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An irrigated cotton farm emissions case study in NSW, Australia

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ABSTRACT

The primary source of emissions in broadacre cropping is synthetic fertiliser applied to farmland, creating nitrous oxide from chemical processes in the soil. In high yielding irrigated cotton production, nitrogen remains a key input to maintain yields and maximise crop returns. This study aims to identify immediate strategies available to broadacre irrigation to reduce emissions and maintain profitability. Four emission mitigation strategies on a large broadacre irrigation farm in Northern New South Wales producing cereals, pulse and cotton crops were modelled. The results show rotating cotton with pulse crops, instead of wheat, can achieve an 8% reduction in emissions and increase whole farm gross margin by 12%, due primarily to the current historically high chickpea price and a reduction in applied nitrogen. Combining enhanced efficiency fertilisers in cotton crops in a more comprehensive abatement strategy has shown an indicative 13% emissions reduction from the baseline scenario, with a 6% reduction in farm gross margin from the increased fertiliser cost. However, uncertainty regarding the impact of EEFs on cotton yield in vertosol soils is noted. The soil sequestration from including a tree-lot in the emissions reduction strategy reduced whole farm emissions by 11% and reduced whole farm gross margin of 3%; however, difficulty in establishment and high establishment costs can add economic risk. Combining all three emissions reduction strategies results in a significant emissions reduction of 33% and a 4% gain in whole farm gross margin. Sensitivity analysis highlights gross margins results to be particularly sensitive to chickpea price movement. With this desktop modelling in mind, the discussion draws on industry research revealing that at a field scale, carefully balanced agronomic nuances exist between cotton cropping rotations and secure economic outcomes. The addition of achieving environmental objectives simultaneously with these variables is yet another future challenge facing government emissions abatement incentive programs and broadacre cropping businesses.

1. Introduction

Identifying management strategies that deliver favourable environmental outcomes while maintaining profitable farming businesses is a challenge. Furthering this challenge is the instability in government carbon and energy policy initiatives aiming to reduce greenhouse gas (GHG) emissions.

Emissions in the agriculture sector include methane and nitrous oxide, which are generated by biological processes. The cropping sector in Australia contributes 2.5% to national GHG emissions and overall, agricultural emissions are expected to grow by 23% from 2012 to 123 M tonnes (Mt) CO_2e by 2030 (Department of the Environment, 2013). The Australian Government reports on emissions across different industry sectors in the National Greenhouse Gas Inventory (NGGI) accounts (Australian Government, 2013). Currently, a key component of Australia's emissions reduction efforts is the Federal Government's Emissions Reduction Fund (ERF), a market-based mechanism designed to encourage lowest cost GHG abatement through participation in a reverse auction selling Australian Carbon Credit Units (ACCU) to government as sole purchaser. Although broadacre agriculture currently has little financial incentive and few available offset methods to enable participation in the ERF (Welsh et al., 2015), policy makers continue to encourage industry sectors within agriculture to work towards participation. In doing so, the agricultural sector can formally contribute to the national effort of meeting agreed reduction targets by 2030, as outlined in the COP21 Paris Agreement (UNFCCC, 2015).

Since the Carbon Farming Initiative Act was legislated in 2011 (ComLaw, 2011) a number of industry emission accounting tools have been developed to assist agricultural producers and farm advisors to understand the drivers of emissions by designing production scenarios

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Abbreviations: ACCU, Australian Carbon Credit Units; EF, Emission Factors; ERF, Emissions Reduction Fund; EEF, Enhanced efficiency fertiliser; GHG, Greenhouse gas; NGGI, National Greenhouse Gas Inventory; ST, Scenario Tool

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within each industry model and recording changes from a baseline (Australian Carbon Traders, 2015). This paper aims to outline four emission reduction strategies appropriate for cotton production systems and considers changes in farm emissions and gross margin.

2. Methods

In this paper, cropping and emissions scenarios (cropping rotations, changes in fertiliser management, land-use changes) have been analysed for a case study farm using the FarmGas Calculator Scenario Tool (ST) developed by the Australian Farm Institute (Australian Farm Institute, 2016). Separate gross margin budget analysis was conducted indicating the change in farm gross margin and the marginal cost of abatement.

2.1. Site characteristics

The case study farm, Togo Station, is an 11,000 hectare (ha) broadacre irrigated and dry-land farm in the Lower Namoi catchment of Northern New South Wales, Australia. The nearest town is Narrabri, which is approximately 30 km to the east of the farm. Topography is flat, open treeless floodplain with causeways weaved into irrigable and dry-land cropping land. Site details are summarised in Table 1.

Fig. 1 illustrates the farm layout of Togo Station and cropping enterprises for the year 2014–15.

Cotton is the primary source of income for the farming business, with the choice of rotation crops influenced heavily by the goal to optimise future cotton yields through disease break, water use and nutrient use efficiency (Back, 2015). Although access to irrigation water fluctuates on an annual basis, for simplicity this study assumes a steady state of 4389 ha of cotton grown in rotation with a range of dry land crops. These crops are sown directly into freshly prepared fields after cotton harvest, relying on residual irrigation moisture and in-crop rainfall. The cropping rotation is assumed to be one summer crop (cotton) immediately followed by one winter crop, a fallow period of 12 months before being returned to cotton over a three-year period. Wheat is the preferred winter crop occupying approximately 75% of the cropping area. Chickpeas, safflower and canola make up the remaining 25% of rotational crops in the baseline scenario (Table 3). A uniform rate of nitrogen fertiliser is assumed for all fields, regardless of previous crop.

2.2. System modelling

Emissions modelling and analysis is presented for four on-farm strategies for emission abatement. These strategies were chosen in conjunction with the case study farm management as being realistic to implement with little disruption to the existing cropping program. Table 2 outlines the four scenarios and key assumptions.

Table 1
Details of the case study farm Togo Station, Narrabri.

Particulars	Details
Nearest township	Narrabri
Catchment	Lower Namoi Valley
State	New South Wales
Country	Australia
Latitude	30^{0}11′21.09″S
Longitude	149^{0}40′05.29″E
Elevation	207 m
Irrigable land	8777 ha
Dry land farming	500 ha
Causeways and support land	1723 ha
Average annual rainfall[a]	661.6 mm

[a] Australian Bureau of Meteorology, 2016.

2.3. Scenario a. Pulse rotation

This strategy involves growing cotton in rotation with chickpeas. As a pulse crop, chickpeas fix nitrogen that allows for a reduction of applied fertiliser in the following rotation crop (in this case cotton). It is assumed the 80 kg N/ha produced from the pulse crop is a direct substitute for 80 kg N/ha applied fertiliser. However, uptake of nitrogen and yield can vary depending on source. A recent study by Rochester and Bange (2016) found the uptake of applied nitrogen fertiliser varied between 27 and 38% with organic soil nitrate providing the balance. The study found over the longer term, reliance on N fertiliser increased as yields increased. Rochester (2011) found recovery rates of N fertiliser rates were lower in legume-based cotton systems, suggesting lower nitrogen use efficiency and a preference to uptake organic N over applied N.

Other agronomic benefits of a varied rotation may be lost when removing all other crops from the farming system. One study found, when grown in rotation with cotton, wheat offered the highest gross margins per ha and per mega litre of water used (Powell and Scott, 2015) and improved overall soil quality due to a range of factors including the high density of sub-soil root structure of wheat (Hulugalle and Scott, 2008). Further to this, other studies have shown cotton seedling establishment can be compromised following a legume rotation, and hence yield (Rochester et al., 2001). Disease risk is also increased by sowing leguminous rotation crops which do not offer a break to the soil born disease verticillium wilt. This can negatively impact lint yield and fibre quality.

It has been assumed in this analysis that irrigated cotton yield will not change from the cotton wheat rotation in the baseline scenario. A 5% yield decrease for the cotton crop is considered in the sensitivity testing.

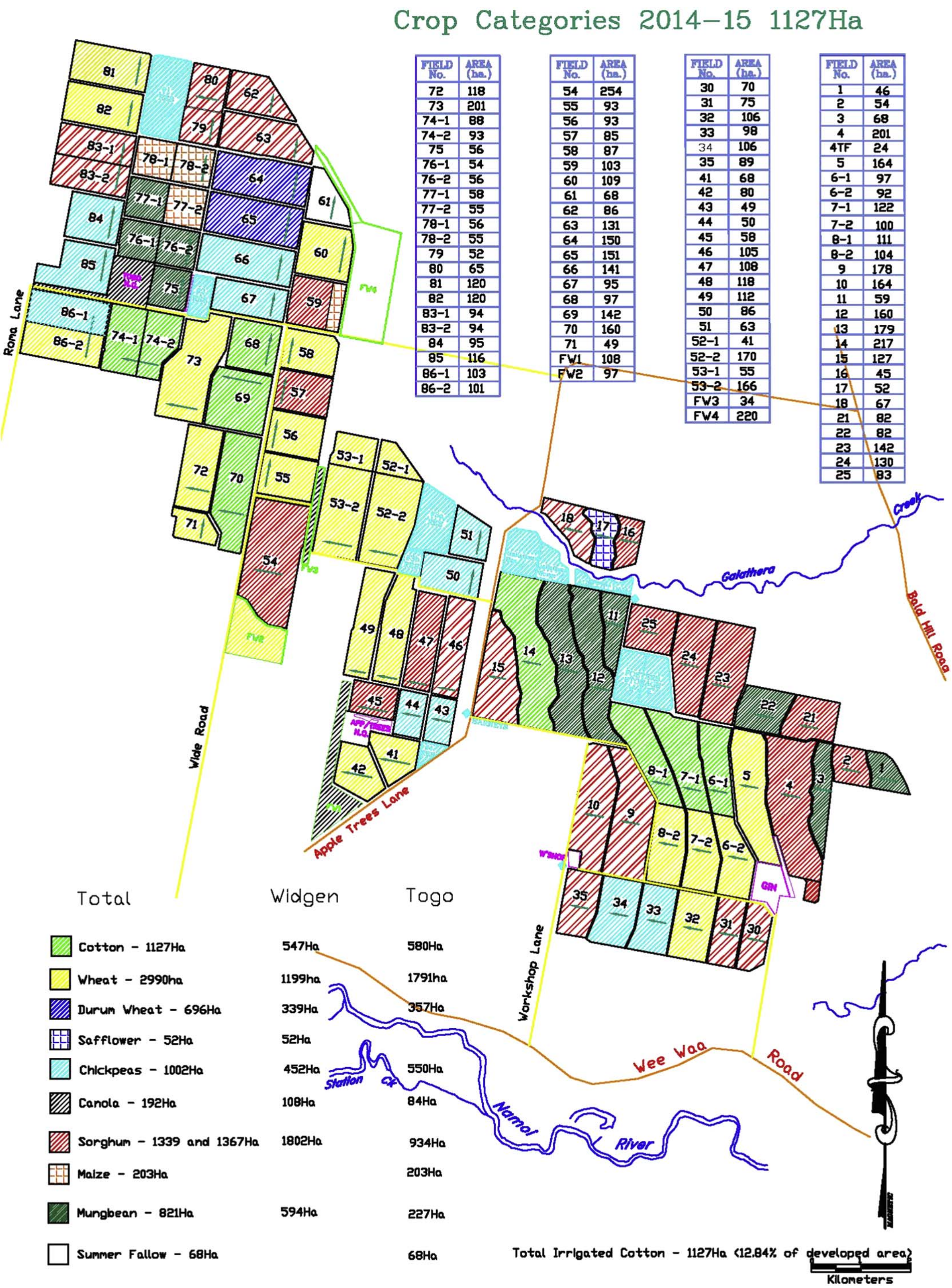
2.4. Scenario b. Enhanced efficiency fertilisers

This emissions reduction strategy involves substitution of granular urea for an enhanced efficiency fertiliser at a price premium to urea of 30%. A range of studies has shown emissions of nitrous oxide from EEFs can be significantly reduced (Chen et al., 2007; De Antoni Migliorati et al., 2014). The benefit of this strategy is that it can be implemented with no disruption or change to the existing farm rotations or management practices.

EEFs have proven to be a useful tool in mitigating nitrous oxide emissions in farming systems (Scheer et al., 2016; Suter et al., 2016), although yield response has been mixed. Cost benefit analysis in North Queensland sugar cane crops have indicated that EEFs are viable (Australian Canegrower, 2016; Pivot, 2014). However, research by Chen et al. (2007) suggests irrigated cotton utilises added nitrogen poorly, and trials with EEFs showed less than optimal uptake of nitrogen, below those required (222 kg N/ha) for maximum yield. Some studies have shown the effectiveness of EEFs to be limited on heavy clay soils with poor drainage (Johnstone and Norton, 2010) i.e. greater access to nitrogen has not translated into yield increases, which does apply to the grey-black vertosols on the case study farm. The yield assumptions for the EEF scenario in FarmGas assume cotton lint yield is not compromised by the change in nitrogen fertiliser products from the baseline scenario. For simplicity N rates have remained the same. A 5% cotton yield decrease in association with the EEF is considered during sensitivity testing.

2.5. Scenario c. Establishment of a tree-lot

A feasibility study by the Australian Farm Institute (2013) on establishing a tree-lot was used to estimate the costs and returns of participating in the ERF using the afforestation method, whereby the tree-lot would generate ACCUs. The FarmGas Scenario Tool provides an estimate of the potential quantity of carbon that might be sequestered



Crop Categories 2014–15 1127Ha

FIELD No.	AREA (ha.)
72	118
73	201
74-1	88
74-2	93
75	56
76-1	54
76-2	56
77-1	58
77-2	55
78-1	56
78-2	55
79	52
80	65
81	120
82	120
83-1	94
83-2	94
84	95
85	116
86-1	103
86-2	101

FIELD No.	AREA (ha.)
54	254
55	93
56	93
57	85
58	87
59	103
60	109
61	68
62	86
63	131
64	150
65	151
66	141
67	95
68	97
69	142
70	160
71	49
FW1	108
FW2	97

FIELD No.	AREA (ha.)
30	70
31	75
32	106
33	98
34	106
35	89
41	68
42	80
43	49
44	50
45	58
46	105
47	108
48	118
49	112
50	86
51	63
52-1	41
52-2	170
53-1	55
53-2	166
FW3	34
FW4	220

FIELD No.	AREA (ha.)
1	46
2	54
3	68
4	201
4TF	24
5	164
6-1	97
6-2	92
7-1	122
7-2	100
8-1	111
8-2	104
9	178
10	164
11	59
12	160
13	179
14	217
15	127
16	45
17	52
18	67
21	82
22	82
23	142
24	130
25	83

	Total	Widgen	Togo
▨	Cotton - 1127Ha	547Ha	580Ha
▨	Wheat - 2990ha	1199ha	1791ha
▨	Durum Wheat - 696Ha	339Ha	357Ha
⊞	Safflower - 52Ha	52Ha	
▨	Chickpeas - 1002Ha	452Ha	550Ha
▨	Canola - 192Ha	108Ha	84Ha
▨	Sorghum - 1339 and 1367Ha	1802Ha	934Ha
⊞	Maize - 203Ha		203Ha
▨	Mungbean - 821Ha	594Ha	227Ha
☐	Summer Fallow - 68Ha		68Ha

Total Irrigated Cotton - 1127Ha (12.84% of developed area)

Fig. 1. Farm map of Togo Station showing the crops grown and crop areas in the 2014–2015 cropping season.

in plots of trees planted on the farm. FarmGas calculations use the National Carbon Accounting Toolbox (NCAT) method to estimate carbon sequestered over the life of the tree-lot and results are reported on an average per annum basis. The price of ACCUs used in the tree-lot analysis was $13.95 for the modelled period, as per the ERF auction results on 16 April 2015 (Clean Energy Regulator, 2015).

Successful establishment of the tree-lot in dry land conditions is essential to achieving modelled sequestration rates. Environmental plantings established under a range of climatic factors may greatly reduce plant population rates and force second and third attempts at seeding (Johnson et al., 2009). The gross margin analysis considers variable costs on an annual basis. As the cost of tree-lot establishment is considered a capital investment, it is not included in the analysis. The annual cost of the tree-lot of $736/ha does include the interest costs of establishing the tree-lot and the opportunity cost of converting dry-land farming into a tree-lot. The opportunity cost of removing this land from farm production has been estimated by averaging the dry-land gross margin across all enterprises for the current year. The value of biodiversity has not been accounted for.

2.6. Scenario d. Pulse rotation, EEF and tree-lot

Commercial farms aiming to reduce emissions may use a combination of strategies to achieve their target. This scenario highlights the

Table 2
Abatement scenarios and key case study assumptions on Togo Station, Narrabri, NSW.

Scenario	Land use change	Key assumptions
a. Pulse Rotation	Change the cropping rotation to chickpeas planted in rotation with irrigated cotton	Chickpea rotation fixing 80 kg of N/ha[b], reducing cotton N fertiliser rate from 300 kg N/ha[c] to 220 kg N/ha
b. EEF	Enhanced efficiency fertilisers (EEF) applied to irrigated cotton crop	Apply half of the 300 kg N/ha as EEF. 150 kg N/ha EEF applied pre-plant. 150 kg N/ha applied water-run[c], as urea. N fertiliser Emissions Factor (EF) used in FarmGas calculations reduced from 0.0055 to 0.00385 for Enhanced Efficiency Fertilisers[d]
c. Tree-lot	500 ha tree-lot[a] on a dry land paddock	Successful establishment of mixed species tree-lot in dry land conditions
d. Pulse rotation + EEF + Tree-lot	500 ha tree-lot replacing dry land cropping rotation Chickpeas planted in rotation with irrigated cotton EEFs used on irrigated cotton crop	Successful establishment of tree-lot in dry land conditions Chickpea rotation adding 80 kg of N/ha, reducing cotton N fertiliser rate to 220 kg N/ha Emission factor used in FarmGas calculations reduced from 0.0055 to 0.00385 for EEFs

[a] Australian Farm Institute (2013).
[b] GRDC (2013).
[c] Back (2015).
[d] Soares et al. (2015).

benefits and costs of combining all three scenarios, which results in the farm growing cotton in rotation with chickpeas, using EEFs on the cotton crop and establishing a tree-lot.

2.7. *FarmGas modelling and gross margin analysis*

Emission scenarios on the case study farm were estimated using the FarmGAS Calculator ST. This tool enables the user to investigate GHG abatement options through modifications of emission calculations and ‘what if’ scenarios for a range of agricultural enterprises including beef and sheep production, broadacre cropping systems, intensive livestock systems, horticulture and tree-lots. Smith et al. (2014) used the FarmGas calculator in a study to determine whole farm emissions of a mixed farming enterprise at Wee Waa, New South Wales. The Australian Farm Institute (2013) used the FarmGas calculator to analyse economics and emissions for an environmental eucalypt plantings in three separate locations in Australia.

The default settings in the FarmGas calculator are based on the internationally accepted accounting method used by the Department of the Environment (DotE) to estimate Australia's emissions from the agricultural sector (Australian Farm Institute, 2014). FarmGas calculator does not calculate some soil-based emissions such as agricultural liming and the application of organic fertilisers, nor carbon sequestration from activities which affect soil carbon, as these calculations and data input requirements are either too complex, or the emissions are not included in the 2014 NGGI methodology for the agriculture sector (Australian Farm Institute, 2014).

The “cotton” and “N fixed by legume crop” Emission Factors (EF) were replaced in the FarmGas calculator to reflect the latest values published in the National Inventory Report (Department of the Environment, 2015). The cotton EF was reduced from 0.550% to 0.385% in the EEF calculations based on published research findings (Soares et al., 2015). The FracWET EF remains at 0.192% for dry land crops and is 0.932% for the irrigated cotton.

A crop “gross margin” is the gross income from an enterprise less the variable costs incurred in achieving it. It does not include fixed or overhead costs such as depreciation, interest payments, rates or permanent labour. Farm gross margins can be a useful guide to compare management strategies and rotations, however do not capture the full costs of production, consider cashflow impacts or provide any guide of risk (NSW Government, 2016). Crop yields, fertiliser rates and gross margins were provided by the property managers of Togo Station. Current market rates of commodities were sourced from Narrabri commodities trading house Agvantage Commodities (2015). All remaining farm cropping calculations and costs have been extracted from the New South Wales Department of Primary Industries Cropping Gross Margin Analysis (NSW Government, 2012; Powell, 2015).

2.8. *Sensitivity testing rationale*

An analysis using static values and assumptions is subject to change or error (Pannell, 1997). Additional analysis was conducted where there was uncertainty with analytical assumption. This included the commodity prices of chickpeas, cotton, EEF premium and a potential cotton yield reduction from either the chickpea rotation or the EFFs.

The chickpea price at the time of analysis of $800/t was significantly higher than the long-term average price of $470/t. In the base scenario, the breakeven yield was 0.6 t/ha (less than half the assumed yield of 1.5 t/ha) and the breakeven price at the assumed yield was $322/t. To understand the sensitivity of the chickpea price on the analysis, a price of −/+ 40% ($480/$1120) was considered. The cotton price which historically shows less variation had a price range of +/− 10% ($450/$550) considered. The EEF premium of 30% compared to urea was tested at 10% and 50%. As there was uncertainty in the research about potential cotton yield reductions when including chickpeas in a cotton rotation and in conjunction with the application of EEFs a 5% yield decrease was assumed and analysed.

The baseline price of nitrogen fertiliser has not been sensitivity tested, only the EEF premium. A recent study by (Welsh et al., 2017) notes the current nitrogen fertiliser price per tonne is at historical lows in Net Present Value terms, offering future opportunities for sensitivity testing and whole farm GHG modelling.

The sensitivity analysis was conducted to indicate the change in economic results, should any of the above key variables change.

3. Results

The three year rotational cropping summary for the case study farm baseline scenario was summarised on an annual basis in Table 3. Tables

Table 3
Baseline cropping scenario on Togo Station, Narrabri, NSW showing crop areas (ha), yields (t/ha), prices ($/t), costs ($/ha) and total GHG emissions (CO2e t/ha) for the 2014–15 cropping year.

Baseline scenario cropping enterprise	Area (ha)	Yield (/ha)	Price ($/t)	Costs ($/ha)	CO_2e (t/ha)
Irrigated cotton	4389	11 bales	500	4000	1.77
Dry land chickpeas	1003	1.5 t	800	483	0.30
Dry land wheat	3322	2.5 t	340	294	0.13
Dry land canola	125	1.2 t	500	471	0.15
Dry land safflower	439	1.5 t	600	220	0.03
Farm total/average	9278				0.92

Table 4
Pulse scenario cropping rotation for Togo Station, Narrabri, NSW showing crop areas (ha), yields (t/ha), prices ($/t), costs ($/ha) and total GHG emissions (CO2e t/ha) for the 2014–15 cropping year.

Pulse scenario 1 cropping enterprise	Area (ha)	Yield (/ha)	Price ($/t)	Costs ($/ha)	CO_2e (t/ha)
Irrigated cotton	4389	11 bales	500	3884	1.39
Dry land chickpeas	4899	1.5 t	800	483	0.30
Farm total/average	9278				0.85

Table 5
EEF scenario cropping rotation for Togo Station, Narrabri, NSW showing crop areas (ha), yields (t/ha), prices ($/t), costs ($/ha) and total GHG emissions (CO2e t/ha) for the 2014–15 cropping year.

EEF scenario 2 cropping enterprise	Area (ha)	Yield (/ha)	Price ($/t)	Costs ($/ha)	CO_2e (t/ha)
Irrigated cotton	4389	11 bales	500	4131	1.52
Dry land chickpeas	1003	1.5 t	800	483	0.30
Dry land wheat	3322	2.5 t	340	294	0.13
Dry land canola	125	1.2 t	500	471	0.15
Dry land safflower	439	1.5 t	600	220	0.03
Farm total/average	9278				0.80

Table 6
Tree-lot scenario cropping rotation for Togo Station, Narrabri, NSW showing crop areas (ha), yields (t/ha), prices ($/t), costs ($/ha) and total GHG emissions (CO2e t/ha) for the 2014–15 cropping year.

Tree-lot scenario 3 cropping enterprise	Area (ha)	Yield (/ha)	Price ($/t)	Costs ($/ha)	CO_2e (t/ha)
Irrigated cotton	4389	11 bales	500	4000	1.77
Dry land chickpeas	1003	1.5 t	800	483	0.30
Dry land wheat	2822	2.5 t	340	294	0.13
Dry land canola	125	1.2 t	500	471	0.15
Dry land safflower	439	1.5 t	600	220	0.03
Tree-lot	500	1.79 t	14	736	−1.79
Farm total/average	9278				0.82

Table 7
Pulse + EFF + tree-lot scenario cropping rotation for Togo Station, Narrabri, NSW showing crop areas (ha), yields (t/ha), prices ($/t), costs ($/ha) and total GHG emissions (CO2e t/ha) for the 2014–15 cropping year.

Pulse, EEF, tree-lot scenario 4 cropping enterprise	Area (ha)	Yield (/ha)	Price ($/t)	Costs ($/ha)	CO_2e (t/ha)
Irrigated cotton	4389	11 bales	500	4000	1.20
Dry land chickpeas	4389	1.5 t	800	483	0.30
Tree-lot	500	1.79 t	14	736	−1.79
Farm total/average	9278				0.61

Table 8
Emission abatement strategy results for Togo Station, Narrabri, NSW showing per cent change in whole farm abatement CO_2e, per cent change in whole farm gross margin, marginal cost/benefit per unit CO_2e from baseline and per cent change in whole farm emissions intensity (CO_2e t/cotton lint bale).

Scenario	Δ Whole farm abatement (CO_2e)	Δ Whole farm gross margin (per cent)	Marginal cost or (benefit) abatement ($ per t CO_2e) from baseline	Whole farm emissions intensity (CO_2e t/bale)
Baseline	0	0	0	0.177
1. Pulse	−8%	+12	(1566)	0.162 (−8%)
2. EFF	−13%	−6	519	0.155 (−13%)
3. Trees	−11%	−3	276	0.158 (−11%)
4. Multi	−33%	+4	(128)	0.118 (−33%)

4–7 outline the cropping summary for each of the modelled emission reduction scenarios.

Table 8 summarises the GHG emissions and gross margin results of each scenario. Gross margin calculations consider the impact on variable costs of each land use change.

The economic analysis of each scenario provides a useful guide to risk assessment and likelihood of up-take by the grower of each abatement strategy. The estimated emissions from each cropping scenario using the FarmGas calculator, indicates replacing cereals and other non-leguminous crops with a legume can have a positive impact in reducing whole farm emissions. In comparison to the other scenarios, the pulse rotation is the least effective abatement strategy making the smallest reduction to farm emissions with a reduction of 8%. The substitution of EEFs into the cotton rotation shows a substantial reduction in the amount of GHGs produced from a cotton crop (reduction of 13%), although reducing whole farm gross margin by 6%. The addition of a 500 ha tree-lot into the case study farm, replacing non-irrigable farm land (500 ha) provides some diversity in the abatement strategies (reduction of 11%). Combining all three emission reduction strategies results in a significant emissions reduction of 33% with a 4% gain in whole farm gross margin.

Each abatement scenario has a varied financial impact, ranging from a cost of $519/t CO_2e to a benefit of $1566/t CO_2e. The strategies with an increase in area grown to the high value chickpea crop have improved the whole farm gross margin. Long-term research by Hullugalle and Scott (2008) also suggests a chickpea crop is a sustainable option compared to wheat due to the moisture conservation properties provided by the above ground biomass. The gross margin results are sensitive to the historically high value of the chickpea price, which is analysed in the sensitivity testing. At a 30% premium to urea, the EEFs are the most costly emission abatement strategy at $519/t CO_2e. The EEF premium is also discussed in sensitivity testing.

The tree-lot is also a costly abatement strategy in this desktop analysis primarily due to the high opportunity cost and inability to register sizeable commercial revenue from sequestering carbon. However, the biodiversity benefits such as reduced erosion, increases in flora and fauna and improved water quality have not been accounted for. The tree-lot FarmGas calculations showed only meagre annual carbon sequestration (1.79 t CO_2e/ha/yr) when compared with those tree-lots in higher rainfall zones (> 800 mm p.a.) that could be expected to sequester between 5 and 15 t/ha/year CO_2e (Australian Farm Institute, 2013).

The assumption that the tree-lot is successfully established in dry land by direct seeding is critical to the modelling results. A study on native species establishment by Dalton (1992) found bi-monthly watering and residual weed control for a 3-metre radius to critically influence seedling survival in arid zones. A successful establishment is required for a tree-lot to sequester the quantities of CO_2e indicated by FarmGas ST output.

With the combination of all three emission reduction strategies, a 33% reduction in emissions is achieved with a 4% increase in the farm gross margin. The additional profit from the high value chickpeas offsets the cost of establishing the tree-lot and the additional premium of the EEF. This scenario indicates how a farm may use a combination of strategies to reduce emissions while ensuring farm profit is maintained. The risks discussed for the individual strategies remain in the combination strategy.

Empirical evidence within other Australian agricultural industries to reduce farm emissions complements these results. Harrison et al. (2016) also found that a combination of management strategies was needed in extensive beef farming to enhance live weight turnoff and reduce emissions intensity. Doran-Browne et al. (2016) found planting trees for carbon sequestration an effective carbon offset management strategy, however his study did not consider the costs of sequestration and the case study area was in South-East NSW (an area of high rainfall). In a whole farm systems analysis of 60 Tasmanian dairy farms Christie et al. (2016) concluded that N fertiliser applications should be a target area to lower emissions.

Researching the marginal abatement cost of crop-livestock broadacre farming in Western Australia, Tang et al. (2016) modelled a low cost of \$29.30/t CO_2e when considering combinations of land use; livestock, cereals and legumes. Within the paper Tang et al. (2016) compared his results to other recent Australian studies in broadacre industries with abatement costs ranging from \$50–\$80/t CO_2e. The abatement cost within this study range from a cost of \$519/t CO_2e to a benefit of \$1566/t CO_2e. It is difficult to compare these to existing studies that are in different industries, regions and consider unique abatement strategies.

The fourth Emissions Reduction Fund auction in November 2016 achieved an average price of \$10.69 (Clean Energy Regulator, 2016) indicating that in some industries the cost of abatement is considerably lower than others. In addition to the abatement cost are the transaction costs associated with participating in the ERF (e.g. initial accreditation, ERF registration and independent auditing required for projects). For the cotton industry these costs are currently prohibitive primarily due to the low potential of total farm abatement and the minimum abatement requirement of projects (Welsh et al., 2015).

3.1. Sensitivity testing results

Some of the key variables that the results are sensitive to include the commodity prices of chickpeas, cotton, EEF premium and the cotton yield in the pulse rotation and in conjunction with EEFs.

The chickpea price at the time of analysis of \$800/t is significantly higher than the long-term average price of \$470/t. In the baseline analysis, changing to a pulse rotation results in an increased farm gross margin and there is an economic benefit, rather than cost of abatement. To understand the sensitivity of the chickpea price on the analysis, a price of −/+ 40% (\$480/\$1120) is considered, see Fig. 2.

A 40% reduction in the chickpea price brings the price in line with long term average pricing. The 40% price reduction results in a 22% reduction in farm gross margin and makes this abatement strategy the most costly at \$1010/t CO_2e. In the combined strategy scenario abatement also changes from a benefit to a cost of \$439/CO_2e, with the chickpea price reduction. As expected, a 40% increase in the chickpea price makes the scenarios including this strategy even more profitable (see Fig. 2).

As all scenarios grow the same area of irrigated cotton, a change in the cotton price affects the scenarios equally so does not change the cost ranking of the strategies.

At a premium of 30% to urea, the EEF scenario is the most costly abatement strategy. When an EEF premium of 10% was modelled, the cost of the emissions strategy dropped by 66% to \$174/t CO_2e, making it a cheaper option than the tree-lot. An EEF premium of 50% increased the cost of the strategy by 66% making it substantially more expensive than the other modelled emission reduction strategies.

All scenarios are sensitive to the cotton gross margin; a potential yield reduction because of either the pulse rotation or EEF application significantly changes the results of the analysis. For the pulse rotation, instead of increasing farm gross margin (by 12% in the baseline), the yield reduction of the cotton results in a reduced gross margin of 1% from the baseline. The pulse rotation remains the most cost effective strategy (with chickpeas at \$800/t) at \$101/t CO_2e, followed by the tree-lot and then the combined strategy at \$293/t CO_2e and the EEF strategy remains the most expensive at \$519/t CO_2e. If the use of EEF on the cotton results in a 5% yield reduction, this strategy becomes three times more expensive changing from \$519/t CO_2e to \$1608/t CO_2e. These results show that a change in cotton yield can quickly change the cost of emissions abatement and farm profitability. With any changes to management strategy, crop yields need to be monitored closely.

Fig. 2. Sensitivity of the pulse rotation to the chickpea price.

4. Discussion/conclusion

This study has shown that trade-offs exists between GHG and profitability of an irrigated cotton farm in some abatement scenarios. Using the FarmGas ST, estimated on-farm emissions for a large broadacre cropping enterprise can be reduced by changing land use, cropping enterprises and fertiliser programs. A combination of these strategies, if successful, can lead to substantial reductions in whole-farm emissions and emissions intensity per cotton bale by as much as 33%, while maintaining farm profitability.

Altering cotton crop rotations to increase the area of pulses has shown a reduction in GHG and an increased profit with the chickpea price at historic high levels. Opportunities will exist to reduce emissions and increase profits; however, as a long-term emissions abatement strategy (which assumes historic average pricing), including a pulse rotation is likely to be costly with a low impact on emissions.

Changing fertiliser programs towards EFFs has shown good potential to provide emissions abatement under FarmGas modelling. The benefit of this strategy is that it is simple to implement with no changes required to the farming program. Although it is easy to implement, the cost of this strategy will limit likely uptake by farmers. Also, more product research will be necessary to validate the yield effects of EEFs in vertosol soils prior to potential industry adoption of this environmentally friendly product.

The most capital-intensive and seemingly risky abatement strategy is establishing a tree-lot to sequester carbon. Cotton is grown in areas with high solar radiation as an agronomic pre-requisite. In Australia, these regions are in mid-latitudes with inherently variable rainfall subject to periods of extreme maximum temperatures adding risk to establishment of non-irrigated crops. Even though the establishment cost was not considered in the modelling, the high opportunity cost to plant a tree-lot on prime agricultural land has made this a costly strategy. One alternative for cotton growers in arid areas may be to purchase land in a non agricultural, higher rainfall region to increase the chance of successful establishment and improve carbon sequestration yield.

Modelling has indicated opportunities for further research that include; validation of EEFs and cotton yield in vertosol soils where cotton is grown, further investigation into cotton yields in a chickpea rotation and the potential use of cover cropping to ensure enhanced groundcover and moisture conservation following chickpea rotation thus ensuring disease, erosion and soil health is maintained.

The combined scenario which incorporates all three modelled emission abatement strategies indicates how in practice, farm managers could use a combination of strategies to achieve emission reduction goals. From year to year different strategies may be more attractive depending on commodity pricing, disease status and environmental conditions. These variable farming conditions need flexible and adaptive approaches to farm management. Future government programs would ideally incentivise farmers who deal with this level of flexibility and participate in emissions reduction and/or abatement.

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