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Climate change, water security and the need for integrated policy development: the case of on-farm infrastructure investment in the Australian irrigation sector

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Abstract

The Australian Government is currently addressing the challenge of increasing water scarcity through significant on-farm infrastructure investment to facilitate the adoption of new water-efficient pressurized irrigation systems. However, it is highly likely that conversion to these systems will increase on-farm energy consumption and greenhouse gas (GHG) emissions, suggesting potential conflicts in terms of mitigation and adaptation policies. This study explored the trade-offs associated with the adoption of more water efficient but energy-intensive irrigation technologies by developing an integrated assessment framework.

Integrated analysis of five case studies revealed trade-offs between water security and environmental security when conversion to pressurized irrigation systems was evaluated in terms of fuel and energy-related emissions, except in cases where older hand-shift sprinkler irrigation systems were replaced. These results suggest that priority should be given, in implementing on-farm infrastructure investment policy, to replacing inefficient and energy-intensive sprinkler irrigation systems such as hand-shift and roll-line. The results indicated that associated changes in the use of agricultural machinery and agrochemicals may also be important.

The findings of this study support the use of an integrated approach to avoid possible conflicts in designing national climate change mitigation and adaptation policies, both of which are being developed in Australia.

Keywords: water security, greenhouse gas emissions, irrigation technologies, integrated trade-offs framework, Australia

 Online supplementary data available from stacks.iop.org/ERL/7/034006/mmedia

1. Introduction

Agricultural productivity in Australia grew by an average of 2.8% per year over the past 30 years, a rate which was

higher than that of the economy as a whole. This growth was largely due to the intensification, mechanization and modernization of agricultural systems (AGO 2006). A key mode of intensification involves moving from dryland to

irrigated farming systems. However, predicted climate change and increasing climate variability present irrigated agriculture with some significant challenges. Being a dry continent, Australia is highly vulnerable to risks associated with increasing water scarcity, and saving water and increasing water use efficiency are major challenges at all levels. One of the options well received by farmers is the conversion of less efficient irrigation systems to efficient pressurized systems (Green *et al* 1996, Lal 2004). For example, two-thirds of irrigators in the Murray–Darling Basin (MDB) changed their water management practices during 2004–05, and of these, 35% adopted pressurized irrigation techniques (Mackinnon *et al* 2009). The Australian government is also helping farmers to upgrade irrigation infrastructure through its \$5.8 billion Sustainable Rural Water Use and Infrastructure programme (DSEWPC 2011).

The decision to invest in new irrigation technology largely depends on two key factors: the water conservation benefits and the costs associated with implementing technology change (Mackinnon *et al* 2009, Qureshi *et al* 2001). However, other significant factors such as associated changes in energy dependency and greenhouse gas (GHG) emissions have been largely ignored in irrigation technology adoption decisions (Zillman *et al* 2008, Jackson *et al* 2010). Significantly, it might be expected that conversion to new pressurized irrigation systems would result in a net increase GHG emissions per hectare. More intensive land use might involve more fuel, farm machinery and agrochemicals, and the production, packaging, transportation and application of these also requires significant energy resources, leading to an increase in GHG emissions (Jackson *et al* 2010, Maraseni *et al* 2007, 2009a, 2009b, 2010a, 2010b). Of the total energy used in agriculture globally, 51% is expended in farm machinery manufacturing and 45% in the production of chemical fertilizers. In addition, increased fertilizer use contributes significantly to emissions. Between 1987 and 2000, nitrogen (N) fertilizer use in Australia increased by 325% (Dalal *et al* 2003), with more than 50% of the applied N either lost through leaching into the soil or released into the atmosphere as nitrous oxide (N₂O) (Verge *et al* 2007), a GHG which has 298 times more global warming potential than CO₂.

The impact of water management policies in driving increased energy consumption and GHG emissions has been largely ignored at the policy level (Khan *et al* 2004). Ideally, mitigation and adaptation strategies should complement each other in order to address climate change risks (Maraseni *et al* 2009b); however, within the water sector the relationship is potentially a reciprocal one. Water management policies and measures aimed at water resource use mitigation (effectively climate change adaptation in a drying climate) can in fact drive higher GHG emissions, and so be counter-productive when evaluated in terms of climate change mitigation. In the context of predicted climate change, and the proposed implementation of GHG reduction policies such as a carbon tax or an emission trading scheme (ETS), the perception of net economic and social benefits may no longer be valid. There is therefore an urgent need to critically evaluate energy-intensive responses to scarcity in

the water sector in order to understand the links between water use and GHG emissions (Pittock 2010). Not to do so, risks contradictory policy signals which may contribute to maladaptation (Barnett and O'Neill 2010). A topical example is the Wonthaggi Desalination Plant, a Victorian Government strategy to drought-proof Melbourne's water supply. This is an energy-intensive adaptation, reportedly contributing over 900 000 tonnes per annum of CO₂-e GHG emissions, which will drive positive feedbacks to the climate system (Barnett and O'Neill 2010).

This study evaluates the trade-offs associated with the adoption of more water efficient but energy-intensive forms of on-farm irrigation technologies through an integrated assessment framework. This novel cross-factoral approach makes a significant contribution to carbon accounting of crop production in general and the assessment of impacts of agricultural intensification through irrigation in particular.

Previous studies have compared the energy consumption of various irrigation technologies (Mrini *et al* 2001, Topak *et al* 2005, Chen and Baillie 2007, Baillie 2009). However, these studies fail to provide a complete picture as they have not analysed GHG emissions associated with the use of primary farm inputs, including farm machinery, fuels to run farm machinery and agrochemicals (fertilizers, manures, insecticides, herbicides, fungicides, plant regulators etc). The frequency (and amount) of farm inputs for the same crop may vary significantly under different irrigation systems, resulting in change in their relative energy use and GHG emissions. To pick up the range of variation and make reasonable policy recommendations, this study undertook five different case studies, incorporating a range of irrigation technologies and cropping systems.

2. Methods

2.1. Brief description of case studies

Case studies conducted under this project used information on fine-scale farm-level variability to inform an objective integrated analysis of the value of adopting new crop irrigation technologies. These studies involved detailed face-to-face interviews with irrigators who had converted their conventional irrigation systems to one of the newer pressurized irrigation systems. Interviews were based around a structured questionnaire, but also involved a less formal conversation (recorded in note form) regarding additional information about individual enterprises. Farmers were asked to provide information on machinery use, agrochemical inputs, irrigation water use and technology, energy use, crop yields, and income associated with a single crop rotation.

Enterprises assessed included three cotton farms on the Darling Downs, a vegetable (lettuce) farm in the Lockyer valley and a pasture-cropping (lucerne) farm on the Southern Downs (all in southern Queensland, eastern Australia). Irrigation technology transitions investigated were: from flood (furrow) to overhead sprinkler (lateral-move) in case studies 1 and 2; from flood (furrow) to trickle irrigation in case study 3; from overhead sprinkler (hand-shift) to trickle irrigation

Table 1. Key characteristics of case study farms.

Case study	Key characteristics					Irrigation technology					
	Location	Crop	Cropping area (ha)	Area under pressurized irrigation (ha)	Old		New		Yield (tonne/ML)	Yield (tonne/ML)	
					System	Water use (ML/ha)	System	Water use (ML/ha)			
1	Darling downs	Cotton	607	154	Flood (furrow)	6	Flood (furrow)	4	Sprinkler (lateral-move)	0.37	0.65
2	Darling downs	Cotton	1335	563	Flood (furrow)	5	Flood (furrow)	4	Sprinkler (lateral-move, centre-pivot)	0.41	0.58
3	Darling downs	Cotton	1011	37	Flood (furrow)	6	Flood (furrow)	5	Drip	0.4	0.5
4	Lockyer valley	Lettuce	80	80	Sprinkler (hand-shift)	3.75	Sprinkler (hand-shift)	1.785	Drip	17.8	20.9
5	Southern downs	Lucerne	750	620	Sprinkler (roll-line)	16	Sprinkler (roll-line)	8	Sprinkler (centre-pivot)	0.93	2.44

in case study 4; and from overhead sprinkler (roll-line) to improved overhead sprinkler (centre-pivot) systems in case study 5 (table 1). All five case study enterprises operate under highly seasonal and variable climatic conditions typical of southern inland Queensland. New irrigation technologies provide greater control over water application rates and timing and are a critical component of risk management strategies on these properties. Further detail is provided in the supplementary information (available at stacks.iop.org/ERL/7/034006/mmedia) to this paper.

2.2. Integrated modelling

An integrated framework was used to assess the effectiveness of different irrigation technologies at the farm level. This approach evaluated trade-offs between irrigation technologies, before and after conversion, in terms of water use efficiency and productivity, water savings, energy and GHG emissions, and relative costs of irrigation and associated equipment. As a general principle, trade-off analysis shows that, in order to obtain more of a desirable outcome of a system for a given set of resources and technology, less of another desirable outcome is obtained (Stoorvogel *et al* 2004). The framework has three main components—GHG modelling, hydrological modelling, and costs and benefits estimations—providing not only reliable estimates of water savings and GHG implications, but also estimates of trade-offs between achieving water security and environmental security.

For each case study, the type and quantity of farm inputs used, and the amount of energy consumed (and GHG emissions) due to production, packaging, storing, transportation and application of farm inputs for the same crop before and after using particular irrigation technology were investigated.

2.3. Greenhouse gas modelling

The GHG modelling component of the integrated framework compares emissions between two different irrigation systems due to: (1) the use of electricity, diesel and aviation gas for various farm operations; (2) agrochemical (all types of fertilizers, herbicides, insecticides and fungicides) production, packaging, storage and transportation; (3) soil derived nitrous oxide (N₂O) from nitrogen (N) fertilizer usage; and (4) farm machinery production and use. These are the major sources of GHG in a farming system (Maraseni *et al* 2007, 2009a, 2009b, 2010a, 2009b, Maraseni and Cockfield 2011) and are likely to vary due to changes in irrigation system. For example, a pressurized irrigation system could increase pumping (electricity and diesel) related GHG emissions but may decrease agrochemicals related GHG emissions due to adoption of precision agriculture (applying agrochemicals through irrigated water in response to crop requirements at particular stages of growth). It is likely that soil carbon sequestration rates will also vary between different irrigation technologies; however, it was not possible to include irrigation induced changes in soil carbon in the analysis, as there is currently no research in this area.

2.3.1. GHG emissions due to the use of electricity, diesel and aviation gas. The amount of electricity, diesel and aviation gas used for different farming operations (cultivation, planting, fertilizer and pesticide application, irrigation, harvesting etc) was extracted from farm records and verified with farmers. Energy content factor and GHG emission amounts were derived from DCC (2009), Mandal *et al* (2002) and Ozkan *et al* (2004). For example, energy content factor and GHG emission amounts for: (1) diesel and diesel oil are 38.6 MJ l⁻¹ and 75.2 gCO₂ MJ⁻¹; (2) aviation gas 33.1 MJ l⁻¹ and 72.4 gCO₂ MJ⁻¹; and (3) electricity MJ kWh⁻¹ and 281 gCO₂ MJ⁻¹ (DCC 2009, Mandal *et al* 2002, Ozkan *et al* 2004). Emissions factors for diesel and aviation gas include both combustion emissions factors (69.9 gCO₂e/MJ), and indirect emissions factors related to extraction, production, transport and delivery lost (5.3 gCO₂e/MJ). Similarly, emissions factor for electricity include emissions due to consumption (Scope 2; DCC 2009), and indirect emissions attributable to the extraction, production and transport of electricity and to the electricity lost in delivery in the network (Scope 3; DCC 2009). Emissions factors for electricity vary by energy mix, which is significantly different in different states of Australia. As all case studies are in southern Queensland, the Queensland emissions factor has been used here.

2.3.2. Emissions from production, packaging, storage and transportation of agrochemicals. Agrochemicals include fertilizers and chemicals (herbicides, insecticides, fungicides and plant growth regulators) used in cropping, with their production, packaging, storage and transportation requiring energy and contributing to GHG emissions. The amounts and types of different agrochemicals and manure before and after adopting a new irrigation technology come from farm surveys. The proportions of major elements in each fertilizer were estimated using its chemical formula and molecular and atomic weights. Conversion factors of 0.5 for herbicides and 0.25 for insecticides and plant growth regulator were used to obtain the approximate active ingredients in the mix (O'Halloran *et al* 2008). CO₂e emission factors for the production, packaging, storage and transportation of each kilogram of element (in fertilizer) and active ingredient (in herbicide, insecticide and plant regulators) are adopted from Lal (2004). The difference in GHG emissions from all agrochemicals provides the information about the changes in emissions from the agrochemicals due to changes in irrigation system.

2.3.3. Emissions of N₂O from soils due to N-fertilizer and manure application. The IPCC has set a default emission factor of 1.25% N₂O–N emissions per kilogram of applied N. However, research has shown large variations from the IPCC default emission factor. In Australia, the Cooperative Research Centre (CRC) for greenhouse accounting has established a set of emission factors suitable for Australian agricultural systems (O'Halloran *et al* 2008). The values used in the present study were: all irrigation crops, 2.1% (2.1 kg N₂O–N/100 kg N); irrigated pasture, 0.4%; and all

horticulture and vegetables, 2.1% (O'Halloran *et al* 2008). The total amount of N₂O–N was calculated and converted into N₂O (by multiplying by 1.57, the molecular weight of N₂O mol⁻¹ of N₂) and then into CO₂e.

We acknowledge that there could be some variation in N₂O emissions factors for the applied N-fertilizers for the same crops under different irrigation systems. For example, Sánchez-Martín *et al* (2008) conducted a study to understand the differences in N₂O emissions from two different irrigation (furrow and drip irrigation) systems in Spain. They found that drip irrigation reduced total N₂O emissions by 70% compared to the value for furrow irrigation, probably due to the lower amount of water applied and the different soil wetting patterns associated with drip irrigation systems. In Australia, the Climate Change Research Programme (CCRP 2012) is conducting intensive research to develop a nitrous oxide database which will be available through a web portal (www.N2O.net.au). However, at this stage, this information is not currently available. Consequently, we used the same emissions factors for the same crops under different irrigation systems (as discussed above). The application of manure also emits some amount of N₂O from the soil. However, since the overall amount of GHG emissions for manure is already considered in section 2.3.2 it is not discussed separately.

2.3.4. Emissions due to the production of farm machinery.

Several studies have estimated GHG emissions resulting from the production of a kilogram of farm machinery (Stout 1990, Helsel 1992, Maraseni *et al* 2007, 2009a, 2009b). Maraseni *et al* (2007) investigated peanut–maize cropping in southeast Queensland, Australia, and calculated GHG emissions due to the production of each kilogram of farm machinery and accessories. In that study, GHG emissions due to farm machinery usage were directly related to fossil fuel consumption, and estimated to be equivalent to 14.4% of the emissions from fossil fuel usage (Maraseni *et al* 2007, 2009a, 2009b, 2010a, 2010b, Maraseni and Cockfield 2011). This value is adopted in the current study. We acknowledge that there could be significant differences in GHG emissions associated with the production of farm irrigation machinery. However, energy used for the production and transportation of irrigation machinery and accessories in different irrigation systems, and associated GHG emissions, was not considered in this study since there has been no research reported in this area.

2.4. Hydrological modelling

Field experiments are the most accurate method for determining potential water savings. However, crop models such as soil, water, atmosphere and plant (SWAP) and Agricultural Production Systems sIMulator (APSIM) can provide useful estimates of potential water savings (Khan *et al* 2004, 2008a) where empirical data is unavailable. Khan *et al* (2004, 2008a, 2008b) and Khan and Abbas (2007) have effectively employed SWAP models to estimate potential water savings resulting from improved water management and

new technologies (drip and sprinkler irrigation systems) under a range of soil and climatic conditions.

Following Khan *et al* (2004), Khan and Abbas (2007) and Kroes *et al* (2008), the SWAP model was applied to provide an estimate of potential water savings. This approach calculates water and solute balances in the saturated and unsaturated zones of cropped soils, based on model inputs including meteorological, crop growth and drainage data. In this study, the model was simulated for the period between January 1980 and December 2007 under three different soil types (from light dispersible clays to heavy alluvial black cracking clays) with high soil moisture-holding capacity, two groundwater levels and three timings of irrigation.

SWAP modelling identified the range of potential water savings achievable with technology conversion under different cropping conditions, and enabled us to validate the farmers' assessments of (actual) water savings so as to ensure that our GHG and economic modelling did not over or under estimate results. Subsequent GHG and economic modelling was based on the validated farmers' estimates.

2.5. Economic modelling

A key component of the integrated framework was to undertake a benefit–cost analysis (BCA). In addition to the net present value (NPV) and break even (BE) water saving (ML/ha) were calculated to assess the economic viability of the conversion from the existing irrigation system to the new, more water-efficient irrigation system. The investment in the modern irrigation systems can be treated as economically viable if the present value of benefits is greater than the present value of costs (NPV > 0). BE estimates are crucial from both the farmer and infrastructure investment points of view to know the threshold level of water saving that must be realized before profit can be made.

Modern irrigation systems are complex and require significant initial capital investment. The stream of benefits flow over the life of a system, usually 15–25 years depending on the type of system. To measure economic returns from the on-farm investment in such technologies, the benefits from the new system were measured, taking into account the total impacts of the option: improvement in yield, quality, shift in cropping rotation, reductions in input costs, labour savings, water savings, and the benefit (or cost) of GHG emission/reduction, and other benefits. The costs of irrigation technology were divided into fixed costs (machinery, soil moisture monitoring equipment, pipes, concrete, etc) and variable costs (mainly for operation and maintenance such as power, fuel, usual maintenance and corner losses, if any).

Sensitivity analysis was used to test the robustness of the economic analysis by changing the values of key benefit parameters such as water saving, labour and yield benefits, water sharing, GHG emission prices, sprinkler irrigation technology life and interest rates. Temporary water trading was not considered; instead, a water sharing scenario based on 50:50 water sharing was considered.

The farm-level irrigation technology modernization model 'Waterwork' (Khan *et al* 2010) was used to evaluate

Table 2. Benefit and cost parameters used in the economic analysis of five case studies in southern Queensland.

Case study	Irrigation technology conversion	Parameter					
		Capital cost (\$/ha) ^a	Yield increase per ha (%)	Labour savings (%)	Water savings per ha (ML and %)	Irrigation efficiency	Change in nitrogen inputs (kg/ha)
1	Flood (furrow) to sprinkler (lateral-move)	3250	18	20	2.0(33)	90	-200
2	Flood (furrow) to sprinkler (centre-pivot)	1990	20	20	1.0(20)	90	-100
3	Flood (furrow) to drip	1950	12	15	1.0(17)	90	0
4	Sprinkler (hand-shift) to drip	5000	18	40	2.0(52)	92	+200
5	Sprinkler (roll-line) to sprinkler (centre-pivot)	2400	36	40	8.0(50)	90	0

^a Dollars are AUD.

the economics (costs and benefits) of technology adoption. The model was simulated for 25 years with an interest rate of 5%. In addition, the current temporary and permanent water trading prices, as a substitute for a water price through the water sharing⁴ and buyback programme⁵, were used in the economic modelling.

2.5.1. Economic model parameters and assumptions. The estimates of economic model parameters, both costs and benefits, were obtained through interviews with farmer, irrigation auditors, experts and/or dealers and literature reviews. A summary of the key parameters used in the economic models is given in table 2.

Assumptions included:

- quality improvements were only modelled for lettuce since the improvement in lettuce quality resulted in significantly higher market prices. Based on the farmer’s assessment, lettuce grown using drip irrigation brings 10% higher market prices;
- average temporary (allocation) water trading prices were assumed to be \$300/ML, whereas average permanent (water entitlement) water trading prices were assumed to be \$1500/ML (Murray Irrigation Ltd 2009);

⁴ Water sharing arrangements refer to the entitlement to exclusively access a defined share of water from a specific consumptive pool. This is defined in the relevant water plan for that water body or jurisdiction. In the case of investment in water-efficient irrigation technologies, the Australian Government, under the water for the future programme, may contribute towards the cost of irrigation technology conversion in return for access to a percentage of a farmer’s nominal entitlements which may be used to provide environmental flows or traded on the water market. For example, with a 50% financial contribution, the Government takes 50% of the annual water savings achieved through the new irrigation technology (a 50:50 water sharing arrangement).

⁵ The water buyback programme is an important component of the water for the future initiative for restoring balance in the Murray–Darling Basin. The Australian Government has committed \$3.1 billion over 10 years to purchase water in the Murray–Darling Basin. The programme will complement a range of other measures to achieve sustainable water management in the Basin (DSEWPC 2011).

- commodity prices and fuel prices were assumed to be constant over the period of analysis;
- tax savings are possible but are not included in the analysis; and
- the model did not include carbon prices in the base case; however, a price of \$10/tCO₂e and \$30/tCO₂e was used in order to evaluate the impact of a carbon price.

Once the GHG emissions from the changes in farm inputs were quantified for the different irrigation technologies, it was assumed that an introduced carbon price would increase the price of these farm inputs directly proportional to their GHG intensities, and that this increase in price would be passed on in full to the farmer. In reality, this assumption may serve as a reasonable proxy for how a carbon price may impact farm production as the demand curve for essential farm inputs is highly inelastic.

Figure 1 provides a conceptual flow diagram of the integrated analysis conducted in this study.

3. Results

3.1. Greenhouse gas emissions from different sources

Highest overall GHG emissions were associated with lucerne cropping under a conventional roll-line irrigation system (15 214 kg CO₂e/ha), while lowest emissions (3380.7 kg CO₂e/ha) were found in cotton farming systems using pressurized overhead lateral-move sprinkler irrigation systems (table 3). Adoption of new irrigation technologies contributed to an overall reduction in GHG emissions in four of the five case studies reported; total GHG emissions from cropping under the new technologies ranged from 52% (case study 5; conversion from roll-line to centre-pivot sprinkler-irrigated lucerne cropping) to 199% (case study 3: conversion from flood- to drip-irrigated cotton cropping) of total emissions for the conventional irrigation systems (table 3).

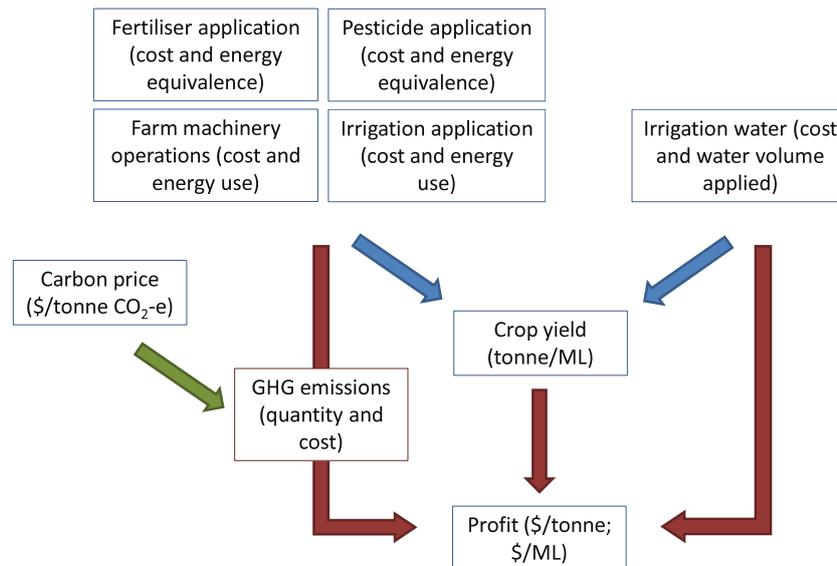


Figure 1. A conceptual flow diagram of the integrated analysis conducted on irrigated cropping systems adopting new irrigation technologies in southern Queensland.

The comparison of GHG emissions from individual sources reveals that irrigation-related emissions were highest from the lucerne cropping systems (case study 5); those from farm machinery (other than irrigation machinery) operations were highest from the lettuce farming systems (case study 4); those from agrochemical-related GHG emissions were found in cotton farming systems under flood and trickle irrigation systems (e.g. case study 3); and GHG emissions from soils due to use of N-fertilizer were highest for cotton farming systems under flood irrigation (case studies 1–3).

Comparison of GHG emissions per kilogram of crop harvested showed lucerne under roll-line irrigation having the largest emissions, followed by lucerne under centre-pivot sprinkler irrigation and cotton under trickle irrigation. The lowest emissions were observed in lettuce cropping under both irrigation systems. In contrast, if the comparison is made per megalitre of irrigation water, the lettuce farming systems were the highest emitters, followed by lucerne and cotton. As expected, on this basis (i.e., per ML), all pressurized irrigation systems emitted higher levels of GHGs than their counterparts.

These figures show that there is great variation in GHG emissions from different sources between different cropping systems. These variations could be due to different paddock histories, irrigation types, soil types and crop types. In some areas soil may be poor, requiring more fertilizers, and resulting in higher fertilizer-related emissions. Some crops (for example lettuce) need more intensive cultivation and harvesting operations, so farm machinery-related emissions could be higher than in other crops. Other crops (such as lucerne) need more frequent irrigation, so irrigation-related emission will be higher for them than the other crops. Therefore, without comprehensive analysis of GHG emissions from various sources, a complete picture cannot be drawn. Accounting for emissions from some sources and omitting those from others gives misleading information, from which

we may draw misleading conclusions, leading in turn to potential maladaptation.

3.2. Water saving estimates

The SWAP model was applied to estimate the potential water savings, and validate the estimates provided by the case study farmers. The results show that potentially up to 4.5 ML/ha water savings are possible. Among all the pressurized systems, drip irrigation systems generated the highest levels of potential water savings; however, high-end water savings were highly dependent on the technology, soil type, climate, crop and management of the system (table 4).

3.3. Economic evaluations

The economic evaluation results show that all selected case studies generated positive economic returns (table 5), mainly due to water savings, increased productivity and labour savings. The estimated break even (BE) water savings varied, depending on the crop and irrigation technology. For example, for the lettuce cropping system, increased yield and labour savings were sufficient to recover costs within the first year of investment. The adoption of drip irrigation for cotton cropping delivered the lowest economic return, with a net benefit of \$114/ML/yr, mainly due to the limited water savings achieved (table 5); however, this was still an economically viable option at this farm.

Very high economic returns were apparent for the adoption of centre-pivot irrigation technology on the lucerne farm (case study 5). However, since total water savings in this case study included 30% water savings achieved through deficit irrigation, a separate economic analysis was conducted on water savings achieved without deficit irrigation practices. The results showed that the centre-pivot was still an economically viable option with high NPV (\$913 019).

Table 3. Differences in GHG emissions (kgCO₂e/ha) due to various sources associated with the adoption of water use efficient pressurized irrigation systems in five case study farming enterprises in southern Queensland.

Sources of emissions	Emissions (kgCO ₂ e/ha)																													
	Case study 1 (cotton)					Case study 2 (cotton)					Case study 3 (cotton)					Case study 4 (lettuce)					Case study 5 (lucerne)									
	Flood (furrow)	Sprinkler (lateral-move)	% change	Flood (furrow)	Sprinkler (lateral-move)	% change	Flood (furrow)	Drip (trickle)	Flood (furrow)	% change	Drip (trickle)	Sprinkler (hand-shift)	% change	Drip (trickle)	Sprinkler (roll-line)	% change	Drip (trickle)	Sprinkler (hand-shift)	% change	Drip (trickle)	Sprinkler (roll-line)	% change	Drip (trickle)	Sprinkler (hand-shift)	% change	Drip (trickle)	Sprinkler (roll-line)	% change		
Farm machinery operation (section 2.3.1)	405.9	231.1	-43.1	238	238	0.0	271.4	227.9	271.4	0.0	2390.60	-16.0	1844.90	83.7	-22.8	1844.90	2390.60	-16.0	1844.90	83.7	-22.8	1844.90	2390.60	-16.0	1844.90	83.7	-22.8	1844.90	2390.60	-16.0
Irrigation ^a (section 2.3.1)	744.9	1236.70	+66.0	1250.40	1433.40	+14.6	678.8	4725.80	678.8	+14.6	2577.10	+596.2	1288.60	15018.43	-50.0	1288.60	2577.10	+596.2	1288.60	15018.43	-50.0	1288.60	2577.10	+596.2	1288.60	15018.43	-50.0	1288.60	2577.10	+596.2
Agrochemicals (section 2.3.2)	1209.40	749.1	-38.1	979.5	760	-22.4	1438.60	1440.00	1438.60	-22.4	677.3	+0.1	1209.80	491.1	+78.6	1209.80	677.3	+0.1	1209.80	491.1	+78.6	1209.80	677.3	+0.1	1209.80	491.1	+78.6	1209.80	677.3	+0.1
Emissions from soils due to N-fertilizer use (section 2.3.3)	2033.80	1129.90	-44.4	1807.80	1355.90	-25.0	1611.30	1611.30	1611.30	-25.0	935.3	0.0	1826.50	0	+95.3	1826.50	935.3	0.0	1826.50	0	+95.3	1826.50	935.3	0.0	1826.50	0	+95.3	1826.50	935.3	0.0
Farm machinery ^b (section 2.3.4)	58.4	33.3	-43.0	34.3	34.3	0.0	39.1	32.8	39.1	0.0	344.3	-16.1	265.7	12.1	-22.8	265.7	344.3	-16.1	265.7	12.1	-22.8	265.7	344.3	-16.1	265.7	12.1	-22.8	265.7	344.3	-16.1
Total emissions	4452.90	3380.70	-24.1	4310.20	3821.80	-11.3	4039.40	8038.00	4039.40	-11.3	6924.60	+99.0	6435.50	15605.33	-7.1	6435.50	6924.60	+99.0	6435.50	15605.33	-7.1	6435.50	6924.60	+99.0	6435.50	15605.33	-7.1	6435.50	6924.60	+99.0
GHG emissions (kg CO ₂ e/kg of crop)	2	1.3	-35.0	2.2	1.7	-22.7	1.9	3.4	1.9	-22.7	0.2	+78.9	0.2	0.2	9.6	0.0	0.2	+78.9	0.2	9.6	0.0	0.2	9.6	0.2	3.6	3.6	3.6	3.6	3.6	3.6
GHG emissions (kg CO ₂ e/ML of water)	742.2	836.9	+12.8	862.1	955.5	+10.8	696.4	1674.60	696.4	+10.8	1846.60	+140.5	3605.30	950.9	+95.2	3605.30	1846.60	+140.5	3605.30	950.9	+95.2	3605.30	1846.60	+140.5	3605.30	950.9	+95.2	3605.30	1846.60	+140.5

^a Energy used to pump water from water storage to field, and to operate irrigation machinery and pressurize water for crop application.

^b Exempting irrigation machinery.

Table 4. SWAP model simulation results for average water use and potential water savings for different crops grown under different irrigation technologies in southern Queensland.

Case study	Irrigation technology conversion	Crop	Modelled water use (ML/ha)			Modelled range of water saving (ML/ha)						Actual reported water savings
						Sprinkler			Drip			
			Low	Avg.	High	Low	Avg.	High	Low	Avg.	High	
1	Flood (furrow) to sprinkler (lateral-move)	Cotton	5.5	6.8	7.8	0.5	1.2	2.0	—	—	—	2.0
2	Flood (furrow) to sprinkler (centre-pivot)	Cotton	5.5	6.8	7.8	0.5	1.2	2.0	—	—	—	1.0
3	Flood (furrow) to drip	Cotton	5.5	6.8	7.8	—	—	—	1.0	1.5	3.0	1.0
4	Sprinkler (hand-shift) to drip	Lettuce	—	4.0	—	—	—	—	1.4	1.6	2.0	2.0
5	Sprinkler (roll-line) to sprinkler (centre-pivot)	Lucerne	11.0	12.5	14.0	1.5	2.0	3.5	2.1	3.1	4.5	8.0 ^a

^a Farmer’s assessment also includes deficit irrigation practices. ‘—’ not applicable.

Table 5. Economic evaluation of modern pressurized irrigation technology adoption for five case studies in southern Queensland.

Case study	Irrigation technology conversion	NPV (AUD/ha)	Break even water saving (ML/ha)	Net benefit (AUD/ML of saved water)
1	Flood (furrow) to sprinkler (lateral-move)	340 726	0.52	437
2	Flood (furrow) to sprinkler (centre-pivot)	725 884	0.71	220
3	Flood (furrow) to drip	87 501	0.83	114
4	Sprinkler (hand-shift) to drip	453 257	0.00 ^a	4613
5	Sprinkler (roll-line) to sprinkler (centre-pivot)	2071,074	0.05	414

^a Increase in yield and labour saving is more than enough to justify investment.

Similarly, the net benefit of conversion to the centre-pivot system was about \$285/ML/year.

Sensitivity analysis was performed for a range of parameters. Economic returns were found to be most sensitive to water savings, increased yield and labour savings (table 6). The sensitivity analysis with regard to a 50:50 water sharing arrangement, using permanent water trading pricing as a substitute for the water price, indicates that farmers are better off using water savings on their land rather than trading water. Sensitivity analysis, particularly with respect to carbon priced at \$30/tCO₂e, also shows that increased GHG emissions will reduce economic returns in all except one instance (i.e., case study 4) where reduction in overall GHG emissions generated possible benefits, although these were minimal.

3.4. Trade-off analysis

A trade-offs matrix of the outcomes of converting from older irrigation systems to new pressurized drip and sprinkler irrigation systems, based on the five case studies, is given in table 7. This matrix shows that, in three out of five case studies, irrigation-related GHG emissions increased with the adoption of new irrigation technologies. However, as shown in case studies 4 and 5, conversion of older inefficient and energy-intensive sprinkler irrigation systems (hand-shift and roll-line) to drip and efficient sprinkler irrigation technologies significantly reduced both irrigation-related and total GHG emissions. This creates a win-win situation where water

savings and GHG reductions can be achieved both as a result of technology adoption and farm-level input.

Overall GHG emissions were reduced in four of the five case studies as a result of the adoption of new irrigation technology. In those four case studies, it was found that GHG emissions resulting from the use of farm machinery in farming operations either declined or remained constant with the adoption of new irrigation technologies. A similar trend was observed in terms of agrochemical-related emissions (fertilizers, pesticides). In case study 4 (the irrigated lettuce production system), total GHG emissions increased; however, higher productivity under the more efficient drip irrigation system still resulted in lower GHG emissions per kg of yield than was evident under the less efficient hand-shift sprinkler system. We believe that overall reduction in agrochemical-related emissions may not have been solely due to the conversion, but may result, in part, from new experience with precision agriculture and increasing awareness of environmental concerns.

Results from these five case studies indicated large variations in water and energy use at the field level between different cropping systems. While the new irrigation technologies used less water per hectare of crop, irrigation (pumping of water) related GHG emissions per ML of water and per hectare increased significantly with the adoption of new irrigation technologies. On the other hand, due to increased production, emissions per kg of crop yield fell in all cases except case study 3. In this instance, the new drip

Table 6. Sensitivity analysis of modern pressurized irrigation technology adoption for five case studies in southern Queensland.

Case study	Irrigation technology conversion	Base case scenario (AUD/ha)	Water saving reduced by 50% (AUD/ha)	GHG emission price @ 30\$/tCO ₂ -e (AUD/ha)	Zero labour benefits (AUD/ha)	Zero yield increase (AUD/ha)
1	Flood (furrow) to sprinkler (lateral-move)	340 726	164 787	335 532	319 949	83 434
2	Flood (furrow) to sprinkler (centre-pivot)	725 884	-183 224	689 257	420 662	-43 275
3	Flood (furrow) to drip	87 501	-88 769	74 360	32 568	-110 342
4	Sprinkler (hand-shift) to drip	453 257	182 200	454 007	422 180	121 291
5	Sprinkler (roll-line) to sprinkler (centre-pivot)	2071 074	1106 028	1904 589	1886 091	1081 045

Table 7. Trade-offs matrix for conversion to new pressurized drip and sprinkler irrigation systems based on five case studies in southern Queensland.

Case study	Irrigation technology conversion	Emissions (kg CO ₂ e/ha/yr) (new minus old irrigation system)		Water saving (ML/ha/yr)	Estimated net present value (AUD/ha/yr)
		Irrigation-related emissions	Total emissions		
1	Flood (furrow) to sprinkler (lateral-move)	491.8	-1072.2	2.0	582
2	Flood (furrow) to sprinkler (centre-pivot)	183.0	-488.4	1.0	176
3	Flood (furrow) to drip	4047.0	3998.6	1.0	95
4	Sprinkler (hand-shift) to drip	-1288.5	-489.1	2.0	9065
5	Sprinkler (roll-line) to sprinkler (centre-pivot)	-7509.2	-7509.2	8.0	1657

irrigation system used much more electricity than the old flood irrigation system and the irrigation-related emissions for the trickle irrigation system were 1.8 times higher per kg of crop yield than for the flood irrigation system.

4. Discussion

All five case studies generated positive economic returns, mainly due to water savings, increased productivity and labour savings. Evidence from the case studies indicates that expanded on-farm water use is a more economically efficient option than permanent trade, given the potential for increased yield, and labour and input savings. However, temporary water trading or seasonal water sharing for environmental purposes could be an option at a suitable water price where this is possible, although, in many cases, physical constraints on water transfers would not enable trade to occur.

The case study analyses generally found that GHG emissions due to the use of farm machinery operation and agrochemicals declined with conversion to new irrigation technology. However, reduction in agrochemical-related emissions may not be solely due to new irrigation technologies, as new experience with precision agriculture may also play a role. It is also acknowledged that the comparison of energy and water consumption of various irrigation technologies over a single cropping season cannot give a complete picture without accounting for paddock

history. A more comprehensive analysis would be possible where energy and water consumption data was collected over a complete rotation of crops to account for inter-seasonal differences and subsidies (e.g. fertilizer inputs) that extend across more than one growing season.

Similarly, emissions of N₂O from soils due to the use of nitrogen fertilizer and soil carbon sequestration rates in various irrigation systems could vary significantly. However, these were not able to be accounted for in this study, since there is no research on emissions factors for different irrigation technologies. As a result, the same N₂O emission factors were used for all irrigation systems for the same crop in this study. Also, for the same reason, variation in soil C sequestration amounts for different irrigation systems were not considered. There is a clear research gap in this area. Current irrigation management guidelines aim to minimize the N₂O emissions from soils due to applied N-fertilizers, by (1) maintaining water-filled pore space at <40%; (2) reducing soil compaction and thus increasing oxygen diffusion in soils; (3) reducing the readily available carbon supply as it enhances microbial proliferation and thus N₂O emissions; and (4) removing residual nitrate from the soil by growing cover crops (Lal 2004). Therefore, in the future, we may expect these approaches to result in lower N₂O emissions than are estimated in this study.

While the SWAP model results and farmers' assessments indicated considerable potential for water savings through the adoption of new irrigation technologies, it is important

to recognize the ‘water saving’ may have a number of different meanings. From a farmer’s perspective, water saving is likely to mean using less irrigation water to grow a given crop. However, reduced applications for a given crop do not necessarily mean that total water use is reduced at the farm level or system level if the saved water is used to irrigate additional crop area. In this case, there may be no net benefit to other users downstream. However, if farmers divert less irrigation water from a watercourse, perhaps by availing themselves of the government’s water sharing arrangements, then one might assume that the saved water is available to downstream users or can be used for environmental purposes.

5. Conclusions and policy level implications

Current ‘conventional’ irrigation practices are generally characterized by low WUEs, creating the potential for significant water savings, resulting in either increased productivity or increased water availability for alternative uses (e.g. environmental flows to maintain ecosystem services). Modern pressurized irrigation systems have the potential to save large volumes of water. However, achieving maximum efficiencies depends greatly on the design and management of the system (Raine *et al* 2000). Higher levels of water savings are possible with proper design, training, and better management of irrigation and pumping systems. This was evident in this study, with some growers achieving high-end water savings through better management. In these cases, irrigation technology delivered greater efficiencies with suitable management, and thus saved significant volumes of water, compared with the older labour-intensive irrigation systems.

The analyses reported here indicate significant variation in GHG emissions across different irrigation technologies, and different crop types, farming systems and locations (water source, soil type, climatic factors). Indications are that a range of management decisions in addition to the adoption of efficient irrigation technologies will influence water savings as well as irrigation-related energy use, GHG emissions and associated costs.

Economic efficiency is also a major consideration, both in Australia and overseas. The initial capital costs associated with conversion potentially limit the rate of adoption of new technologies, while operating costs can mean that the overall financial position of farmers is compromised; significant costs may be associated with energy requirements to operate particular types of systems. However, all five case studies generated positive economic returns, mainly due to water savings, increased productivity and labour savings.

Evidence from these examples also indicates that expanded on-farm water use is a more economically efficient option than permanent trade on the water market, given the potential for increased yield, and labour and input savings. Nonetheless, temporary water trading or seasonal water sharing for environmental purposes could be an option at a suitable water price where physical constraints on water transfers enable trade to occur.

This study highlights the complexity involved in evaluating the effectiveness of achieving on-farm water use efficiency through conversion to new water use efficient irrigation systems. The trade-offs analysis raises a critical point, indicating that both mitigation and adaptation have to be evaluated at the same time in order to optimize economic investments in irrigation technologies while managing climate change. The use of pressurized systems can result in significant benefits in terms of savings and economic returns. However, the risk of increasing energy consumption and GHG emissions should be carefully considered. A more targeted approach that achieves balance between improvement in water use and the potential increase in energy consumption is required. Without this, a focus on improving IE to create water savings could subject irrigation enterprises to unexpected increases in energy consumption and escalating costs.

Priority should be given to replacing older, inefficient and energy-intensive sprinkler irrigation systems, such as hand-shift and roll-line. This will not only save water but also save considerable energy in addition to GHG reductions due to improved farming operations. This creates a win-win situation where water savings and GHG reductions can be achieved both as a result of technology adoption and farm-level input.

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References

- AGO 2006 *Reducing GHG Emissions from Australian Agriculture: The Role of Benchmarking in Driving Best Management Practice* (Canberra: Australian Greenhouse Office (AGO))
- Baillie C 2009 Energy and carbon accounting case study on Keytag A Project Report for the Cotton Research and Development Corporation (CRDC) (Toowoomba: National Centre for Engineering in Agriculture (NCEA))
- Barnett J and O’Neill S 2010 Maladaptation *Glob. Environ. Change* **20** 211–3
- CCRP 2012 Australia’s Farming Future *Climate Change Research Program* (Canberra: Australian Government Department of Agriculture, Fisheries and Forestry)
- Chen G and Baillie C 2007 Development of Energy/Calc—a tool to assess cotton onfarm energy uses *NCEA Publication 1002565/1* (Toowoomba: National Centre for Engineering in Agriculture (NCEA))
- Dalal R C, Wang W, Robertson P and Parton W J 2003 Nitrous oxide emission from Australian agriculture lands and mitigation options: a review *Austra. J. Soil Res.* **41** 165–95
- DCC 2009 *National Greenhouse Gas Accounts (NGA) Factors* (Canberra: Department of Climate Change (DCC)) (available online at www.climatechange.gov.au/, accessed April 2010)
- DSEWPC 2011 *Sustainable Rural Water Use and Infrastructure* (Canberra: Department of Sustainability, Environment, Water, Population and Communities (DSEWPC)) (available online at www.environment.gov.au/water/programs/srwui/index.html, accessed March 2011)
- Green G, Sunding D and Zilberman D 1996 Explaining irrigation technology choices: a microparameter approach *Am. J. Agric. Econ.* **78** 1064–72

- Helsel Z 1992 *Energy in World Agriculture* ed R C Fluck (Amsterdam: Elsevier) pp 177–201
- Jackson T M, Khan S and Hafeez M 2010 A comparative analysis of water application and energy consumption at the irrigated field level *Agric. Water Manage.* **97** 1477–85
- Khan S and Abbas A 2007 Upscaling water savings from farm to irrigation system level using GIS-based agro-hydrological modelling *Irrig. Drain.* **56** 29–42
- Khan S, Abbas A, Gabriel H F, Rana T and Robinson D 2008a Hydrologic and economic evaluation of water-saving options in irrigation systems *Irrig. Drain.* **57** 1–14
- Khan S, Akbar S, Rana Y, Abbas A, Robinson D, Dassanayke D, Hirsi I, Blackwell J, Xevi E and Carmichael A 2004 Hydrologic economic ranking of water saving options Murrumbidgee valley *A Study Conducted for the Pratt Water Murrumbidgee Valley Water Efficiency Feasibility Project* (Canberra: CSIRO Land and Water)
- Khan S, Mushtaq S, Ahmad A and Hafeez M 2008b Trade-off analysis for restoring environmental flows through irrigation demand management *Aust. J. Water Res.* **12** 1–20
- Khan S, Mushtaq S and Chen C 2010 A decision support tool for irrigation infrastructure investments *Irrig. Drain.* **59** 404–18
- Kroes J G, Van Dam J C, Groenendijk P, Hendriks R F A and Jacobs C M J 2008 *SWAP Version 3.2. Theory Description and User Manual* (Wageningen: Alterra)
- Lal R 2004 Carbon emission from farm operations *Environ. Int.* **30** 981–90
- Mackinnon D, Mallawaarachchi T and Ashton D 2009 *Irrigation in the Murray–Darling Basin: Investment in On-Farm Irrigation Infrastructure, 2006–07* (Canberra: Australian Bureau of Agricultural and Resource Economics (ABARE))
- Mandal K G, Saha K P, Ghosh P K, Hati K M and Bandyopahyay K K 2002 Bioenergy and economic analysis of soybean-based crop production systems in Central India *Biomass Bioenergy* **23** 337–45
- Maraseni T N and Cockfield G 2011 Does the adoption of zero tillage reduce greenhouse gas emissions? An assessment for the grains industry in Australia *Agric. Syst.* **104** 451–8
- Maraseni T N, Cockfield G and Apan A 2007 A comparison of greenhouse gas emissions from inputs into farm enterprises in Southeast Queensland, Australia *J. Environ. Sci. Health A* **42** 11–9
- Maraseni T N, Cockfield G and Maroulis J 2010a An assessment of greenhouse gas emissions from the Australian vegetables industry *J. Environ. Sci. Health B* **45** 578–88
- Maraseni T N, Cockfield G and Maroulis J 2010b An assessment of greenhouse gas emissions: Implications for the Australian cotton industry *J. Agric. Sci.* **148** 501–10
- Maraseni T N, Mushtaq S, Hafeez M and Maroulis J 2009a Greenhouse implications of water reuse in the Upper Pumpanga River Integrated Irrigation System, Philippines *Agric. Water Manage.* **97** 382–8
- Maraseni T N, Mushtaq S and Maroulis J 2009b Greenhouse gas emissions from rice farming inputs: a cross country assessment *J. Agric. Sci.* **147** 117–26
- Mrini M, Senhaji F and Pimentel D 2001 Energy analysis of sugarcane production in Morocco *Environ. Sust. Dev.* **3** 109–26
- Murray Irrigation Ltd 2009 *Annual Report* (Deniliquin: Murray Irrigation) (available online at www.murrayirrigation.com.au/files/3291653.pdf, accessed May 2010)
- Mushtaq S and Maraseni T N 2011 Technological change in the Australian irrigation industry: implications for future resource management and policy development *Waterlines Report* (Canberra: National Water Commission) (available at <http://nwc.gov.au/publications/waterlines/technological-change-in-the-australian-irrigation-industry-implications-for-future-resource-management-and-policy-development>)
- O'Halloran N J, Fisher P D and Rab M A 2008 *Discussion Paper 4* (Sydney: Horticulture Australia)
- Ozkan B, Akcaoz H and Fert C 2004 Energy input–output analysis in Turkish agriculture *Renew. Energy* **29** 39–51
- Pittock J 2010 A pale reflection of political reality: integration of global climate, wetland, and biodiversity agreements *Clim. Law* **1** 343–73
- Qureshi M E, Wegener M K, Harrison S R and Bristow K L 2001 Water resource management *Economic Evaluation of Alternative Irrigation Systems for Sugarcane in the Burdekin Delta in North Queensland, Australia* ed C A Brebbia, K Anagnostopoulos, K Katsifarakis and A H D Cheng (Boston: WIT Press) pp 47–57
- Raine S R, Foley J P and Henkel C R 2000 *Drip Irrigation in the Australian Cotton Industry: A Scoping Study* (Toowoomba: National Centre for Engineering in Agriculture (NCEA))
- Sánchez-Martín L, Arce A, Benito A, Garcia-Torres L and Vallejo A 2008 Influence of drip and furrow irrigation systems on nitrogen oxide emissions from a horticultural crop *Soil Biol. Biochem.* **40** 1698–706
- Stoorvogel J J, Antle J M, Crissman C C and Bowen W 2004 The trade-off analysis model: integrated biophysical and economic modelling of agricultural production systems *Agric. Syst.* **80** 43–66
- Stout B A 1990 *Handbook of Energy for World Agriculture* (London: Elsevier)
- Topak R, Suheri M and Calisir S 2005 Investigation of the energy efficiency for raising crops under sprinkler irrigation in a semi-arid area *Appl. Eng. Agric.* **21** 761–8
- Verge X P C, Kimpe C D and Desjardins R L 2007 Agricultural production, greenhouse gas emissions and mitigation potential *Agric. For. Met.* **142** 255–69
- Zillman N D, Redgwell C, Omorogbe O and Barrera-Hernandez K L 2008 *Beyond the Carbon Economy: The Energy Law in Transition* (Oxford: Oxford University Press)