of complete plants were removed from each experiment plot. The collected plants were weighed (wet and dry), milled and analysed for N concentration using a Lachat QC8500 Series 2 flow injector.

Experiment harvest was conducted by a John Deere 7760 “baler” cotton harvester. One bale was produced from each plot, and weighed separately. The picker was cleaned to ensure no carryover of excess lint to the next plot. A subsample was collected from each plot bale, ginned at the Australian Cotton Research Centre (Narrabri), with the turnout percentage used to determine final plot yields.

N Use Efficiency (NUE) was calculated using five different equations (Bronson, 2008) and (Rochester, 2010).

Crop internal NUE $(iNUE) = \frac{Yield}{N\ uptake}$ Eq 7.1

Agronomic NUE $(agroNUE) = \frac{yield\ (fert) - yield\ (nil\ fert)}{Applied\ N\ rate}$ Eq 7.2

Applied NUE $(aNUE) = \frac{Yield}{Applied\ N}$ Eq 7.3

Recovery efficiency % $(recNUE) = \frac{N\ uptake\ (fert) - N\ uptake\ (nil)}{Applied\ N\ rate}$ Eq 7.4

Physiological NUE $(phyNUE) = \frac{yield\ (fert) - yield\ (nil\ fert)}{N\ uptake\ (fert) - N\ uptake\ (nil)}$ Eq 7.5

Irrigated Water Use Index (IWUI) and Gross Production Water Use Index (GPWUI) were used to determine the Water Use Efficiency (WUE) of the different treatments in Experiment One (Montgomery et al., 2012).

$$IWUI = \frac{Yield}{Applied\ Irrigation\ water} \quad \text{Eq 7.6}$$

$$GPWUI = \frac{Yield}{Applied\ irrigation\ water + effective\ rainfall + used\ soil\ moisture} \quad \text{Eq 7.7}$$

Analysis was conducted using GenStat (VSN International Ltd.). Differences between N and irrigation treatments were analysed using ANOVAs, least significant difference values, and the linear and non-linear lines of best fit.

RESULTS & DISCUSSION

Experiment one

The different irrigation techniques had a significant ($P<0.001$) effect on N lost through the tail water run-off from the field (Table 7.2). Irrigation treatment I-3, which had twice the volume of applied irrigation water resulted in a decrease in the tail water concentration of N. The decrease was 50 % less than the N concentration from the tail collected from the I-2 treatment. Irrigation date had an affect ($P<0.001$) on the N concentration of the tail water (Figure 7.2). After the initial large N loss in the tail water from the first irrigation, all treatments from the 80th day after the first irrigation event were considered to have low amounts of N concentration as they contained less than 1 kg N ha^{-1}. This trend correlates with findings from MacDonald (2016) highlighting the importance of managing the first irrigation that occurs after N application. Interestingly the application of 30 kg N ha^{-1} through fertigation on the 30/11/16 did not cause a spike of N loss from the field. Although the applied N rate was quite small (10% of the total N applied to the field) the result augurs well for investigating various forms and application methods of N to improve NUE.

*Table 7.2. Nitrogen loss (kg ha^{-1}) from each treatment for each of the 7 irrigations measured. The * denotes where differences in nitrogen losses were significantly different between treatments (where, *** denotes a $p<0.001$, ** $p<0.01$, and * $p<0.05$).*

Treatment	29/09/15 ***	13/10/15 ***	30/11/15 *	6/01/16	9/02/16	19/02/16	2/03/16 **	TOTAL **
I-1	15.56	10.84	1.15	1.63	-0.03	0.22	-0.09	29.28
I-2	26.91	7.14	9.11	4.07	0.00	0.04	-0.04	47.27
I-3	15.93	7.63	5.88	2.30	0.02	0.05	-0.07	31.82

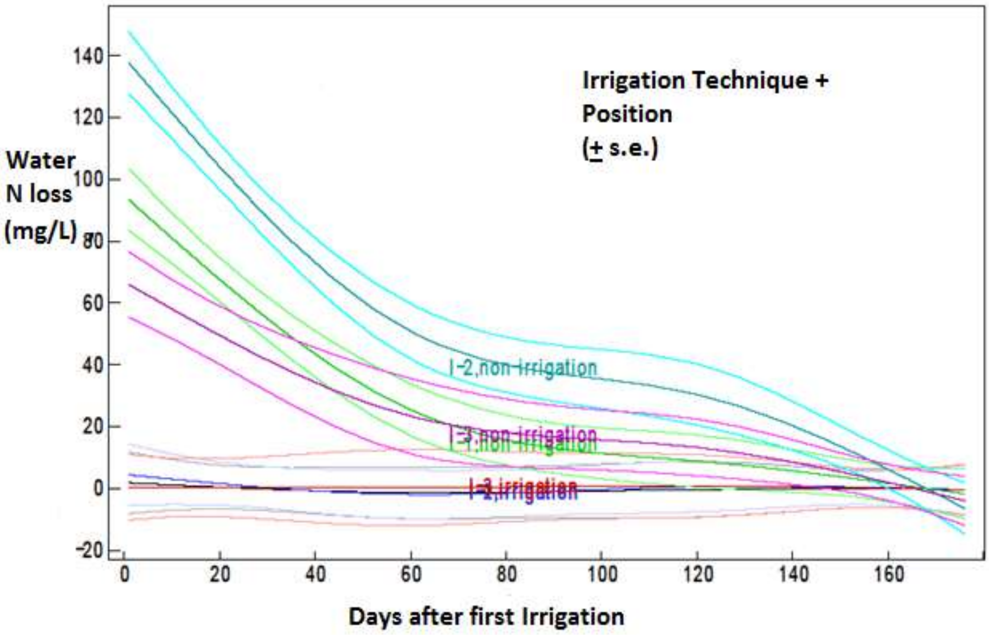


Figure 7.2. Tail water nitrogen concentration over the cotton season

There was no significant difference in yields or plant biomass production of the irrigation treatments from Experiment One (Table 7.3). The minimal difference in yield means that improvements made by the different irrigation techniques won't affect the yield potential of cotton crops. Treatment I-1 improved the ability of plants to uptake N (P<0.01), while Treatment I-3 resulted in the lowest uptake of N of the three treatments with 188 kg N ha^{-1}. Although the greater volume of applied irrigation water in Treatment I-3 reduced N loss, the irrigation technique may have caused prolonged water stress to the crop causing lower N uptake. A solution would be to use the I-3 technique for the early two irrigations, then resort to a more traditional single siphon technique that has a lower flow rate during the peak growth stages.

*Table 7.3. Experiment One: Mean cotton yield, total plant biomass and plant N uptake. A ** denotes where N uptake was significantly different between treatments (p< 0.01).*

Irrigation Treatment	Yield (kg/ha)	Yield (bales/ha)	Plant Biomass (t/ha)	N uptake** (kg N/kg)
I-1	2568.87	11.32	10.90	232.32
I-2	2591.10	11.41	11.41	213.32
I-3	2498.36	11.01	11.01	188.73

The technique used to apply irrigation water to crops had an influence on the N uptake of the crop and thus the NUE. Bronson (2008) found that irrigation systems such as drip irrigation and pivot sprinklers had greater N efficiency than a flooding furrow irrigation system. As the N rates were equal for all the treatments in Experiment One, the NUE differences found was the affect that irrigation had on N uptake. Recovery NUE calculates the percentage of total N uptake by plants divided by the applied N.

Experiment One found I-1 had greater recovery NUE ($P<0.05$) than I-2, and I-3, 25%, 18% and 8%, respectively (Table 7.4). Conversely both crop iNUE and physiological NUE show that I-3 had greater production of lint per uptake of N ($P<0.01$). Rochester (2013) found the economic optimum iNUE for the cotton industry to be 12.4 ± 0.4, with lower values indicating the cotton was over fertilised and conversely the high values under fertilised. Using that theory, treatment I-2 with an iNUE value of 12.23 would be classified as the treatment with optimum NUE.

*Table 7.4. Experiment One: Crop Nitrogen Use Efficiencies. A ** denotes significant values of p<0.01, and a * denotes p<0.05.*

	Recovery NUE*	Agronomic NUE	Crop internal NUE**	Physiological NUE**	Applied NUE
	%	Kg lint/ kg N	Kg lint/ kg N	Kg lint/ kg N	Kg lint/ kg N
I-1	25	2.44	11.26	15.50	10.28
I-2	18	2.53	12.23	16.68	10.36
I-3	8	2.16	13.29	56.82	9.99

The water use efficiency of Experiment One was not significantly different at both indexes (IWUI and GPWUI) (Figure 7.3). This is explained by the fact that Experiment One did not contain varied rates of irrigation application, but rather various irrigation techniques. Although treatment I-3 received higher volumes of water applied, the shorter application time mitigated the extra volume. Therefore there no difference between the total amounts of applied water to the three treatments. Montgomery et al. (2014) found that the Australian cotton industry's GPWUI to be 1.12bales ML^{-1}, while Experiment One had GPWUI values of 1.17, 1.18 and 1.14bales ML^{-1} for I-1, I-2 and I-3, respectively (Table 7.5).

Table 7.5. Water use Indexes: IWUI (Irrigated Water Use Index) and GPWUI (Gross Production Water Use Index). There were no significant differences between the three irrigation treatments.

Treatment	IWUI (bales ML^{-1})	GPWUI (bales ML^{-1})
I-1	1.58	1.17
I-2	1.59	1.18
I-3	1.54	1.14

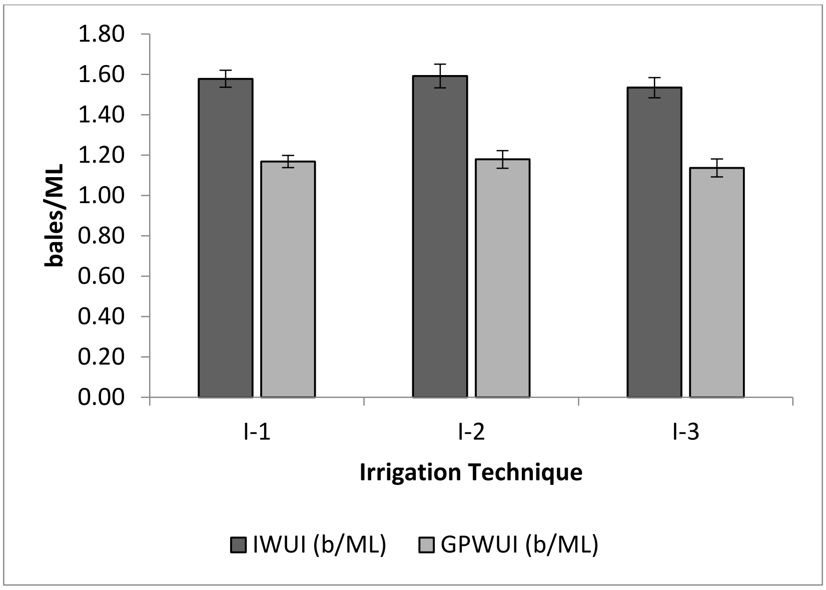


Figure 7.3. Water Use Efficiency, given as IWUI (Irrigated Water Use Index) and GPWUI (Gross Production Water Use Index). There were no significant differences between the three irrigation treatments.

Experiment Two

The tail water collected from Experiment two followed a similar trend to the collected tail water of Experiment One. The N concentration in the water after the early varied irrigation events were higher ($P<0.001$) compared to the late season irrigations (Table 7.6). The two irrigation rates (50 and 70 mm) showed no difference in the removal of N in the irrigation tail water. Applied N rate and the position of the collected sample were significant for the first irrigation event ($P<0.05$ and $P<0.001$, respectively) and the combination of those two treatments (applied N rate and position of collection was significant at $P<0.01$). The fact that irrigation rate did not have an effect on tail water N concentration is because the early irrigation events on the experiment were conducted at the same time. These irrigations were applied during the early vegetative stages of the trial, so no deficit scheduling of irrigations were required. The start of the varied rate irrigation scheduling occurred on the fourth irrigation to the experiment (16/01/2016, only the 50mm rate was watered), by this stage the bulk of the N that was lost through the tail water had already occurred. This is important as that it explains that a more intensive irrigation schedule (such as the 50 mm treatment) will not have a significant impact on the N loss within the tail water over a growing season. This supports the trend that the major loss of N from a cropping system through irrigation occurs in the irrigation events immediately after the bulk N application.

The varied rate of applied N in Experiment Two influenced the cotton yields ($p<0.05$) and the uptake of N by the plant ($p<0.01$). The experiment yields increased with the higher N rate, the exception being the 350 kg N/ha rate at the 70 mm irrigation rate (Figure 7.4). That treatment yielded 11.83 bales/ha compared to the 250 kg N/ha at the 70 mm irrigation rate which yielded 11.99. The yield trends of the 50 and 70 mm irrigation rates support the findings of Baird (2015), which found that with a 70 mm irrigation rate the optimum N rate was 250 kg N/ha (13.66 bales/ha), while for the more intensive 50 mm irrigation rate, the higher yield was found with the higher 300 kg N/ha (13.39 and 13.16 bales/ha respectively. The 350 kg N/ha N rate at the 70 mm irrigation rate also resulted in lower crop N uptake ($p<0.01$) compared to high 350 kg N/ha with 50 mm irrigation rate and the 250 kg N/ha rate at the two irrigation rates (50 and 70 mm). Similar to Baird (2015) there was no significant difference between the yields of the 250 kg N/ha and the higher 350 kg N/ha treatments. Supporting work by Rochester (2010) that stated the optimum N application rate for modern high yielding cotton crops to be 220 kg N/ha.

Table 7.6. Average nitrogen run-off losses under different irrigation deficit and N rate treatments.

Irrigation Deficit (mm)	**Applied N rate (kg N ha^{-1})**	**Furrow where sample was collected**	**N run-off loss (kg N ha^{-1})**				
			30/11/15	6/01/16	9/02/16	19/02/16	2/03/16
50	150	irrigation	-1.95	1.77	NA	0.80	0.11
50	150	non-irrigation	25.87	6.66	NA	1.99	-0.60
50	250	irrigation	-2.76	3.44	NA	0.71	0.65
50	250	non-irrigation	4.54	12.98	NA	-1.89	0.05
50	350	irrigation	1.27	2.47	NA	0.94	0.92
50	350	non-irrigation	13.19	6.49	NA	0.69	1.76
70	150	irrigation	-1.45	5.42	-0.38	0.91	-0.53
70	150	non-irrigation	30.16	2.51	1.08	0.35	0.82
70	250	irrigation	-6.84	3.44	1.95	0.46	-1.06
70	250	non-irrigation	4.87	12.98	1.60	1.08	-0.77
70	350	irrigation	-1.38	2.83	-0.33	1.02	0.62
70	350	non-irrigation	8.37	2.53	0.40	-0.13	0.63

Table 7.7. Experiment Two: Average lint yields and crop N uptake between all treatments. Interaction between irrigation rate and N application rate was not significant. Irrigation rate had no significant effect on yield or crop N uptake. N applied rate significantly affected yield ($p<0.05$) and crop N uptake ($p<0.01$).

Irrigation Deficit (mm)	**N rate (kg N ha^{-1})**	**Yield (kg ha^{-1})**	**Yield (bales ha^{-1})**	**Crop N uptake (kgN ha^{-1})**
50	0	2020.40	8.90	196.26
50	150	2542.83	11.20	232.41
50	250	2682.95	11.82	243.54
50	350	2801.80	12.34	294.97
70	0	1867.28	8.23	168.61
70	150	2561.25	11.28	260.86
70	250	2720.97	11.99	278.63
70	350	2686.48	11.83	250.25

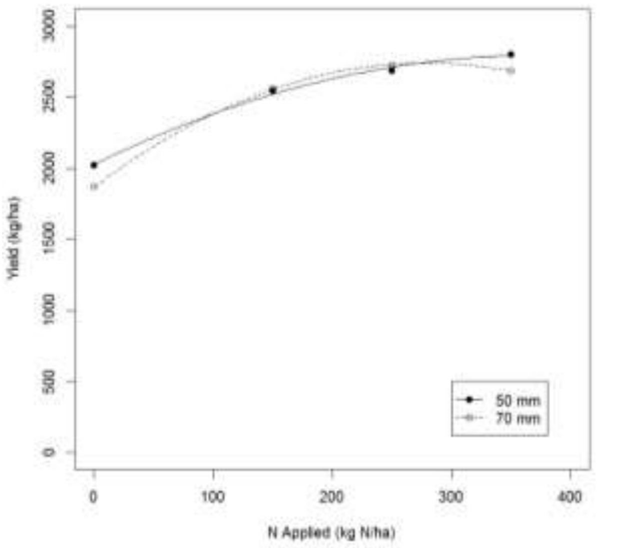


Figure 7.4. The measured lint yield as a function of varied applied N rates (0, 150, 250 and 350 kgN ha^{-1}) and irrigation deficits (50 or 70mm).

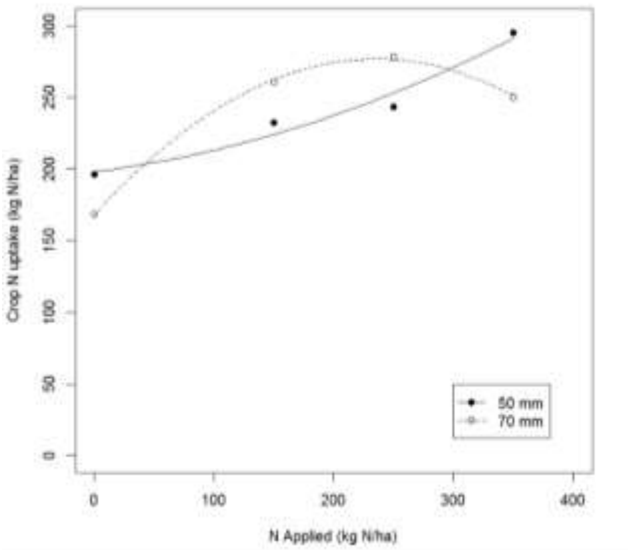


Figure 7.5. The measured crop N uptake as a function of varied applied N rates (0, 150, 250 and 350 kgN ha^{-1}) and irrigation deficits (50 or 70mm).

The varied N rate in Experiment Two had a significant ($p<0.001$) effect on the Agronomic NUE and Applied NUE. The two efficiency indexes highlighted a trend where the increase in N application decreased the NUE factor. Both indexes indicated the higher 350kg N/ha applied N rate was excessive, while the 150 and 250kg N/ha applied N rate resulted in optimum NUE. The crop iNUE values for Experiment 2 are confined to a range between 10 -12kg lint/kg N. The range is lower than the optimum industry range Rochester (2010) calculated of 12.7 to 13.3kg lint/kg N (Figure 7.4). The fertiliser recovery on average was below 50% (Figure 7.5)

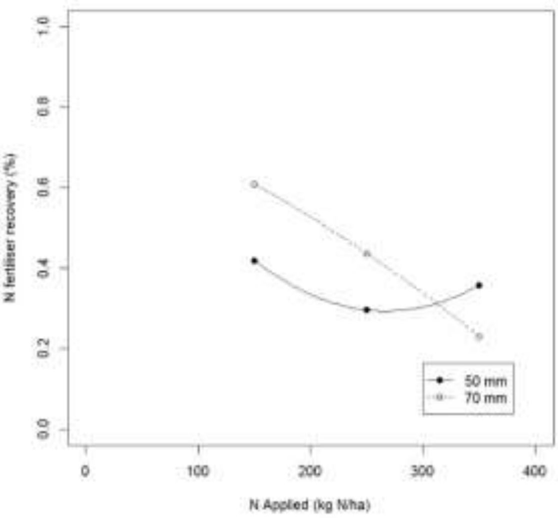


Figure 7.6. The measured crop N fertiliser recovery as a function of varied applied N rates (0, 150, 250 and 350 kgN ha^{-1}) and irrigation deficits (50 or 70mm).

Water use efficiency in Experiment Two was influenced by the N rate applied ($p<0.001$) and the applied irrigation rate ($p<0.01$) (Table 7.8). The 50mm irrigation rate received two more irrigations than the 70mm irrigation rate, and as a result received an extra 0.58 ML ha^{-1} of plant available water. The lower applied water and the similar yields resulted in the 70 mm irrigation treatments to have better IWUI than the 50 mm treatments. These results show that growers can reduce applied irrigation water to their crops resulting in better WUE and produce similar yields.

The GPWUI for Experiment Two again compared favourably with the industry average of 1.12 bales/ha (Montgomery et al. 2014). The 350kg N/ha N rate resulted in the highest GPWUI within the 50mm irrigation rate (1.21 bales ML^{-1}), while the 250 kgN ha^{-1} had the highest GPWUI in the 70 irrigation rate (1.24 bales ha^{-1}; see Figure 7.7). This result is a continuation of the figures that Baird (2015) received from a varied N and irrigation trial and highlight the importance that should apply suitable N rates to complement their irrigation management.

Between 29 to 47 kg N ha^{-1} was lost as in irrigation run-off. These figures are higher than those previously reported total N loss through irrigation tail water at ACRI (15 kg N/ha) (Macdonald et al. unpublished data). Such differences may be due to differences in N application and N rates used.

Loss of N in run-off followed a similar pattern to those seen from irrigation at ACRI (Macdonald et al. unpublished data). The trend showed the large loss of N in the tail water from the irrigation immediately after the N application at the start of the season (50% of total season N loss) before reducing to minimal losses with the later irrigation applications. The large loss of N that occurs from irrigated crops in the irrigation event that follows the application of N should be further examined. Optimising N application to crop N requirements may reduce N run-off losses.

Table 7.8. Influence of different N rate and irrigation deficit treatments on water use efficiency (WUE), measured as IWUI (Irrigated Water Use Index) and GPWUI (Gross Production Water Use Index). The interaction between irrigation deficit and N rate on WUE was not significant. N application rate significantly affected both IWUI (p<0.001) and GPWUI (p<0.001). Irrigation deficit significantly affected IWUI (p<0.05) but not GPWUI.

Irrigation Deficit (mm)	N Rate (kgN ha^{-1})	Total Available Water (ML ha^{-1})	IWUI (bales ML^{-1})	GPWUI (bales ML^{-1})
50	0	10.40	1.15	0.87
50	150	10.40	1.45	1.10
50	250	10.40	1.53	1.16
50	350	10.40	1.59	1.21
70	0	9.82	1.15	0.86
70	150	9.82	1.57	1.17
70	250	9.82	1.67	1.24
70	350	9.82	1.65	1.22

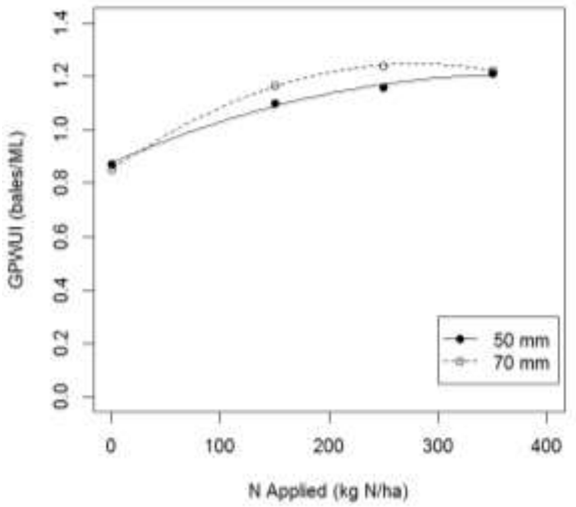


Figure 7.7. The measured GPWUI (Gross Production Water Use Index) as a function of applied N rates (0, 150, 250, and 350 kgN ha^{-1}) and irrigation deficits (50 or 70 mm).

Optimal NUE and WUE was achieved under an N rate of 250kgN ha^{-1} under a 70mm deficit. There was no significant gain in yield under either a higher N rate (350kgN ha^{-1}) or more intensive irrigation (50mm deficit) for yield. This optimal N rate is similar to the optimum N rates of 250 kgN ha^{-1}(Baird 2015) and 220 kgN ha^{-1} (Rochester 2003). Ensuring the applied input rates are optimum will improve the efficiency of the irrigated system and reduce the excessive N lost from a cropping system.

Although grower interest is high for new modern irrigation systems (such as sprinklers, drip and bankless), only 23% of Australian cotton growers had made changes to improve their standard irrigation system in the past 5 years (Roth 2014). Projects such as the Sustaining the Basin- Irrigated Farm Modernisation

Program is improving the uptake of modern irrigation systems, but research is still required to investigate the management strategies to fulfil the full potential of efficiency and productivity gains from modern irrigated systems. Janat (2008) studied various N and irrigation rates in cotton and concluded that between 30 and 50% of water applied by a traditional furrow irrigation system is wasted.

Conclusions

Over all the treatments between 29 to 47 kg N ha^{-1} was lost as in irrigation run-off. Approximately 50% of total N losses occurred in the first irrigation following N application. This first irrigation also used the most water compared to other irrigations, using 20% of total water applied in the season. Efforts to reduce N losses should focus these early irrigations. Of the treatments studied, the best NUE and WUE were achieved under an N rate of 250kgN ha^{-1} under a 70mm deficit. Reducing the amount of N lost and the amount of water applied in the first season irrigation would benefit NUE and WUE. Further investigations are required to better understand the effects of different methods of splitting and the timing of N application on NUE and WUE.

PROJECT DISCUSSION AND FUTURE RESEARCH NEEDS

Cotton grown in an irrigated system accounts for the majority of cotton production in Australia. Traditional furrow irrigation systems accounted for 92.1% of irrigated cotton (Roth 2014). A highly valuable commodity, the expansion of cotton production in Australia is increasing. The continual development, improvement and uptake of management practices are required to ensure the future of Australia's cotton industry is environmentally and economically sustainable.

Nitrogen (N) fertiliser use within the cotton industry is high. Increasing nitrogen use efficiency (NUE) and reducing N losses is a continual goal. Management of N losses can be achieved through better management of N fertiliser and irrigation systems.

In Australian cotton production systems, irrigation run-off water is captured and reused on farm. Nitrogen lost from the field can be recycled if applied back to the field before it is denitrified, up-taken, stored, lost through percolation or denitrified during the off-season from the storage sediments.

This project sought to measure and quantify the causes of nitrogen field N losses in run-off water and indirect N_2O-N emissions. The project also aimed to develop solutions to ameliorate N losses and N_2O-N losses which could easily be utilised by growers without significant yield penalties.

Cotton Nitrogen Budget

Plant N fertiliser recovery was 32% of what was applied, despite using optimal an optimal N rate (232 kg N ha^{-1}) and appropriate agronomic split application (upfront and mid-season application). During the season large N losses occurred from the field via the atmospheric, deep drainage and surface run pathways (143 kg N ha^{-1}). The losses occurred directly after fertilisation, predominantly at the start of the season when the majority of the fertiliser was applied (180 kg urea N ha^{-1}). This indicates that the form, placement and timing of the fertiliser were not synchronise with soil and crop N dynamics and irrigation practice.

The soil organic pool supplied 159 kg N ha^{-1}, in addition to fertiliser N, to the cotton plant. A large amount of the fertiliser (62 kg N ha^{-1}) remained in the soil organic N pool at the end of the season, and some N was returned to the field as plant stubble. However, these N sources are smaller than the soil N use by the plant. Based on the N inputs, losses and storage budget, a 45 kg N ha^{-1} soil deficit was observed over the season. Deficits in soil N are concerning because they represent loss of soil organic carbon, and declining soil health. Further longer term work is required to quantify the magnitude and significance of the soil N stock.

Tail Water Losses

Runoff N losses are driven by movement of fertiliser and soil N from the field. Under close to optimum N rates (around 200-250 kg N ha^{-1}) we measured run-off losses between 10-50 kg ha^{-1}. More specifically, when urea was broadcast on the surface of furrow irrigated cotton system, 23% of the applied fertiliser (260 kg ha^{-1}) was lost in run-off. The majority of the N losses occurred during the first irrigation, and was lost as NO_3-N, urea-N and DON-N. After fertilisation, irrigation water can dissolve and leach N compounds from the soil into the run-off water. This N loss represents a reduction in crop NUE. There are a number of strategies which can be used to reduce N run-off losses.

Firstly, N run-off losses can be reduced through reuse of N enriched tail/run-off water. The cotton irrigation is a closed system. N present in the water will either be lost via denitrification, stored in drainage sediments or reapplied on to fields in subsequent irrigations. Although the rates of N loss from the irrigation system are unknown, the fast return of N enriched irrigation water could be used for fertigation, augmenting the existing N fertiliser.

Secondly, N losses could be reduced through variation in the magnitude and method of N application. Moving to drilled from broadcast urea application has the potential to reduce N run-off losses by 50%. Similarly, we found that when N in mounds on the side furthest away from the irrigation furrows N-run off losses were reduced by 35%. Where WUE was constant, irrigation flow volume and length of irrigation had no effect on N losses. Interestingly, plots with higher N rates did not show the highest amounts of N run-off losses (see Table 7.6). Clearly the processes controlling N run-off losses from both fertiliser and mineralised soil N are more complex than we might initially imagine.

Ground water

Leaching of nitrogen (N) in intensive irrigated agriculture can be a significant loss pathway. Though many studies have focussed on mineral N losses, particularly nitrate, dissolved organic N (DON) has received less coverage.

Over a five year period (2008-2013) 108mm of deep drainage was measured under an irrigated cotton-wheat-maize rotation on a cracking clay (Grey Vertosol) soil. Approximately 3% of the 740 kg N ha^{-1} applied was lost via deep drainage. The majority of the N loss occurred during the first 3-4 irrigations and the N loss or its composition were not affected by the product or timing of the fertiliser application. The N in the drainage was composed of 12.8 kg NO_x-N ha^{-1}, 8.7 DON-N and 0.1 NH_4^+-N kg ha^{-1}. DON is an important component (40%) of N lost via deep drainage.

The fate of N lost via deep drainage is unknown. In 2000, concentrations of NO_3-N in ground water was 1.0 mg L^{-1}. A portion of groundwater N may be converted to N_2O. If groundwater with a NO_3-N concentration of 1.0 mg L^{-1} was used to irrigate fields, IPCC estimates suggest that approximately ~1.4% of total N_2O emissions would be emitted via this indirect pathway. Indirect emissions could contribute significantly to the overall greenhouse gas emission footprint of irrigated agriculture. However uncertainties in groundwater N concentrations and indirect N_2O-N production from groundwater N exist. Direct measurements of the N_2O-N water surface emissions, and improved monitoring of temporal and spatial surface and ground water total N concentrations are needed to refine estimates of N loss and indirect emissions from ground water.

Indirect Losses

Up to 3.5% of N fertiliser applied is lost directly from cotton fields as N_2O gas. The IPCC estimate suggest 0.0025 kg of N_2O-N may be produced indirectly from groundwater and surface drainage for each kg of N that is lost via run-off and leaching.

IPCC based estimates, using data from the Australian Cotton Research Institute, suggest that long term (2000-2010) 0.90 kg N_2O-N ha^{-1} yr^{-1} may be lost as direct surface emissions and 0.41 kg N_2O-N ha^{-1} yr^{-1} lost as indirect emissions. Of these indirect emissions, 0.30 kg N_2O-N ha^{-1} yr^{-1} would originate from the land surface as a result of reusing N-rich tail water, 0.08 kg N_2O-N ha^{-1} yr^{-1} from the head ditch, and 0.03 kg N_2O-N yr^{-1} from the tail drain. In total 31.3 % of the emissions could be potentially emitted via the indirect pathway at the farm scale using river water and recycled tail water for irrigation. A key uncertainty here is contribution of the fertigation N to emission from the land surface. The current emission factor derived for the cotton industry is a function of the applied fertiliser and does not include the N applied via the irrigation water.

However, IPCC estimates carry a large degree of uncertainty. A comparison of estimates of indirect N_2O-N emissions from the first 3 months of the cotton season showed that IPCC estimates over estimated total emissions. Indirect N_2O emissions, estimated using dissolved N_2O from irrigation tail drains were 0.503± 0.339 kg ha^{-1} of the irrigation surface area. In contrast, N_2O emissions estimated using the IPCC methodology were 0.843± 0.022 kg ha^{-1} of irrigation surface area. These indirect emissions were small and only accounted for 2% of total N_2O-N emissions and 0.02% of applied N across the whole farm.

The applicability of current IPCC emission factors

Accurate estimates of regional and national scale N_2O budgets remains a global priority. Current estimates of indirect N_2O emissions are largely based on the use of universal (‘Tier 1’) IPCC emission factors. Data on N_2O emissions across a range of land-use types and climates are necessary to provide more reliable regional and national estimates of N_2O emissions. We found that IPCC estimates of flux overestimate indirect emissions from irrigated cotton by a factor of at least 3.7.

IPCC EFs are based on the assumed relationship between DIN and N_2O-N emissions. We found moderate positive, nonlinear relationships between N_2O-N chamber-measured flux and concentrations of both dissolved inorganic nitrogen (DIN), dissolved total nitrogen (DTN) and dissolved N_2O-N. However there was also no relationship between concentrations of dissolved N_2O and DIN or DTN. Clearly no simple relationship between DIN and N_2O-N exist. As such, applications of IPCC methodology to estimate indirect N_2O emissions are unlikely to be accurate. A better understanding of the processes controlling N_2O production, and attempts to reconcile top-down and bottom-up estimates are necessary if we are to develop better estimate and mitigate indirect N_2O emissions.

Future Questions

Across the Australian cotton industry rates of N application may range between 93 to 500kgN ha^{-1} (Roth Rural, 2013, personal observations). Our study measured indirect emissions under an average N rate of 250 $kgNha^{-1}$. Under higher N rates, the proportion of N lost via irrigation runoff may vary substantially from what we observed. The effect of higher DIN concentrations on indirect N_2O emissions from irrigated cotton is unknown. Extending measurements of indirect emissions across a greater range of N rates will be required to develop better estimations of emissions.

Complex relationships between N_2O production and emissions exist. Measured emissions, in this project, were limited to the middle of the day, and only over the summer cropping system. N_2O emissions may also vary on a diurnal (e.g. Clough et al., 2007, Xia et al., 2013), seasonal (e.g. Clough et al., 2006, Harrison and Matson, 2003) and spatial (e.g. Rosamond et al., 2012, Turner et al., 2015) scale, though these temporal and spatial patterns may result from changes in other factors such as temperature and oxygen saturation and nitrate loading (Harrison et al., 2005, Rosamond et al., 2012). A better understanding of the controls on both N_2O production and outgassing through undertaking measurements of indirect emissions across a greater range of spatial and temporal scales.

Reduction of the apparent differences between bottom-up and top-down estimates of indirect emissions will increase our ability to accurately predict and manage indirect emissions. Further progress may be made using field-based and manipulative experiments which examine a wider range of factors associated with N_2O production (e.g. NPOC and oxygen saturation) and outgassing (e.g. wind speed).

Farming Practices to mitigate N losses and indirect N_2O emissions

Placement

Furrow irrigation is the most common irrigation method for cotton grown on vertisols. High losses of N occur early in the season, soon after fertilisation and the first application of water. In particular, N run-off losses are highest in the first irrigation following N application.

During 2014-2015 and 2015-2016 nitrogen in irrigation water and run-off (resulting from irrigation and rainfall) was measurement in a tillage cropping rotation experiment. In the continuous cotton treatments (2014-2015) when urea was broadcast on the surface of furrow irrigated cotton system, 8% of the applied fertiliser (260 kg N ha^{-1}) was lost from the field in the tail water in addition to the 10 kg DON-N kg N ha^{-1} present in irrigation head ditch water. The majority of the losses from the soil occurred during the first irrigation as nitrate and urea. Given that N may be returned to the field from recycling of irrigation water, contribution of N via irrigation should be included in the overall N budget to improve NUE.

Nitrogen run-off losses from continuous cotton were reduced by 50% when subsurface banding (100 mm) of the urea was used, this equated to a saving of 5% of the applied N. These results indicate that subsurface banding will reduce run-off losses in irrigated cotton production systems relative to broadcasted urea which is furrow irrigated in the continuous cotton treatments.

In a second treatment in irrigated maize rotation, the broadcasted urea was leached into the soil by rainfall before a 100 mm irrigation event. The run-off losses were similar to those seen under sub surface urea banding and losses were 0.5% of N fertiliser applied to the maize crop. If the broadcast urea is washed into the soil then the run-off losses are greatly reduced. The results suggest that changing the placement change the composition of the N losses.

Simple modifications in fertiliser placement relative to water movement could reduce N run-off losses. The goal here is to disconnect the fertiliser from the run-off water, either through deep placement or placement in the centre of the plant line.

Timing and soil N

The project did not look directly at the timing of fertiliser application. However the large losses of N early in the season suggest that timing of N application is not in synchrony with crop N requirements. Split application of N which better match to crop requirements may help reduce N losses.

Excess N applied may also be stored within the soil. Given the cotton plant uptakes a large proportion of N from the soil, as opposed to fertiliser N, managing long term soil organic nitrogen pools is a key issue. However we still lack a clear understanding of the controls surrounding soil N mineralisation and storage. Future work should investigate the effect of N application on long term soil organic N; and seek to optimise delivery of N produced by soil N mineralisation, rather than fertiliser N, to the crop.

Irrigation Practice

The reduction of nitrogen loss from the field by irrigating down the furrow adjacent to where the nitrogen was applied, and increasing the volume of applied water for the early crop irrigations are two management options that could be integrated by growers within their farming operation with little to no impact on their current systems.

Five key take home messages for the cotton industry, policy makers and growers:-

1. Further measurement of indirect N_2O-N emissions are required to accurately quantify the losses in semi-arid irrigation cotton production systems. The current IPCC emission factors are not appropriate in all situations.
2. Indirect emissions from the water surface are a small component of the N_2O-N farm footprint. There is significant nitrogen losses from the field with the tail water run-off and when reused on the fields, as is the practice, this may produce N_2O-N. The reuse of N rich water is not accounted for in the emission factors developed for the direct losses and may result in the overestimate in N_2O-N loss from the applied fertiliser. This is an area for further work.
3. Timing, placement, rate, and product need to be significantly improved to reduce losses and improve nitrogen use efficiency. Our work shows that run-off losses are significant during the early irrigations. Research effort should focus on improving nitrogen and water management early in the season.
4. The soil N pool contributes more N to the crop than the fertiliser applied in season. Our studies indicate a potential decline in the soil organic N pool. A decline in soil N has negative implications for maintaining productive agricultural systems. Improving fertiliser and soil organic N pool management is critical to sustainable production. A better understanding of N movement between the pools and controls on rates of storage and mineralisation are key research priorities.
5. Eliminating N losses with the run-off water reduces indirect emissions. Simple management practices such as the manipulation of the placement (subsurface vs broadcast) and rate of N application, changes in irrigation practice, and monitoring N runoff (e.g. using N test strips) can reduce N run-off losses substantially.

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