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To cite this article: Scott Heckbert (2011) Agent-based modelling of emissions trading for coastal landscapes in transition, Journal of Land Use Science, 6:2-3, 137-150, DOI: [10.1080/1747423X.2011.558599](https://doi.org/10.1080/1747423X.2011.558599)

To link to this article: <https://doi.org/10.1080/1747423X.2011.558599>



Published online: 20 May 2011.



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Agent-based modelling of emissions trading for coastal landscapes in transition

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(Received 29 August 2009; final version received 11 October 2010)

Water quality impacts from agriculture and rapid land use change along Australia's coastline pose challenges for maintaining healthy marine ecosystems and community livelihoods. This article presents an agent-based model of an emissions trading scheme to regulate water quality, examining the effect of land use change and different cap levels on the performance of the market. Simulation results suggest that the cap-and-trade system facilitates the expansion of high-input horticulture while maintaining the overall cap level, and that tighter cap levels have income distribution effects. Heterogeneity of productivity influences trading price, volume traded and gains realised from trading; also small homogeneous trading populations produce a thin market; and trading benefits might not justify creation and maintenance of the instrument and effort required to participate. Novel contributions of this article are how cap-and-trade systems function within a landscape in transition, and also modelling the equity of how benefits of trading are distributed across the population.

Keywords: agent-based model; market-based instrument; water quality; cap and trade; Australia

1. Introduction

Market-based instruments for managing emissions are increasingly being used for water quality impacts from agriculture. Implementing measures such as cap-and-trade systems in theory can achieve natural resource management goals at least cost. The design of market-based instruments (MBI) depends on economic and resource conditions and local dynamics can be important. This article presents a case study where a cap-and-trade fertiliser market is used to regulate water quality. Agent-based modelling (ABM) is used to simulate the operation of a fertiliser market for a case study that is representative of many agricultural areas worldwide experiencing decreasing commodity prices, land use change to urban development and increased attention on agricultural emissions. The use of an MBI involves costs of creating and administering the programme, risk exists in how the market will respond to future configurations of land use and social issues warrant an understanding of how benefits will be distributed amongst a heterogeneous population.

Water quality markets are likely to be locally to regionally administered, but the variation in emissions and land uses at this scale can be low and the number of potential participants in the market may be small. As markets depend on heterogeneity in individual

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traders to realise the benefits of trading, there is doubt as to whether MBIs can work where there is little variation in the agriculture economy. The case study and the model presented here act as a test bed to explore these issues.

The case study presented here applied ABM to Queensland, Australia, where rapid land use change along the eastern coastline is occurring in areas historically dominated by agriculture, with conversion largely to residential use. A growing tourism industry fuels urban development, transitioning areas once used for sugar cane production. There is increasing attention on agricultural run-off of nutrients and sediments into adjacent waters of the Great Barrier Reef World Heritage Area, and a policy framework has been put forward to manage water quality from land-based pollutants entering coastal waters (AG 2003). One possibility is using MBIs to regulate agricultural run-off through a cap-and-trade system. However, this policy option must be seen within the context of land use change trends driven by urban development.

An agent-based model of a cap-and-trade system for fertiliser permits is applied to Douglas Shire, Queensland. Farmers are represented by simulated agents who make production decisions and determine price and quantity of trades in a market. Agents are the decision-making unit of the property, which is composed of a number of GIS polygons of each paddock (agricultural plot) within the Shire. Agents face constrained fertiliser application rates through the setting of a cap-and-trade system for fertiliser permits and may trade in a call market to buy and sell fertiliser permits. The outcomes for the fertiliser permit market are estimated for various cap levels and where land use change occurs.

Research questions address how well the MBI operates in an urbanising landscape. More specifically, how do farm profitability and the distribution of profits within the agent population respond to market configurations and land use change? What are modelled fertiliser permit trading prices, what volume is traded and do the gains from trading justify the effort of implementing and maintaining the MBI?

One hypothesis is that the MBI will maintain limits to overall fertiliser application and will allow flexibility for those who wish to purchase additional permits from the trading market. From this perspective, the MBI might assist in managing production decisions in a transitioning landscape. Alternatively, the removal of agricultural lands could undermine the operation of the MBI and hinder its effectiveness, and the market might act as a barrier to producers adopting higher-input and higher-value land uses. The ABM reports on indicators relevant to research questions, such as estimated permit price, trade volume and the gains from trading and cost savings against another policy such as a uniform regulation. The model calculates income equity of the agent population through a Gini coefficient to measure how the cap-and-trade system affects the distribution of income. Simulation scenarios examine the effect of various cap levels and of land use change.

Market-based instruments are increasingly considered as regulatory options for managing public good resource problems such as cumulative impacts of natural resource use (Weber and Adamowicz 2002) and provision of environmental services (Connor *et al.* 2008). Determining which type of MBI and the design principles behind its implementation deserves careful consideration of property rights, risk, flexibility, equity and the evolution of the instrument over time (Whitten and Young 2004), and the institutional setting of the MBI will influence how incentives are perceived and acted upon by traders (see Reeson 2008).

2. Agent-based modelling of market-based instruments

ABM is the computational study of systems of interacting autonomous entities, each with dynamic behaviour and heterogeneous characteristics. Agents interact with each other and

their environment, with direct interactions such as communication, trading and physical contact or indirect through feedbacks from environmental responses or aggregated price signals. Behaviour in agents is represented by decision-making functions and takes into account heterogeneity across individuals, such as unique preferences, assets, skills and information. Simulating the modelled system allows defined scenarios to be tested and compared.

Relevant to this application, ABM has been used to model land use change (e.g. Parker, Manson, Janssen, Hoffmann, and Deadman 2003; Manson and Evans 2007; Polhill, Parker, and Gotts 2008), quantifying cumulative environmental impacts as emergent properties of multiple land uses (Heckbert, Adamowicz, Boxall, and Hanneman 2010) and residential decision-making and urbanisation (Brown and Robinson 2006; Baynes and Heckbert 2010). Policy analysis has been done by Berger (2001) and Happe, Kellermann, and Balmann (2006), who present ABMs of agricultural systems which respond to incentives created through policy configurations. Markets have been implemented in ABMs by McBride (2007) who developed an ABM of the 'zero-intelligence' trading market of Gode and Sunder (1993). Duffy and Unver (2008), Tesfatsion (2007) and LeBaron and Tesfatsion (2008) are applications where agents trade in markets and form pricing decisions. With respect to markets for environmental management, Hailu and Thoyer (2006) presented an ABM to test the effectiveness of different multiple-unit auction designs for water quality auctions. Weidlich, Sensfub, Genoese, and Veit (2008) model electricity and emission trading where agents communicate and trade in power markets and markets for emission allowances. Calibration techniques for deriving behaviour rules of agents include using data from surveys, interviews, participatory modelling (Robinson *et al.* 2007; Heckbert, Baynes and Reeson 2010) and increasingly participatory research with stakeholders and experimental economics informing decision rules of agents (Heckbert 2009; Heckbert and Bishop in press).

ABM is used in the application described here because of the ability to represent trading and the individual decision-making and resource impacts of multiple individuals in space. The model was constructed using Net Logo (v4.0.4) with a functional user interface and interactive spatial map and figures tracking indicators over time (see Figure 1). Spatial data was collated, representing each paddock (agriculture plot) for the case study area, and was ground-truthed during field visits and parameter values listed in Table 1 were elicited from agronomists from research and agricultural extension organisations. The model was constructed to specifically represent a real-world case study for the purposes of policy decision support to inform regional authorities about considerations in creating a cap-and-trade system. The model interface allows decision-makers to alter parameters and to explore outcomes directly as a participatory research tool. The spatial nature of the model allows decision-makers to see how land use change progresses on real-world properties through time. The 3D view allows the model user to zoom, inspect and track individual properties at a paddock-level resolution.

2.1. Production and profits

Agents perform a series of scheduled operations for each time step, representing one year. The agent operations in each time step are presented below in sequential order, beginning with production decisions, through to trading with other agents in the cap-and-trade market. The yearly time step was chosen to reflect the annual nature of fertiliser application to crops and the annual wet/dry season cycle. Agents grow one of two crops, sugar cane or

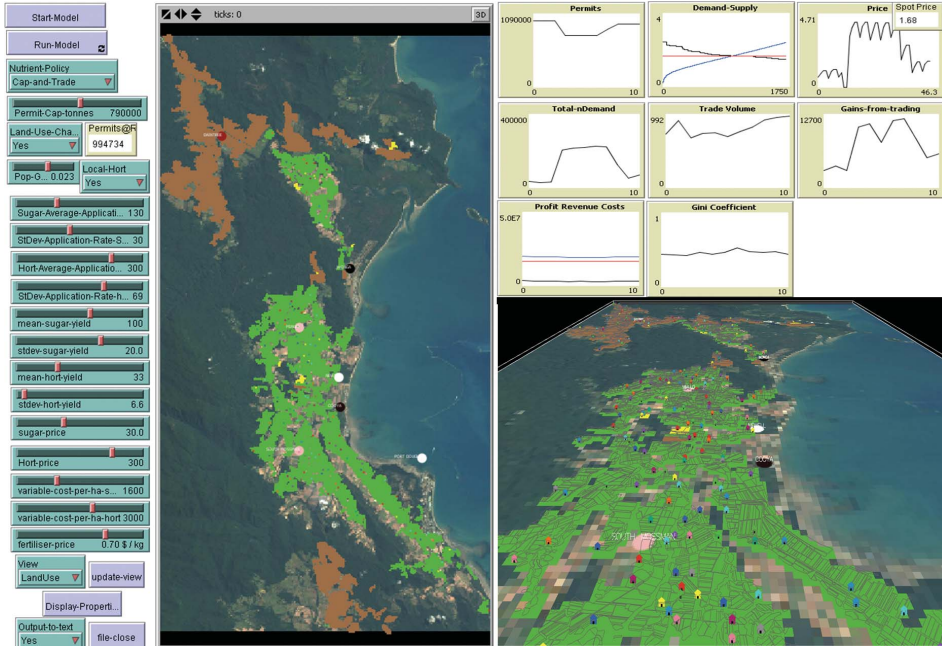


Figure 1. Interactive model interface for setting scenarios and parameters, spatial map with paddock boundaries and properties depicted as houses, and figures tracking simulated model data over time.

Table 1. Parameters and values used for model equations.

| Parameter | Value (sugar/hort) | Equations | Parameter | Value | Equations |
|------------|-----------------------|-----------|-----------------|--------------------------------|-----------|
| RR_i | 130kg/ha 300kg/ha | 1 | PSD_i | 20 6.6 | 3 |
| SD_i | 30kg/ha 69kg/ha | 1 | CP_i | 30 [\$ /t] 300 [\$ /t] | 4, 7, 8 |
| γ_i | 0.07 0.015 | 2 | V_i | 1600 [\$ /ha] 3000 [\$ /ha] | 4 |
| δ_i | -0.023 -0.007 | 2 | ε_i | 126 | 4 |
| β_i | 0.9 0.6 | 2 | FP | 0.7 [\$ /kg] | 4, 7, 8 |
| PP_i | 100 33 | 3 | TP_t | 1004 t for 100% cap | 5 |

horticulture. Fertiliser application rates $N_{j,i,t}$ (kg/ha) for crops $i = \text{sugar or horticulture}$ are initialised at model set-up for each agent $j = 1, \dots, 164$ according to a normal distribution,

$$N_{j,i,t} \sim N(RR_i, SD_i) \quad (1)$$

where RR_i is the mean recommended application rate (kg/ha), and SD_i is the standard deviation which determines the level of heterogeneity in fertiliser application rates across the agent population. The function takes on a temporal element t for each agent j through

trading permits, discussed later. Each agent has a unique production function for sugar cane or horticulture, which share the same functional form and use unique parameters summarised in Table 1. Crop yield is calculated as

$$O_{j,i,t} = \kappa_{j,i} * (1 - \delta_i * e^{-\beta_i * N_{j,i,t}}) - \gamma_i * N_{j,i,t} \quad (2)$$

where $O_{j,i}$ is the crop yield (t/ha) realised using fertiliser application rate from Equation (1), and $\gamma_i, \delta_i, \beta_i$ are static yield parameters. The parameter $\kappa_{j,i}$ is the property-specific yield parameter, and is the point at which production heterogeneity is introduced,

$$\kappa_{j,i} \sim N(PP_i, PSD_i) \quad (3)$$

where PP_i is mean productivity for crop i , and PSD_i is the productivity standard deviation, normally distributed across the agent population. The productivity is set on a property-basis to reflect the set of management practices jointly applied over the property's paddocks, rather than a paddock-specific productivity function. Soils in the area are relatively homogeneous. Variability in production is related largely to management practices, described in Roebeling and Webster (2007).

Agents derive revenues and incur costs from growing crops and from buying and/or selling fertiliser permits (kg), with total profits expressed as:

$$\pi_{j,i,t} = (O_{j,i,t} * A_{j,i,t} * CP_i) - (\varepsilon_i * V_i + V_i * A_{j,i,t} + N_{j,i,t} * A_{j,i,t} * FP) + FR_{j,t} - FC_{j,t} \quad (4)$$

where the first term describes production revenues with $A_{j,i,t}$ being the area (ha) of the property under land use i which is either sugar cane or horticulture and CP_i is the commodity price (\$/t) paid for yield. The second term describes production costs, with variable costs for each land use being V_i (\$/ha), and the parameter ε_i (ha) represents the minimum farm size observed in our data set and used with the variable cost parameter to infer fixed costs for each land use (sugar cane being capital intensive versus labour intensive horticulture). The commercial cost of fertiliser is FP (\$/kg). The last two variables $FR_{j,t}$ and $FC_{j,t}$ are revenues and costs (\$) respectively, incurred from selling and purchasing fertiliser permits.

In the description of profits above, all variables are exogenous and static except $FR_{j,t}$ and $FC_{j,t}$, which are related to trading. We might expect agents to be able to also change their application rate in search of an optimal balance between production revenues and costs, and also select a diversification to a mix of land uses in response to changes in commodity prices. However in this model, these latter two adaptive behaviours are held constant to be able to focus on trading behaviour.

2.2. Market operations

Agents may buy (sell) permits for fertiliser use in a fertiliser permit market. The type of trading mechanism used in this simulation is a multiple call market, where traders submit multi-unit offers as a bundle of permits to be sold at a given price. Various market-based instruments take on designs suited to management goals and the conditions of the traded good, the environmental resource and traders' use of the traded input to production. Cason and Friedman (1996) described the single call market (SCM), and Cason and Friedman (1997) described the continuous double auction (CDA) and the multiple call market (MCM) formats. For SCM, traders independently submit bids and asks that are aggregated into demand and supply curves and cleared at a uniform price once for each

trading period. Information feedback is non-existent during a trading period (Cason and Friedman 1996). In contrast, the CDA market structure allows traders to continuously make, accept and alter buying and selling offers in real-time during a trading period of a given length, thus including information feedbacks in multiple interactions of adjusting offers. Lastly, the MCM market is similar to SCM, in that traders submit bids and asks that they are aggregated and the market is cleared at a uniform price, but the MCM market is cleared several times per period (Cason and Friedman 1996), allowing updating of unsuccessful offers, which facilitates increased information feedback and allows unsuccessful traders to modify offers and resubmit.

One consideration in choosing an appropriate market design is the time commitment from producers in learning and participating in trading. Multiple bartering interactions with one's neighbours and community members regarding fertiliser permits is not necessarily desirable in a small community. Consultations with government authorities and regional natural resource management bodies identified the importance of a straightforward trading format that does not require continuous attention and time commitments from farmers throughout the year. The SCM and variants was deemed suitable, but does not offer flexibility for inexperienced traders, and information feedback is limited given the price signal is only revealed at the end of each period. The CDA market format allows the greatest feedback from trades and hence the best opportunity for learning, and therefore efficiency in overall market performance however requires significant time commitment from traders and constant attention of current conditions in the marketplace. Because of this, CDA was not deemed well suited to the conditions of agriculturalists with limited time and many other important production decisions to attend to. However, a modified MCM format allows the simplicity of the call market, but can accommodate information feedbacks and adjusting of unsuccessful bids. The balance of these points suggests that MCM is a suitable market format to test using the ABM given it involves a straightforward process for traders yet allows learning through feedback.

Market designs for natural resource management issues have been tested in the laboratory setting, reviewed in Reeson and Nolles (2009) and Windle, Reeson, Whitten, and Rolfe (2008). Many are single-unit auctions, as opposed to our situation where multiple units of a homogeneous good (fertiliser) would be traded in price-quantity bundles. Here we follow the example of Hailu and Thoyer (2006) in adjusting the MCM format to a multiple-unit design. Unlike single-unit auctions, multi-unit auctions allow traders to submit offers with quantity and price schedules rather than single quantity-price bundles (Hailu and Thoyer 2006). The population of bidders has private values reflecting different production (demand) and cost (supply) structures, indicating the amount they would be willing to supply at different prices (Hailu and Thoyer 2006).

Considering these design features, the market instrument programmed here involves five steps: (1) granting of fertiliser permits to agents based on land use, (2) agents determine unfilled demand, (3) calculate a willingness-to-pay (WTP) for demanded permits and a willingness-to-accept (WTA) payment for selling portions of their permits already granted, (4) organisation of WTP bids and WTA offers into demand and supply curves with an associated price and (5) trading of permits and funds for successful bids/asks.

Permits $P_{i,t}$ (kg/ha) are assigned to agents based on recommended rates for each land use, rather than auctioned through a bidding process,

$$P_{j,t} = RR_i * A_{j,i,t} \quad (5)$$

Because permits are distributed on a per hectare basis by land use, agents receive an overall allocation depending on the size of their property. From here, demand for additional fertiliser permits $D_{j,t}$ (kg) is the calculated shortfall between the agent's fertiliser application rate and permits available.

$$D_{j,t} = (N_{j,i,t} - P_{j,t}) * A_{j,i,t} \quad (6)$$

At this point agents calculate two price-quantity schedules; one of WTP for demanded permits and one of WTA values for permits the agent might supply to the market. The demand schedule is an array list of WTP values populated with the marginal value $MVD_{j,t}$ (\$/kg) for additional fertiliser units,

$$MVD_{j,t} = (O_{j,i,t}^{n+1} - O_{j,i,t}^n) * CP_i - FP \quad (7)$$

Where $O_{j,i,t}^n$ is yield (t/ha) at fertiliser input level n , which is iterated across the range of $n = P_{j,t}$ to $n = D_{j,t} + P_{j,t}$, and FP again is the price of fertiliser (\$/kg).

In a similar fashion, sellers also calculate a WTA schedule which is again stored as an array list. The WTA is calculated as the marginal cost (\$/kg) of supplying additional permits to the market,

$$MCS_{j,t} = (O_{j,i,t}^n - O_{j,i,t}^{n-1}) * CP_i + FP \quad (8)$$

Where $O_{j,i,t}^n$ is yield across the range $n = P_{j,t}$ to $n = 0$. The WTA and WTP values are then added to a list for a number of times equal to the quantity of the bid. The lists are sorted ascendingly for offers to sell (WTA), and sorted descendingly for bids to buy (WTP). The overall market price SP_t is defined at the pairwise combination where the demand and supply curves intersect.

To represent the MCM format explored here, three trading rounds are run within each time step, all occurring before the start of the growing season when fertiliser is applied. The supply curve is static, and only needs to be submitted once. However, multiple buying rounds are possible, and buying agents may adjust their bid and resubmit twice more, amounting to three buyer calls per season compared with one submission from sellers. The latter point controls on-selling of bought permits, and makes the process of submitting a supply 'function' a simple process for traders. The selection of three iterations was made on the balance of simplicity for a real-world trader, yet mitigates the risk of not being successful in the first or second attempts at trading. In the real world, sellers could submit a price schedule, for example, of around five price-quantity relationships for simplicity's sake, but this would produce a less 'smooth' schedule. On the other hand, it is not reasonable for producers to know with full information about the position of every point on a supply curve so some balance would be struck between simplicity and accuracy. Within the ABM simulation, the entire supply curve is calculated and submitted. Over the three buying iterations, points on the supply curve are not removed and some precision is therefore lost in the price estimate of iteration 2 and 3.

Three buying iterations have the effect of increasing the price as the demand curve shifts upwards. Successful buyers do not bid again in the next iteration and are hence removed from the demand curve revealed in following iterations. Buyers who are not successful again decide on their WTP values as described in Equation (7) and submit

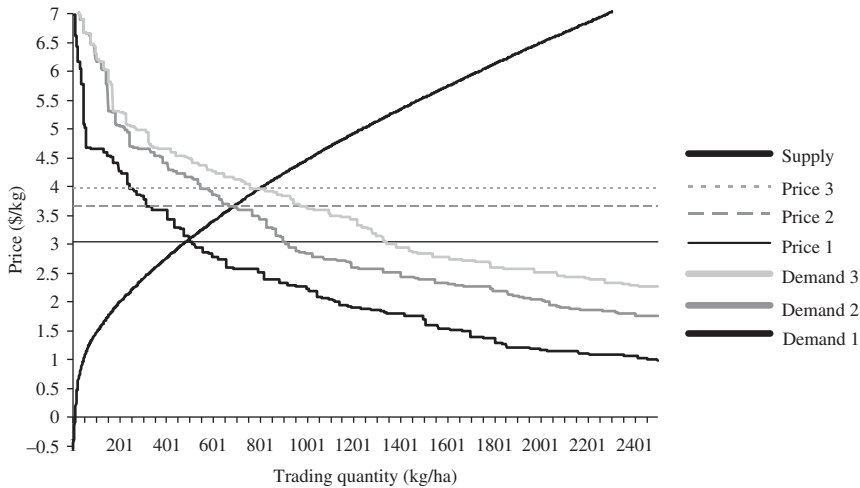


Figure 2. Simulated demand and supply curves in a fertiliser permit trading market. Three iterations of a multiple call market allow unsuccessful buying bids to be adjusted and resubmitted, with the effect of increased price each iteration. The supply schedule is submitted once and remains static during the three buying iterations for $n = 164$ traders.

their bids in the next iteration, but face higher prices. Approximately 75% of trade volume occurs in the first iteration. It should be noted that the assumption of a static supply curve serves to keep prices from a further increase in iteration 2 and 3. If the supply curve was updated after iteration 1, the removal of the lowest priced offers to sell would shift the supply curve to the left. Figure 2 presents three demand schedules and one supply schedule for one instantiation of agents. All bids to buy (offers to sell) above (below) the estimated price are successful, and agents update their available permits accordingly, and lodge a cost $FC_{j,t}$ (revenue $FR_{j,t}$) for Equation (4) based on the amount they each buy (sell).

2.3. Land use change

The final set of operations in each time step reflects land use change patterns occurring in many agricultural regions worldwide where high urban land values are driving conversion of agricultural land to residential use. Land use change in the case study region has been previously explored in Roebeling, Fletcher, Hilbert, and Udo, (2007), which examines the conversion of sugar cane to grazing, horticulture and urban uses. Restrictions on urban development in the region do not allow producers to choose to sell parcels for residential development at will.

Land use change is modelled in a simplified fashion that is exogenous to agent decision-making and calculates the area converted to urban and horticultural land use based on population trends. Change to horticulture is assumed to occur for the smallest properties that have the greatest incentive to diversify, as seen in historical patterns described in Bohnet (2004).

3. Results

Simulations were run for a number of scenarios that explore market and production outcomes. This section presents results from (a) simulations with different cap levels for aggregate fertiliser application (and without land use change), (b) simulations where land

use change occurs, examining how the fertiliser permit trading market functions during this transition. Further results are presented on the effect of agent heterogeneity on market functioning.

Indicators tracked within the model and presented here inform the effectiveness of the MBI. The trading price (\$/kg) and trading volume (t) inform the costs faced by traders and the market throughput. A cost savings (a.k.a., gains from trading) metric is calculated in monetary units for how much market participants have benefitted from trading. This compares a uniform regulation where fertiliser application rates are set at (a maximum of) recommended rates and no trading is conducted. This serves to compare the scenario using a fertiliser permit market to the case where agents all face a uniform standard for application rates, but without the ability to trade, hence a 'cost saving' above regulation without a market. Sugar cane yield for the spatial extent of the case study (t) is impacted by the cap level and trading of fertiliser permits. The distribution of profit within the population of agents is measured by a Gini coefficient, where 0 represents a completely homogeneous population (exactly equal, with all agents receiving the same profits), and where values upwards of 1 occur where the distribution of profit is skewed towards only a few individuals (less equal).

3.1. Scenario: cap levels

Simulations were run testing five cap levels that constrain aggregate fertiliser application. The cap is the total number of fertiliser permits available and is set via the model interface. Five levels were used: 1004 t (100% of recommended rates), 904 t (90%), 803 t (80%), 703 t (70%) and 603 t (60%). The term 'recommended rates' is the fertiliser application rate recommended by agronomists and extension officers (130kg/ha for sugar cane and 300kg/ha for horticulture), multiplied by the area under production. Figure 3 presents model outcomes for (a) trading price (\$/kg), (b) market trade volume (t), (c) cost savings comparing aggregate revenues under the permit market with those realised under a uniform regulation with no trading (\$), (d) total sugar cane yield ('000 t) and (e) the Gini coefficient for farm profits, describing the distribution of profits across the agent population. Values in Figure 3 are mean values for 100 trading periods with re-initialised agent populations each period, and confidence intervals ($\alpha = 0.05$).

The trading price increases super-linearly with lower (more stringent) cap levels, as might be expected. Trade volume increases linearly as less permits are available, and agents price them higher, yet demand more under stricter cap levels. Cost savings from trading versus the case where producers face a uniform regulated application rate increases nearly linearly as well. As would be expected, the total aggregate sugar cane yield decreases as the cap levels tighten, with significantly different results between 70% and 80% restrictions. The Gini coefficient is higher with lower cap levels, indicating that profit distribution becomes less equitable with lower caps. Cap levels between 70% and 80% again become significantly different, indicating the distribution of profits within the agent population begins to change past this point due to concentration of profits within a smaller number of agents.

3.2. Scenario: land use change

Simulations were conducted comparing a baseline scenario to the situation where land use change occurs. The baseline is set at the previously reported cap level of 803 t or 80% of recommended rates, with land use kept static over time. Against this, outcomes are reported for the same cap level of 80%, but with land use change to urban and horticulture use occurring.

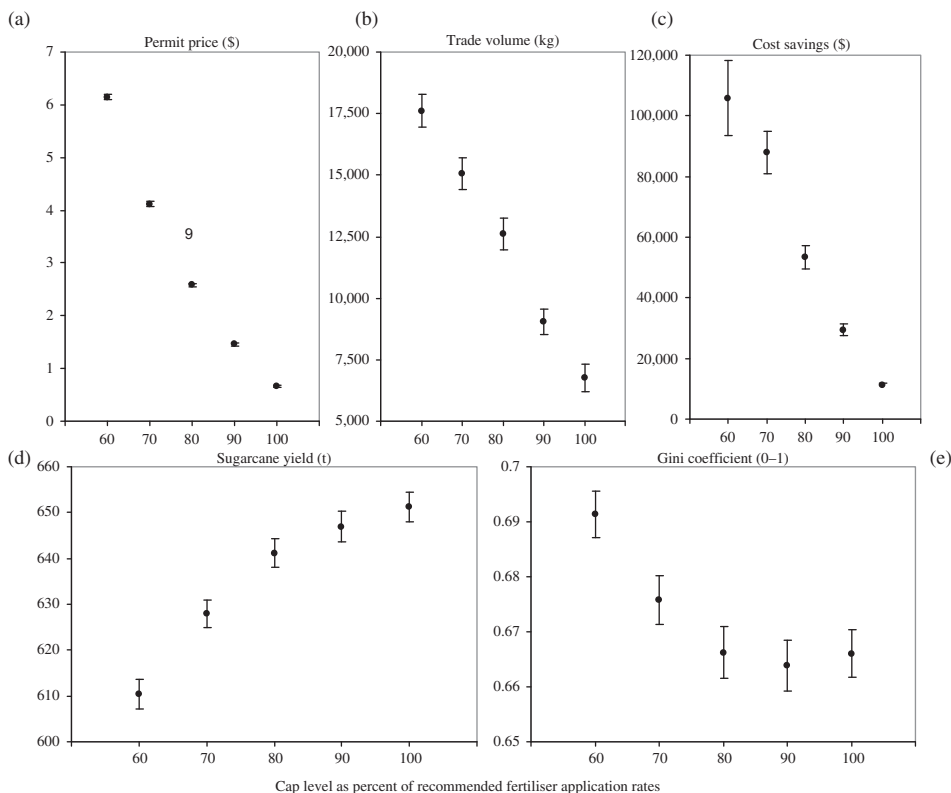


Figure 3. Simulation outcomes for (a) trading price, (b) market trade volume, (c) cost savings comparing aggregate revenues under the permit market with those realised under a uniform regulation with no trading, (d) total sugar cane yield and (e) the Gini coefficient for farm profits, describing the distribution of profits across the agent population. Values are mean estimates for 100 trading periods and confidence intervals.

Increasing urban areas occurs at the expense of sugar cane and grazing, and horticulture converts sugar areas but not grazing. During this transition over time, the fertiliser permit market is played out for the sugar and horticulture properties. Results are presented here for market performance during this land use change situation, with Figure 4 reporting mean values for 15 simulation runs of 65 time steps, and confidence intervals ($\alpha = 0.05$) for (a) trading price (\$/kg), (b) total volume traded (t) and (c) the Gini coefficient for profit equitability [0–1]. The grey line represents mean outcomes and confidence intervals for the baseline scenario of a fertiliser permit market operating without land use change, and the black dashed line reports mean outcomes and associated confidence intervals for the situation where land use change occurs. The temporal extent of 65 years is presented in Figure 4 given that this is an effective length to communicate statistically significant differences in the two scenarios.

The trading price is not significantly different for the two scenarios. Trade volumes for the baseline and land use change scenarios are not significantly different for the first half of the simulation until horticulture area has increased sufficiently to demand a larger amount of permits from sugar cane production, and at this point trade volumes pick up even though fewer permits are available as land conversion to residential use occurs. The Gini coefficient for the land use change scenario decreases and is significantly different than the

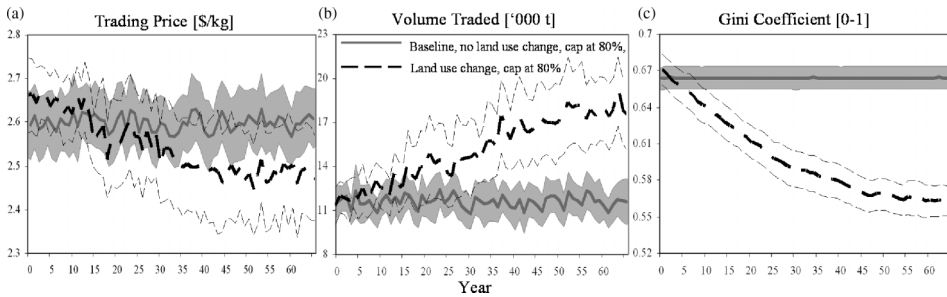


Figure 4. Simulation outcomes for a static baseline (*grey*) and a land use change scenario (*dashed black*) testing the effectiveness of the cap-and-trade system as land use change occurs. Mean values are depicted for 15 simulation runs of 65 time steps and confidence intervals ($\alpha = 0.05$) for (a) trading price, (b) total volume traded (in thousands of tonnes) and (c) the Gini coefficient for equity of profit distribution.

baseline. This indicates that profits are being distributed more evenly within the system as land use change occurs, which is perhaps counter-intuitive given the fragmentation of properties that occurs with the random selection of urban plots. This can be explained by change to horticulture land use, namely that the smallest sugar cane properties are the first to transition, thereby raising the income of these properties that cannot realise economies of scale like larger properties. This has the effect of removing small, and therefore generally less profitable, properties, allowing smaller properties to generate higher income on the same area of land, hence resulting a more equal distribution of income. This pattern reflects the trends reported in Bohnet (2004) that diversification to horticulture has historically been an option for small properties when sugar prices were low.

3.3. Market performance and agent heterogeneity

Throughout the process of testing the model, a variety of sensitivity analyses were performed. The agents' production heterogeneity, controlled via the model interface by moving a slider for parameter $\kappa_{j,i}$ from Equation (3), was found to strongly influence market outcomes. When heterogeneity is low, demand and supply curves are flat, and trade volume is accordingly low. In this case only the outliers have incentive to participate. As productivity heterogeneity increases, the supply and demand curves take on their familiar upward and downward sloping forms.

4. Discussion

Market-based instruments for water quality management are potentially useful for managing agriculture emissions to achieve environmental goals at least cost. This article presents an agent-based model of a cap-and-trade instrument for managing water quality for the Great Barrier Reef, Australia as a case study to model and report on indicators of performance of a fertiliser permit market. Simulation results reveal several expected patterns that are consistent with the emissions trading literature such as equilibrium prices and trading volume both increasing as the cap tightens. The model also finds that outcomes are sensitive to the assumptions about the agent population, specifically whether the number of agents and their heterogeneity of productivity serve to create a 'thin' market. Two novel contributions of this article beyond these expected findings are how the cap-and-trade

system functions as land use change occurs, and also how the benefits of trading are distributed amongst the population of agricultural agents.

Estimates of costs savings are low from trading compared with a regulation requiring uniform standard application rates. Therefore, the benefits of a cap-and-trade instrument might be limited compared with the cost of creating and maintaining the instrument, and modest gains from trading by producers should be viewed in light of the significant time and effort that would be required to participate effectively. The transaction costs of establishing, regulating and participating in such an MBI would likely outweigh the gains. The literature on balancing the benefits and costs of creating an MBI is limited, however comparison can be made to Whitten, Khan, Collins, Robinson, and Ward (2007) where costs (beyond transaction costs) are discussed, including the costs of designing, implementing and enforcing the policy and the ongoing administrative costs to participants under the policy. The latter study identifies that a cap-and-trade system incurs transaction costs associated with trading, as well as 'policy' costs that would need to average less than AUD\$268,000 per annum to yield a net benefit (Whitten *et al.* 2007) in the case study examined therein. In the Whitten *et al.* study, costs of establishing and maintaining the market-based instrument include the costs of creating a registry, defining and assigning property rights and verifying trades. Results for the ABM of a fertiliser trading market involving 164 properties in the Douglas Shire achieves greater cost savings as the cap is tightened, with the highest value of AUD\$110,000 being realised at a cap of 60% of recommended rates. In this instance the cost of implementing the policy, if the Whitten *et al.* study is used as a guide, would likely not warrant the savings to producers.

The population in this case study is likely not large enough and diverse enough in their productivity to warrant the use of a market-based tool that was shown to depend strongly on the level of agent heterogeneity. Further research into crop production functions can help to better inform this issue. However, the future landscape may look very different than the current relatively homogeneous land use pattern dominated by sugar cane, and the facilitation of permits for new land uses could see the benefits of the emissions trading scheme be realised in time.

This article contributes to the emissions trading literature by examining how MBIs operate in a landscape in transition. The model represents shifts in land use from agricultural (sugar cane) to residential use, and also high-value (and high fertiliser input) horticulture. The urbanisation trend effectively removes permits from the market by converting sugar cane farmland, and would thus potentially undermine the effectiveness of the market-based instrument. However, the cap-and-trade system facilitates the transition to horticulture uses by allowing areas converted to horticulture to acquire sufficient fertiliser permits from the market. The market was able to distribute permits for fertiliser application through this transition from one land use to another whereas regulation such as a uniform standard application rate without trading might hinder this transition. Land use change in the model increased trade volume because of the increased need of an expanding horticulture industry that maintains a trade volume that is significantly higher than the scenario without land use change. For these reasons, the cap-and-trade system is seen to do well at accommodating the dynamics of land use change.

This article also contributes to examining how benefits are distributed under a cap-and-trade system, with the model calculating the Gini coefficient as a measure of income inequality amongst farmers. Income is distributed more evenly as land use change occurs, but less evenly as the cap level tightens. This finding has relevance for the broader emission trading literature, for example, whether income equity of participants in a cap-and-trade scheme (e.g. between countries or individual polluting firms) is improved or worsened

under an emissions trading system. Bosello and Roson (2000) argued that distributional effects of emission trading schemes should not be seen as separate to efficiency issues. In the emission trading literature notions of equity for bearing the burden of abatement are frequently discussed, but how the trading instrument affects income inequality within the population of trading participants appears to be little studied. The findings discussed here suggest that the internal dynamics of the regulated industry (in our case diversification patterns to higher value and higher input crops) are critical to whether inequality is increased or lessened by the emission trading scheme.

Acknowledgements

The author acknowledges the contributions of Andrew Reeson, Tony Webster, Cameron Fletcher, Geoff Carlin, Alex Smajgl, Malcolm Hodgen, Michael Hartcher, Stuart Lindsay, Steve Attard, Luis Izquierdo and two anonymous reviewers for their excellent suggestions. Funding was provided by CSIRO Sustainable Ecosystems Sustainable Resource Development Theme and Water for a Healthy Country Flagship.

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