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

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Abstract

The potential contribution of surface and ground water to overall nitrous oxide emissions from irrigated production systems has not yet been quantified. In this study we have used the International Panel on Climate Change (IPPC) emission factor five (EF5) to determine the indirect emissions from the irrigation water surface and from the ground water when it is pumped back onto the surface for irrigation. The additional land surface emission from the irrigation water source N was also calculated and termed the “indirect land surface emission”. The study primarily used data collected (2000-2010) from the Australian Cotton Research Institute, Narrabri Australia to calculate indirect and direct farm emissions during the cotton production season from the research station. The average annual direct and indirect N₂O-N emissions are 0.90 kg N₂O-N ha⁻¹ yr⁻¹ direct; 0.20 kg N₂O-N ha⁻¹ yr⁻¹ indirect emissions from the land surface; 0.13 kg N₂O-N ha⁻¹ yr⁻¹ from the head ditch; 0.05 kg N₂O-N yr⁻¹ from the tail drain. In total 23 % of the emissions could be potentially emitted via the indirect pathway at the farm scale using river water for irrigation. If ground water with a concentration of (1.0 NO₃-N mg L⁻¹) was used to irrigate the crop then in total ~4% of the emissions would be emitted via the indirect pathway at the farm scale. Indirect emissions could contribute

significantly (20-30%) to the overall greenhouse gas emission footprint of irrigated agriculture. But further refinement of the indirect emission factor and improved monitoring of temporal and spatial surface and ground water total N concentrations are required for mass balance calculations. Direct measurement of the N₂O-N water surface emissions is required to validate the IPCC calculated values.

Highlights

- Indirect N₂O-N emissions could be a significant fraction of the total N₂O-N
- Indirect emissions estimates need to be quantified in the field
- Minimising off-field N flux is the key to reducing indirect emissions in irrigated systems

Keywords

Irrigated agriculture; Nitrous Oxide; Indirect Emissions; Nitrate

Introduction

The emission of nitrous oxide (N₂O-N) from agricultural production systems contributes significantly to global warming and stratospheric ozone depletion (Skiba and Rees, 2014). For this reason there has been many studies investigating the relationship between agricultural fertiliser applications, management and N₂O-N flux from the soil (Dalal et al., 2003). These studies have discovered possible large N₂O-N losses from irrigated agriculture systems (Dalal et al., 2003; Scheer et al., 2013), due to N fertiliser application. In cotton production systems, between 0.5 to 10 kg N₂O-N ha⁻¹ have been measured (Macdonald et al.,

2015). More specifically, in irrigated systems N losses via run-off (McHugh et al., 2008) and deep drainage (Chaudhuri et al., 2012) can also 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).

In Australian cotton production systems, at least 80% of the area is irrigated using gravity surface-irrigation systems (Roth et al., 2013). Indirect N₂O-N, as opposed to directly from the soil surface, can be produced along many stages of the irrigation network (Figure 1) and contribute to the total greenhouse gas footprint. There are no current estimates for the potential contributions of surface and ground water to nitrous oxide emissions from irrigated production systems in Australia.

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 km², 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 2).

Climate data

The average rainfall is 646 mm and is seasonally distributed (Figure 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 ($\text{NO}_3\text{-N}$) and ammonium-nitrogen ($\text{NH}_4\text{-N}$) concentration (Table 1) in the lower Namoi catchment was calculated from data collected by McLean (2003). Samples were collected by McLean (2203) after purging bore and $\text{NO}_3\text{-N}$ (Cadmium Reduction) and $\text{NH}_4\text{-N}$ (Nessler Method) determined in the field using a Hach DR3000 Field Spectrometer.

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 $\text{N}_2\text{O-N}$ 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). A brief overview of these studies approach follows. All of the 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.

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 N₂O-N emissions

The direct N₂O-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).

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

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 N₂O-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 N₂O-N ha⁻¹) is the difference between the total N₂O loss and the direct N₂O emission from the fertiliser.

Surface water

Potential indirect N₂O emissions from the surface water (head ditch and tail water) nitrogen concentration within irrigated agricultural systems were calculated using the current emission factor (EF₅; De Klein et al., 2006). The IPCC emission factor for leaching and run-off (EF₅) 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, all three emission factor components were used to calculate the indirect emissions. The indirect N₂O-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 $0.9 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ and the emission ranged between 0.8 to $1.3 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ for the treatments (Table 3). This represents 69% 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 22-31% of the total annual N_2O -N emission. There is a significant

relationship ($p < 0.05$) between rainfall and the total indirect emission data (Figure 3). This relationship is strongly influenced by the data point below 250 mm.

Surface Water

The $\text{NO}_3\text{-N}$ supplied to the field by the irrigation water varied each year (Table 2) and the indirect emissions from the water surface varied as a result. On average $0.24 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ was emitted from surface water within the head ditch. Tail water $\text{NO}_3\text{-N}$ loading was assumed to be $11 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ based on McHugh et al. (2008) and this equates to $0.0825 \text{ N}_2\text{O-N kg ha}^{-1}$. The average surface water emission represents 19% of the total (direct and indirect) average annual $\text{N}_2\text{O-N}$ emissions (Figure 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.

Land surface

The upper bound indirect average annual $\text{N}_2\text{O-N}$ emission was $0.18 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ and the treatment average ranged between 0.1 to $0.3 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ (Table 3). The average indirect land surface emission represents 12% of the total (direct and indirect) average annual $\text{N}_2\text{O-N}$ emissions (Figure 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 $0.1 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ and the treatment average ranged between 0.03 to $0.24 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$. The average lower

bound indirect land surface emission represents 7% of the total (direct and indirect) average annual N_2O -N emissions (Figure 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 the 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 $\text{ha}^{-1} \text{yr}^{-1}$, 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 1). The indirect N_2O emission of groundwater that has been pumped to the surface can be estimated using EF5. The potential emissions of the Namoi ground water once it is pump to the surface are 0.011 kg N_2O -N $\text{ha}^{-1} \text{ML}^{-1}$.

Discussion

Potential contribution of indirect surface water N_2O -N emissions

The direct emissions accounted for 69-79% of the average total yearly emissions (Figure 4). Indirect potential emissions derived from surface waters could contribute on 20-30% of the total N_2O -N kg ha^{-1} . Recent research suggests that the current EF₅ 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 24-30% more $\text{N}_2\text{O-N}$ $\text{kg ha}^{-1} \text{ yr}^{-1}$ 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). 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 $\text{N}_2\text{O-N}$ emissions (Table 2; 2002-2003).

Potential contribution of indirect groundwater $\text{N}_2\text{O-N}$ emissions

Cotton production system during 2001-2010 lost 20 $\text{kg NO}_3\text{-N ha}^{-1}$ below 1.2m due to deep drainage. It is unclear how much of this $\text{NO}_3\text{-N}$ reaches the production aquifer but certainly irrigated cropping systems can significantly increase the $\text{NO}_3\text{-N}$ 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 $\text{NO}_3\text{-N}$ and total N concentration of the groundwater resources within the Namoi Catchment. It is therefore impossible to quantify if the groundwater resource has changed over time due to $\text{NO}_3\text{-N}$ leaching from irrigated

agriculture. Over the last decade there has been improvements in water use efficiency that would have reduced $\text{NO}_3\text{-N}$ leaching (Silburn et al., 2013). Further reductions in $\text{NO}_3\text{-N}$ 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 $30\text{-}530 \text{ kg N ha}^{-1}$. 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 $0.05 \text{ kg N}_2\text{O-N ha}^{-1}$ of indirect emission could be produced during storage prior to irrigation. This alone is 6 % of the direct average annual land surface emission (Table 3) and 4 % of the total N_2O emission. This is much 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 $\text{N}_2\text{O-N}$ emissions at the farm scale ($188 + 13 \text{ ha}$) were $169 \text{ kg N}_2\text{O-N}$ direct; $37 \text{ kg N}_2\text{O-N}$ indirect emissions from the land surface; $1.8 \text{ kg N}_2\text{O-N}$ from the head ditch; $0.6 \text{ kg N}_2\text{O-N}$ from the tail drain. In total 23 % 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 ~4% of the emissions would be emitted via the indirect pathway at the farm scale.

Conclusion

Indirect emission, estimated from EF₅, from irrigated agriculture could potentially account for approximately 20-30% of the total annual N₂O-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 NO₃-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 NO₃-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 N₂O-N water surface emissions are required to validate the IPCC calculated values.

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Table 1. Groundwater nitrate-nitrogen (NO₃-N) and ammonium-nitrogen (NH₄-N) concentration (mg N L⁻¹) within bores from the Namoi Catchment (McLean, 2003) .

Aquifer	Sample number	Nitrate			Ammonium		
		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

Table 2. Estimation of NO₃-N loading in head ditch water and the potential indirect emissions of N₂O-N from the head ditch and surface water in cotton production systems.

Data source	Year	Head Ditch Water		Surface Water Indirect N ₂ O emissions*
		NO ₃ -N (kg ha ⁻¹)	N ₂ O-N (kg ha ⁻¹)	N ₂ O-N (kg ha ⁻¹)
Weaver et al (2013)	2000-01	39	0.3	0.4
	2002-03	109	0.8	0.9
	2005-06	29	0.2	0.3
	2006-07	16	0.1	0.2
Hulugalle et al (2012a)	2007-08	36	0.3	0.4
	2008-09	9	0.1	0.2
	2009-10	18	0.1	0.2
	2010-11	0.04	0.0	0.1

* Tail water nitrate loading assumed to be 11 kg NO₃-N ha⁻¹ (McHugh et al., 2008) and this equates to 0.0825 N₂O-N kg ha⁻¹. Surface water indirect N₂O emissions is the sum of the head ditch emissions and 0.0825 N₂O-N kg ha⁻¹.

376 Table 3. The N fertiliser rate and additional nitrate-nitrogen (NO₃-N) sourced from the irrigation water and the potential direct and indirect N₂O-
377 N emissions (kg N₂O-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 ₂ O emissions (fertiliser N) (kg N ha ⁻¹ yr ⁻¹)				Indirect Land N ₂ O 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				29				0.9				0.2	
2002-03 [*]			150				81				1.0				0.9	
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	0.3	0.1

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

Figure 1. Indirect (open) and direct (patterned arrow) emissions from irrigated production systems. Blue arrows represent transfers of N with water.

Figure 2 Average rainfall and temperature at Narrabri.

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Figure 3 Relationship between rainfall and indirect emissions

Figure 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).