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Tropical Water Quality Hub
National Environmental Science Programme

Final Report

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Griffith UNIVERSITY

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Cover photographs: Carla Brewer

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ACRONYMS

BoM	Bureau of Meteorology
DEHP	Department of Environment and Heritage
DERM	Department of Environment and Resource Management
DNRM	Department of Natural Resources and Mines
DOE	Department of the Environment
DOE	Department of the Environment
DSITI	Department of Science, Information, Technology and Innovation
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
NESP	National Environmental Science Programme
OECD	Organisation for Economic Cooperation and Development
QLUMP	Queensland Land Use Mapping Program
RRRC	Reef and Rainforest Research Centre Limited
SBMP	Smartcane Best Management Practice
TWQ	Tropical Water Quality
WQIP	Water Quality Improvement Plan

ABBREVIATIONS

C&C	Command and Control
COTS	Crown of Thorns Starfish
DEM	Digital Elevation Model
DIN	Dissolved Inorganic Nitrogen
GIS	Geographic Information System
GPS	Global Positioning System
LP	Linear Programming
N	Nitrogen
TDP	Tradable Discharge Permit

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EXECUTIVE SUMMARY

Nitrogen pollution from cane growing activities is a key pollutant of concern in the catchments that drain into the Great Barrier Reef. An 80% reduction in the amount of dissolved inorganic nitrogen by 2025 is targeted in the Reef Long Term Sustainability Plan. Current investment approaches based on subsidising the voluntary implementation of best management practices in nitrogen management are predicted to only achieve approximately one quarter of the target reductions within the timeframe. The Reef Water Quality Taskforce has identified that a transformational change is required in the way land is managed.

A tradeable permit scheme has been identified as one potential transformational change. This scoping project has been funded under the National Environmental Science Program to investigate the potential cost effectiveness of a tradeable water quality permit scheme in comparison to a traditional command and control approach to achieve nitrogen targets. Water quality trading is an emerging field of endeavour across the globe. In its most simplistic formulation it involves a fixed cap on the total amount of emissions, and a tradeable allocation of emission permits among polluters. Buying and selling transactions then reallocate emissions under to the cap to harness market forces to promote cost efficiency in emissions reductions. The approach encourages innovation and flexibility in how regulations are met, thereby potentially lowering regulatory compliance and abatement costs. The trading approach is premised on the fact that pollution abatement costs differ between individuals or enterprises, depending on their size, location, scale, management and efficiency. The majority of water quality trading schemes globally focus on point to non-point trading although the successful Lake Taupo nitrogen market in New Zealand focuses on trading amongst non-point sources agricultural sources.

Key elements of a successful water quality-trading scheme are the establishment of a regulatory cap, clear identification of the pollutants to be traded and geographic trading area, development of trading rules and supportive institutional structures. The threshold issue for trading schemes is whether or not there are enough significant cost differentials amongst polluters to make trading economically efficient. To test this we constructed a model nitrogen trading market based on allocations to apply nitrogen and trading amongst non-point diffuse sources. Diffuse sources form the majority of the pollutant load and nitrogen application rates are considered the key variable in predicting pollutant runoff. The Tully catchment is used as the key case study with consideration given to the implications of the findings in the geographically different Burdekin catchment.

A spatially-specific model of an N-trading market was constructed for the Tully catchment by collating data on sugarcane area, soil class and the Tully drainage network. N-trading was simulated using a grid of 4020 ‘paddock-scale’ 250m x 250m cells, each trading as a separate entity in a centralised smart market.

Relationships from the literature were used to predict how N-fertiliser applications (kg N/ha) affected (i) gross margins from cane production ($/ha), and (ii) nitrogen losses (kg DIN/ha) for each of the 4020 sugarcane grid cells.

The N-trading market imposes an overall cap on the total DIN load at Tully Heads. Market operation is simulated with initial permit allocations of 150, 120, 90 and 60 kgN/ha, as the overall DIN load cap is tightened towards the targeted 80% reduction from the 2009 baseline. Simulations compare outcomes under the trading market with outcomes under mandatory (non-tradable) N-application limits.

Figures ES.1 and ES.2 show model-predicted DIN losses and gross margins from the 2009 baseline condition with uniform application of 170 kgN/ha across the Tully cane lands. Gross margins are higher and DIN losses lower on better quality soils.

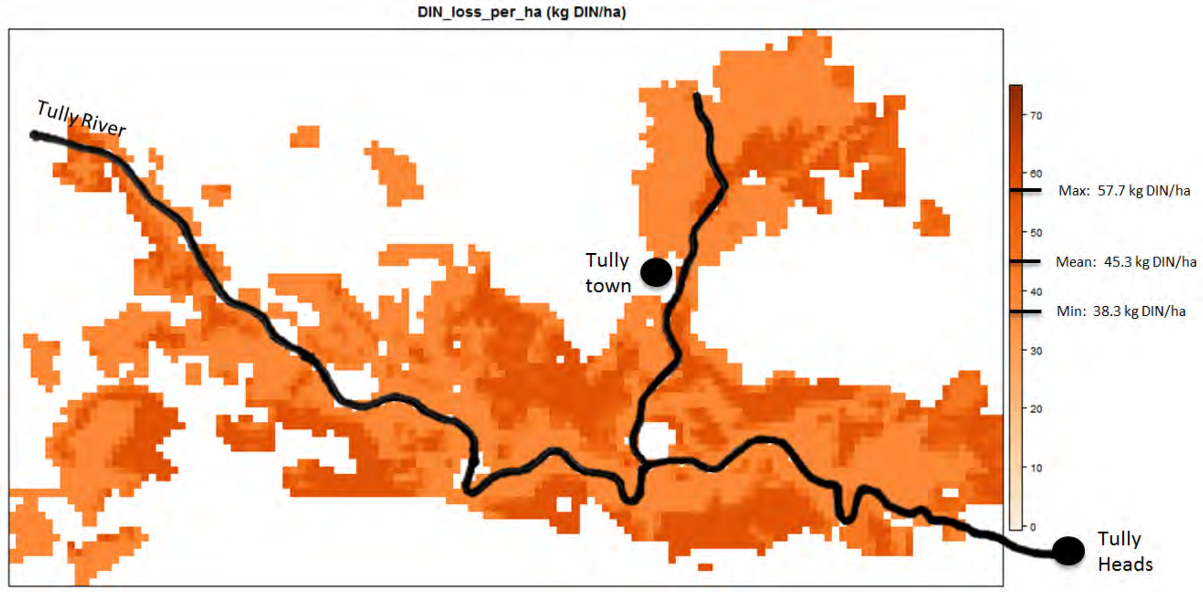


Figure ES.1: Predicted DIN losses from individual paddock-scale grid cells in the Tully cane lands under baseline conditions: uniform N-applications of 170 kgN/ha.

On market start-up, each landholder receives – free of charge – an initial, equal per hectare allocation of N-permits. The sum of N-emissions from initial allocations just matches the DIN load cap at Tully Heads. If a landholder chooses not to trade in the N-market, then N-applications on their paddock will be limited to their initial permit allocation. Landholders can enter bids to buy extra N-permits from the smart market to add to their initial N-allocation, if they know that their gross margin will increase if they are able to apply more nitrogen. Alternatively, landowners could enter offers to sell some unused N-permits from their initial allocation back onto the smart market. Landowners' (bidding + buying) or (offering + selling) exchanges within the smart market are illustrated in Figure ES.3.

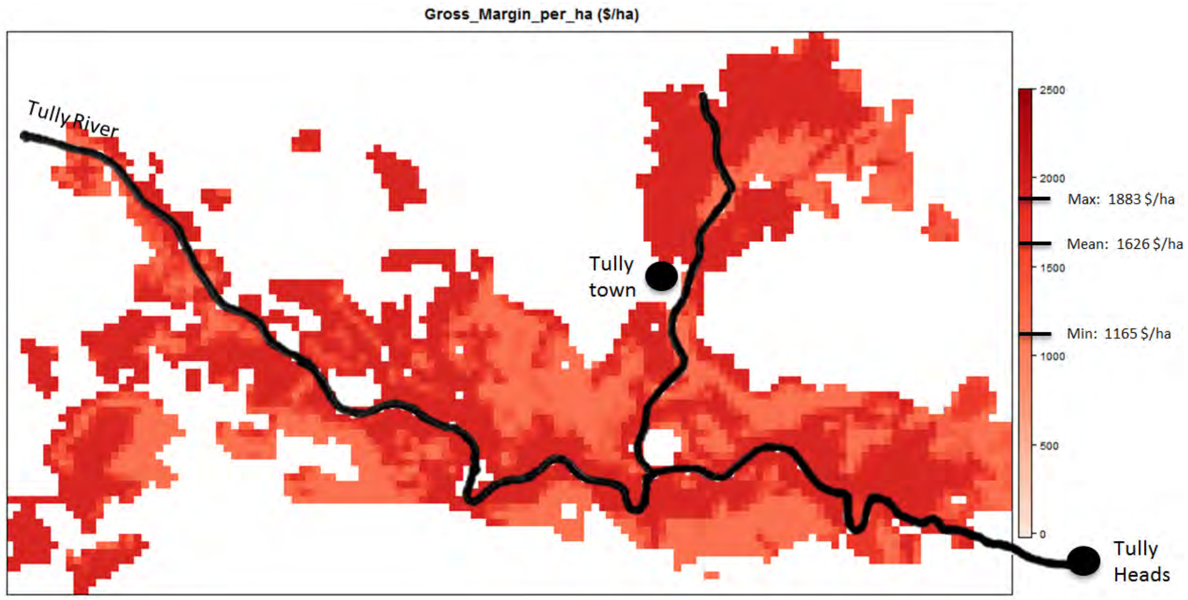


Figure ES.2: Predicted gross margins from individual paddock-scale grid cells in the Tully cane lands under baseline conditions: uniform N-applications of 170 kgN/ha.

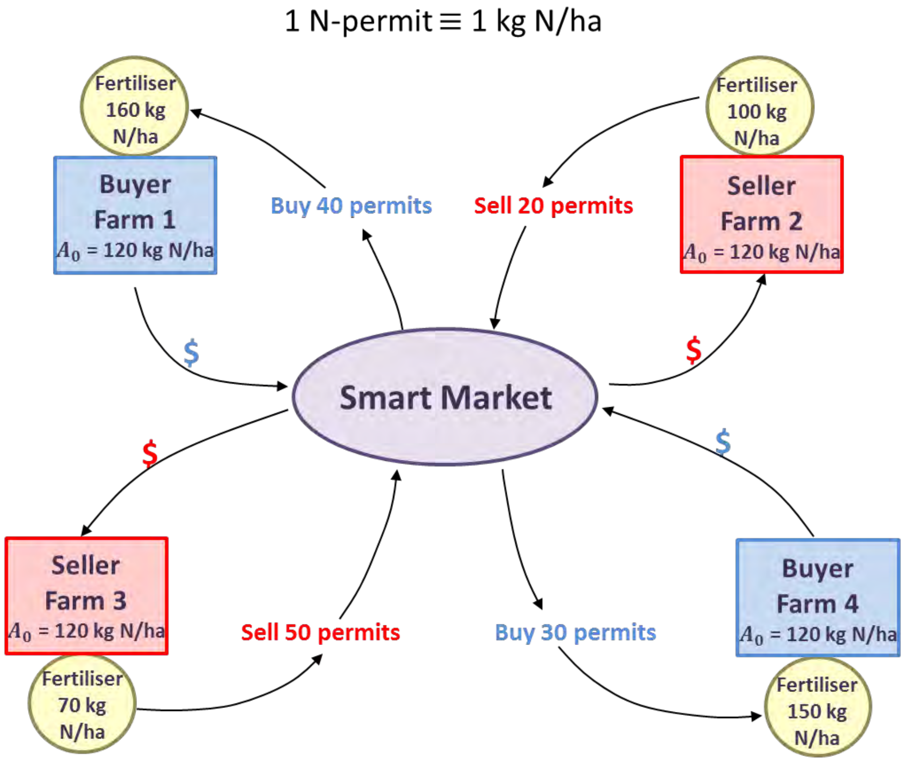


Figure ES.3: Buying and selling N-permits on the centralised smart market, with a uniform initial allocation (A_0) of 120 kg N/ha

All buying and selling transactions are managed through the centralised smart market. ‘Smart’ market action accepts modestly-priced offers to supply N-permits and then sells those permits to buyers who entered high bids for N-permit purchases. This matches overall

N-permit supply with N-permit demand, whilst still ensuring that permit trading does not infringe the overall load cap at Tully Heads. Smart market action ensures that N-permit purchasers are able to buy additional N-permits at the lowest price consistent with securing an adequate supply of permits from N-permit sellers. N-permit sellers also gain from trading because they receive the highest price consistent with matching their supply of N-permits to permit purchasers' demand for N-permits.

Market simulations are extended to include N-credits from constructed wetlands in a common pool with sales and purchases of N-permits. As the DIN load cap at Tully Heads is tightened, the market-clearing price for N-permits and N-credits increases. Higher N-prices under tight DIN load caps are sufficient to persuade some landowners to convert their less-productive cane paddocks to constructed wetlands. These landowners – on the less productive land – find that they can make more money by selling N-credits from their constructed wetlands than they could from growing sugarcane.

Market simulation results suggest that reducing N-fertiliser applications to around 120 kgN/ha may be sufficient to achieve the 50% DIN load reduction target of the Reef Plan. Results also suggest that this 50% reduction could be achieved at modest total cost. The ecologically-relevant 80% DIN load reduction target is more challenging. Our results suggest that a DIN load cap corresponding to uniform N-applications of 60 kgN/ha would deliver close to a 77% reduction. Simulations indicate that an N-trading market with initial allocations of 60 kgN/ha would be a more cost-efficient way of achieving this outcome than a mandatory (non-tradable) N-application limit of 60 kgN/ha.

Including constructed (treatment) wetlands as a source of N-credits has potential to increase the gains from market trading considerably as the DIN load cap is tightened towards the 80% target reduction. Selling N-credits from wetlands provides landowners with an alternative source of income, easing their transition out of cane. The N-credits from wetland also benefit the landowners who remain in cane. With constructed wetlands acting as DIN-sinks, more fertiliser can be applied in the catchment without infringing the total DIN load limit at Tully Heads. This effectively increases fertiliser supply which, in tandem with the lower costs produced by supplying N-credits from wetlands instead of sourcing N-permits from landowners exiting cane, leads to a reduction in the market N-price. A lower N-price makes it less expensive for landowners on better soils to purchase additional nitrogen, so – from all perspectives – outcomes improve.

Results show that there is sufficient variability in gross margins across Tully grid cells to drive an active trading market, with more than half of the grid cells buying or selling N-permits in all simulations (Figure ES.4); gross margins are increased through trading (Figure ES.5).

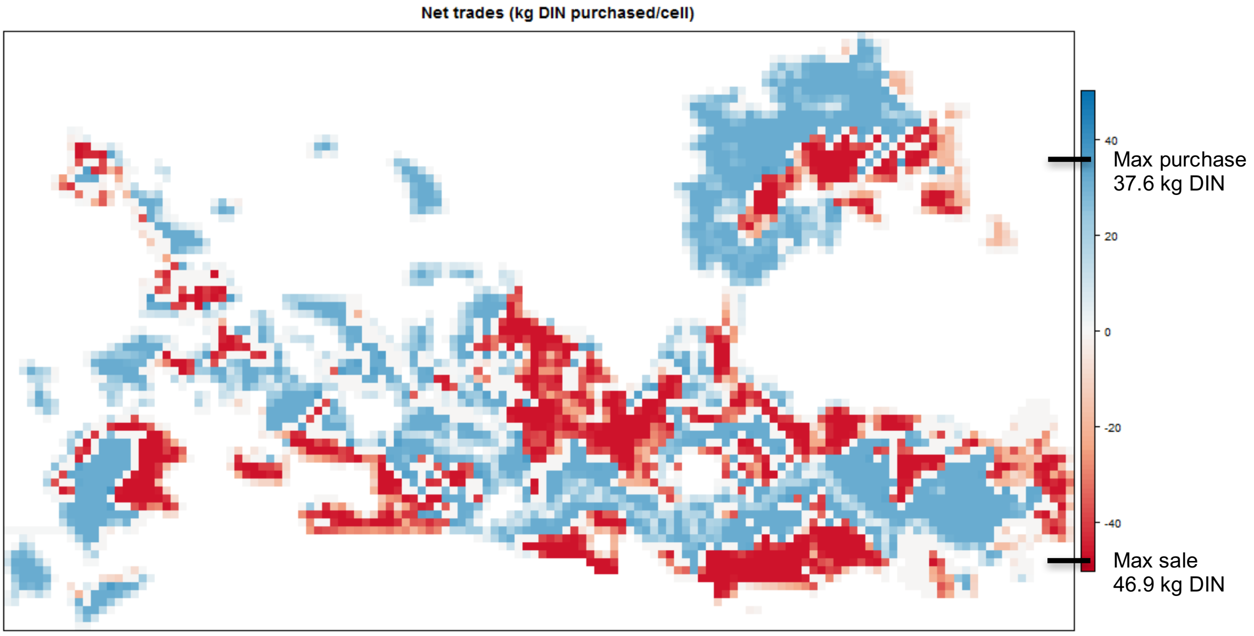


Figure ES.4: N-permit buyers (blue), sellers (red) and non-participants (grey) in N-market trading, from a starting position with uniform initial N-permits allocations of 90kgN/ha. In total there are 1986 buyers, 1306 sellers and 728 non-participants.

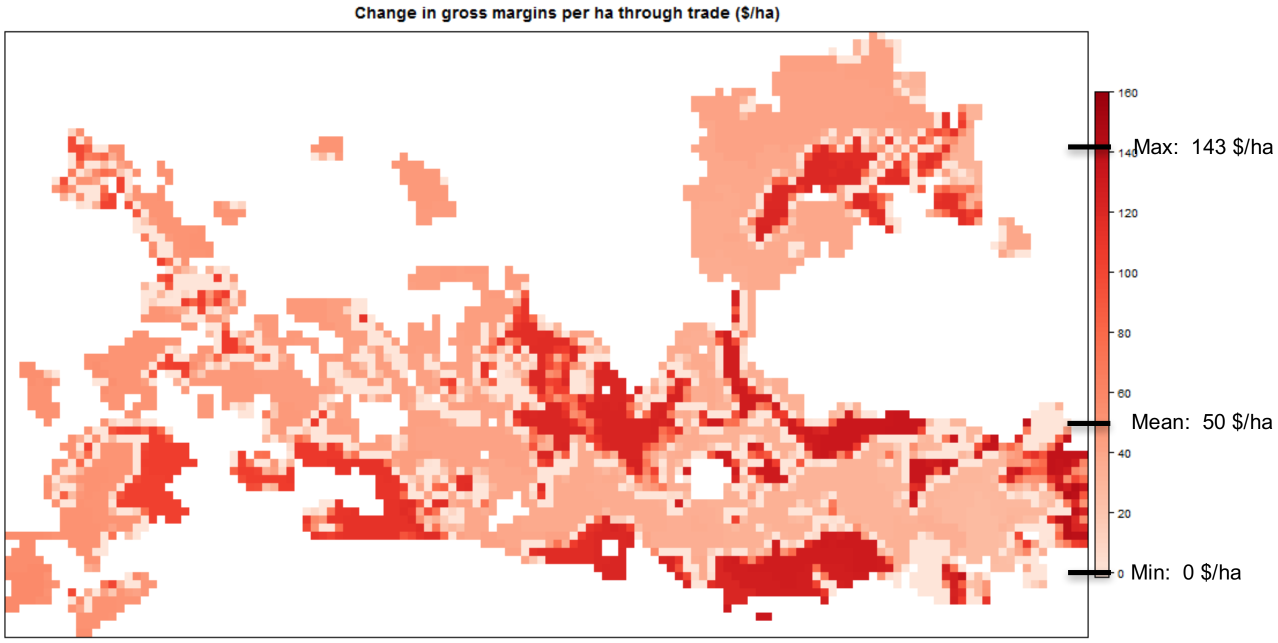


Figure ES.5: Changes in gross margin ($/ha) realised through N-market trading, from a starting position with uniform initial N-permit allocations of 90kgN/ha.

The outcome of spatial modelling indicated that a nitrogen trading market could deliver improved economic efficiency. As the cap tightens the market price for nitrogen increases and conversion of marginally productive cane land in key locations to wetlands becomes economically viable. Trading reduces the total cost impact on the cane growing section of the industry to achieve nitrogen reduction targets. The ability to trade nitrogen savings and reductions in the smart market meant no growers were economically worse off under the trading market compared with a simple command and control approach, and some were considerably better off. Experience elsewhere shows setting up a cap and trade scheme is costly, controversial and time-consuming. In this instance, the modelled economic gains from a non-point-to-non-point trading approach rather than a simple command and control are modest.

Beyond economic efficiency arguments, there are a number of other reasons that a cap and trade scheme should be considered. The approach will put the onus on the industry to meet the targets and to innovate. It will reward growers who can most effectively reduce their nitrogen pollution and maximise production on better soils. The trading approach will help incentivise innovation and implementation of existing best management practice and new approaches. Conversion of land to nitrogen-intercepting wetlands was one innovation modelled, though there may be many others that could be potentially included in the trading framework such as edge-of-field bioreactors. The flexibility involved in the cap and trade scheme may make the introduction of a nitrogen cap more palatable for the industry rather than an inflexible command and control regulatory approach.

Implementation of a non-point-to-non-point trading scheme is a long-term undertaking requiring significant courage, investment and leadership. In the shorter term, this study has identified that the costs to cane growers of reducing nitrogen pollution is comparatively low. The ‘no worsening’ approach to future development highlighted by the Taskforce identifies a significant future opportunity for a stage one water quality-trading program focused on point to non-point trading.

Water quality trading has significant potential for maximising the outcomes of investment to reduce nutrient loads both across and within sectors. Future research should examine the potential for point to non-point smart market trading of nitrogen in key catchments and among urban, industrial and agricultural sectors. The capacity of landholders to participate in nitrogen and other reef stressor trading is not well understood. Experimental and behavioural studies would improve the understanding of factors that influence how participants act in markets with the objective of improving the architectures of these markets. Such a research program would reveal regulatory and price drivers and barriers to participation. Other key research projects should examine the potential for point to non-point trading of sediment reductions in key infrastructure (port) locations and among agricultural sectors. The opportunity exists for investigating and implementing a broader smart market trading approach that involves multiple reef stressors among point and non-point sources. The application of such an approach would involve trading between stressors and sectors to maximise the outcomes from investment.

1.0 INTRODUCTION

The Reef 2050 Long Term Sustainability Plan is the overarching strategy for the management of the Great Barrier Reef (GBR). The Plan aims to coordinate action and guide adaptive management to 2050 and presents actions to protect reef values, health and resilience while allowing ecologically sustainable development and use. Governance Action 6 of the Long Term Sustainability Plan seeks to investigate the effectiveness and cost of robust regulations, a market-based trading mechanism, or a combination of both to reduce nitrogen runoff.

The National Environmental Science Programme Tropical Water Quality Hub under its first, short- term project round has funded this brief scoping study into a nitrogen-trading scheme for catchments draining into the GBR to help inform this investigation. The focus of this research is to explore the potential cost effectiveness of non-point-to-non-point nitrogen-trading schemes to reduce water quality pollution entering the GBR Lagoon.

1.1 Nitrogen as the focus of trading

This investigation focuses on nitrogen as the key pollutant to be controlled. Significant reductions in dissolved inorganic nitrogen (DIN) are targeted as it has been established as a pollutant with significant impacts on key reef ecosystems. Waterhouse et al. (2012) summarise that the primary impacts on corals are driven by enrichment of organic matter in plankton and in sediments leading to declining calcification, higher concentrations of photo-pigments (affecting the energy and nutrient transfer between zooxanthellae and host) and potentially higher rates of coral disease.

Further, crown-of-thorns-starfish (COTS) outbreaks are linked to higher levels of DIN within the water column. High nutrient levels sustain higher levels of large phytoplankton and increase survival rates of COTS larvae (Fabricius et al. 2010). Terrestrially sourced DIN has also been quantitatively linked to the upper thermal bleaching thresholds of symbiotic reef corals on inshore reefs (Wooldridge 2009).

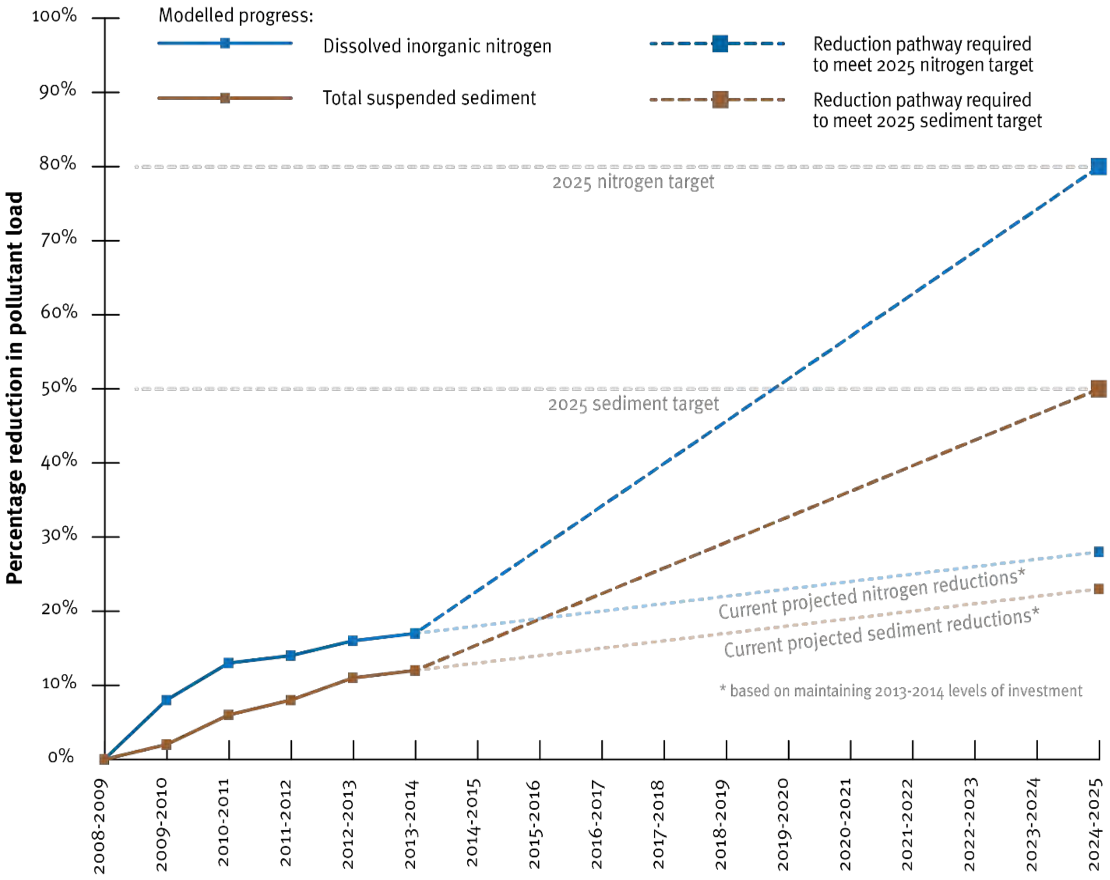
DIN is largely sourced from fertiliser products and its extensive impacts are closely related to its ready bio-availability in the marine environment. According to Waterhouse et al. (2012), a large proportion of the anthropogenic DIN load is derived from sugarcane fertiliser loss. In the Wet Tropics more than 84% of the DIN load discharged to the GBR Lagoon is from sugarcane farming and associated fertiliser application. In terms of DIN load from sugarcane cultivation, the highest loads per unit area are from the Russell Mulgrave, Tully, Murray and Johnstone catchments (Waterhouse et al. 2012).

The Reef 2050 Long-Term Sustainability Plan target is that by 2018 there is **at least a 50 percent reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads** in priority areas, with **an 80 percent reduction in loads targeted by 2025** (Commonwealth of Australia 2015, p.38).

1.2 Current and future approaches to reducing nitrogen

Current approaches to reducing nitrogen pollution have relied primarily on subsidising the voluntary implementation of best management practices in agriculture, particularly sugarcane production. The target for adoption of best practice land management is that 90% of the land area producing cane meets best practice criteria by 2018 (Commonwealth of Australia 2015 p.39). Farmers across more than 40% of cane land area have implemented elements of the voluntary, industry-led Smartcane Best Management Practice (BMP). Under this program farmers self-assess their practice against industry standards and identify opportunities for improvement. When the 2014 Reef Report Card was compiled, only 33, or approximately 1% of the 3,100 cane growers in the Reef Catchments were accredited under the scheme and only 13% of the area under cultivation for sugarcane met best practice criteria for nutrient management (DEHP 2015).

The Great Barrier Reef Water Science Taskforce identified that under the current approach targets for nitrogen reduction will not be achieved by 2025 (Figure 1).



Source: Department of Environment and Heritage Protection (2015) Great Barrier Reef Water Science Taskforce Full Interim Report – December 2015, DEHP, Brisbane.

Figure 1.1: Nitrogen and sediment load reductions required to meet 2025 targets

The Taskforce identified that transformational change is needed over the next 5 to 10 years if targets are to have any chance of being achieved and that a fundamental shift is required in the way land is managed. The taskforce report recognises that ecosystem repair through the restoration of vital riparian and wetland systems that have been lost over the last 100 years will make an important contribution to water quality.

1.3 Regulation to cap nitrogen pollution

Nitrogen pollution impacting on the GBR is a negative externality of sugarcane cultivation in that the price paid for artificial fertilisers does not reflect their potential harm to the environment. Governments historically intervene in markets through policy, regulation, subsidies and incentives to address such short comings, and various reports and bodies have identified the need for an appropriate regulatory intervention to reduce nitrogen pollution and associated water quality impacts on the GBR (DEHP 2015, Brodie et al. 2008, van Grieken et al. 2011).

The Great Barrier Reef Water Science Taskforce supports the use of regulation as part of the policy mix to meet water quality targets, including the regulation of new developments to ensure no net increase in water pollution. The Taskforce recommends that such regulations should be simple, easily measured and developed consultatively. Regulations should target the practices of greatest risk, minimise impacts on those undertaking appropriate practices, and be coupled with supporting mechanisms such as improved communication, education, extension, market based instruments and compliance (DEHP 2015).

The Taskforce Interim Report proposes a two-stage approach to regulating agricultural nutrient sources from cane farming. Stage 1 involves setting a standard for nitrogen application, with the second stage establishing individual permits to cap off-farm nitrogen discharge. Stage 2 requires an end-of-catchment total load limit to be set, with individual farm-level allocations derived from that end-of-catchment load cap. Water quality trading is identified as one potential implementation approach if the end of catchment load limit and individual allocation permitting system identified in Stage 2 is required to be implemented (DEHP 2015).

1.4 Water quality trading

Water quality trading refers to the application of emissions trading to water pollution control (Shortle 2013). Emissions trading is a market-based pollution control instrument that operates within a fixed cap on the total emissions of a pollutant. Pollutant sources are typically provided with an initial allocation of emissions, such that the sum of these initial allocations matches the total cap. Market transactions then re-allocate emissions under the cap by trading (i.e. buying and selling) from the initial allocations among individual pollutant sources. Trading harnesses market forces to promote cost efficiency in emissions reductions (Shortle 2013).

Water quality trading is an emerging market intervention solution to nitrogen pollution, although results and evidence of success to date are mixed (Selman et al. 2009). Water quality trading is a market-based approach that provides for innovation and flexibility in how regulations are met, thereby potentially lowering regulatory compliance and abatement costs in comparison to a command-and-control approach such as a mandatory imposition of a fixed (non-tradable) emissions limit for each individual emitter. The underlying premise of the trading approach is that pollution abatement costs differ between individuals or enterprises, depending on their size, location, scale, management and efficiency. Under a trading mechanism, entities that are able to lower their pollution below the level permitted by their initial allocation at low cost can sell their excess emissions permits to other entities with higher abatement costs. The revenue raised by selling permits provides an incentive to pollute less. Trading also allows those with higher pollution abatement costs to purchase extra pollution permits from entities with lower pollution costs, thereby decreasing their costs of compliance. For some pollutants, changes in land use can actively remove pollutants from the system. Constructed (treatment) wetlands are an example of this for DIN emissions. In these circumstances, active pollutant removal, such as that provided by constructed wetlands, can generate pollution credits which can also be traded on the market. This mechanism can be a particularly cost-effective approach for satisfying ‘no net worsening’ provisions. Emissions credits can thus provide a potential income stream to support land-use conversion.

Water quality trading schemes can involve a combination of trades between point sources and non-point sources of emissions. A 2008 survey of water quality trading schemes worldwide conducted by the World Resources Institute identified 57 programs, of which 26 were active, 21 were under development and 10 were inactive. Many trading schemes developed to date involve trades between regulated point sources, such as sewage treatment plants, under bubble licence conditions. Over 70% of the active water quality trading schemes identified in the World Resources Institute survey involved trades between point and non-point sources. In these instances trading usually results in a point source with high compliance costs purchasing additional pollution permits from non-point sources with lower pollution reduction costs, or purchasing pollution credits from active pollution reduction schemes. Such trades typically involve a highly regulated point source buying additional pollution permits from a non-point source such as agriculture, or pollution credits from land-use change, neither of which are generally controlled by regulatory discharge limits (Selman et al. 2009).

Schemes that involve non-point-to-non-point exchanges within agricultural settings such as that being investigated in this study are a far more recent application of water quality trading. The Lake Taupo Nitrogen Market introduced in 2011 is, however, the most relevant regional example of a non-point-to-non-point trading scheme and the following section briefly outlines the structure and success of this scheme.

1.5 The Lake Taupo nitrogen market

Lake Taupo is a 60,000 ha freshwater lake with a 350,000 ha catchment (about twice as large as the Tully River catchment in North Queensland) in the middle of New Zealand’s North Island, with about 20% farmed, mostly dairy cattle grazing. It is an international tourism icon noted for its pristine, crystal clear water, reflecting extremely low levels of plant nutrients and phytoplankton. Since the late 1990s, development of the catchment has increased nitrogen entering the Lake through ground water and rivers, promoting algal and phytoplankton blooms, degrading the colour and clarity of the lake (Waikato Regional Council, 2004). Stream monitoring showed steadily increasing levels of dissolved inorganic nitrogen (Barns and Young, 2012). Research identified that nitrogen emissions were entering the Lake from both natural processes and human activities, such as pastoral farming, urban runoff and wastewater. The total amount of nitrogen entering the lake was estimated at 1,360 tonnes annually. Of the 556 tonnes of manageable (i.e. human-induced) emissions, 510 tonnes were from pastoral farming.

Following 11 years of protracted negotiations, planning and legal challenges, the Lake Taupo cap and trade scheme and its legal provisions were adopted in 2012. The target of the scheme was to reduce manageable nitrogen emissions to 20% below current recorded levels, so as to restore water quality and clarity to 2001 levels by 2080. The long term 2080 target was chosen because of the slow movement of groundwater through the system. This was equivalent to 153 tonnes of nitrogen annual discharge reduction by 2018. This target was to be achieved through a policy package with three main components designed to give landowners flexibility, while managing overall nitrogen emissions: (1) An overall cap on nitrogen emission levels within the Lake Taupo catchment; (2) The establishment of the Taupo nitrogen market and (3) The formation of the Lake Taupo Protection Trust to fund the initiative.

The overall cap on nitrogen was regulated through land use and discharge controls. Each farm was allocated an individually-calculated nitrogen discharge allowance (the 'initial allocation'), consistent with the overall cap and the desired reduction in emission levels. Enforcement is implemented through a requirement for approved management plans, a regular monitoring programme, and penalties for non-compliance.

The policy allows landowners to buy, sell or lease nitrogen discharge allowances within the catchment. The independent Lake Taupo Protection Trust was established to use public funds to achieve the required 20% nitrogen reduction by buying-back allocated nitrogen discharge allowances and thereby reducing the local economic and social impacts of the nitrogen cap. The Trust's three main operations were purchasing farms within the catchment in order to shift them to low-nitrogen activities permanently; purchasing nitrogen discharge allowances from owners who opted to stay on their land while reducing their nitrogen output; and investing in research to seek cost-efficient ways of using farmland differently to reduce nitrogen outputs (OECD 2015).

According to an analysis of the program by the OECD, by mid-2015 the Trust had executed 23 trades in nitrogen discharge allowances equalling 151 066 kilos of nitrogen (kg N), and there had been 12 other nitrogen discharge allowance trades between regulated farmers (totalling 17 634 kg N). By June 2012, 30 out of 180 farmers had engaged in at least one trade and 17% of the cap had been traded (OECD 2015). The OECD drew the following conclusions about the Lake Taupo program:

- The trading component of the policy package is achieving what it was theoretically meant to do – it is providing the flexibility for land to move to its highest and best use and still meet the overall nitrogen load reduction target
- Trading has allowed this cap to be imposed in a more efficient and flexible manner, theoretically enabling the regulatory cap on emissions to be met at lower cost than stand-alone regulation. Compared to

achieving the cap through regulation alone, the creation of the market provides a net benefit to the farmers in the catchment.
- The purchase and trading in nitrogen discharge allowances is inextricably linked to the resource consent process and would not be possible without a robust regulatory and monitoring system tracking and controlling nitrogen discharge allowance trading.
- The objectives of the policy have been achieved through a combination of government partnerships, the commitment of the local indigenous people, sufficient scientific knowledge, and a series of innovative economic and regulatory actions designed to overcome negative economic outcomes. (OECD 2015).

The OECD concluded that ‘the Taupo nitrogen market has demonstrated the feasibility of a cap-and-trade system for agricultural non-point sources and provided one model for such a system. It shows that it is technically feasible to include non-point sources within a-cap-and trade water quality market, that such a market can function, and that once property rights are clearly established, the additional cost of allowing trading is low’ (OECD 2015 p.16).

1.6 Key aspects of water quality trading schemes

A review of the water quality trading literature identifies a number of key elements of water quality trading programs. These are summarised in the following table.

Table 1.1: Elements of a water quality trading program

Trading Scheme Element	Description
Establishment of a Regulatory Cap on Pollution	The implementation of a nutrient cap that limits overall pollutant discharges has been a key driver behind all the water quality trading schemes established. Binding regulatory limits on pollution levels are required for trading to occur. Such limits are essential to create the incentives for polluters to examine options for cost-effective compliance solutions including trading
Identification of Pollutants to be Traded	Clear identification of the pollutant or currency to be traded is required. Generally, pollutants that cause severe adverse water quality impacts from cumulative loadings are deemed most suitable for trading. Analysis of other trading programs has revealed that nitrogen and phosphorus can be effectively traded to deliver water quality improvements.
Recognition of Differential Costs among Polluters	Trading activity will only occur if the differences in pollution control costs between scheme participants are big enough to produce economic gains from trading, after allowing for ‘transaction costs’ in terms of participants’ time and effort.
Establishment of Geographic Scope of Program	The establishment of a clear geographic area in which trading may take place is required. The identified area will be dependent on the particular characteristics of the locality and the pollutant to be traded. Trading should occur within a hydrologic area that is properly defined to guarantee that trades will maintain water quality standards in the area as well as downstream and in contiguous waters
Development of Trading Rules	Trading rules must be established clearly to assure that water quality goals are met, but must also be established in a manner that encourages and facilitates trading. Rules that are overly complex and costly create barriers to trading

	activity
Institutional Structures	Successful trading requires the development of institutions for organising trade that are trusted by, and effective for, intended program participants.
Development of Trading Ratios	Trading ratios are frequently used to account for a number of factors in water quality trading programs. Factors such as uncertainty in pollution reduction estimates (particularly for non-point source reductions), creating equivalency amongst multiple pollutants, ensuring overall water quality benefits, accounting for the effects of nutrient transport and mitigating buyer risk. Trading ratios are applied to the estimated nutrient reductions to determine the marketable reduction credit. Trading ratios thus provide 'exchange rates' between different pollution reduction activities, or between different locations, or between different time periods or between different pollutants. Key ratios identified in the literature and used in other schemes to enhance water quality outcomes address uncertainty, equivalency, retirement and insurance ratios.
Program Buy In	A stakeholder process that complements the development of a water quality-trading program is important for successful implementation. Early education and ongoing dialogue with relevant stakeholders avoids many potential program barriers. The success of stakeholder engagement processes depends on the process and personalities involved. Bottom up approaches are identified as more successful than top down approaches.

Adapted from Shortle 2012, Selman et al. 2009

1.7 A model Great Barrier Reef non-point nitrogen trading scheme

In its most simplistic formulation a non-point cap-and-trade scheme for nitrogen pollution in catchments draining into the GBR Lagoon would involve the introduction of a geographically-based nitrogen emission cap, the granting of initial allocations of geo-located emissions permits within that cap, the establishment of rules and ratios governing how emissions permits can be traded between participating entities, a central authority or trust that manages the scheme and an appropriate monitoring and regulatory regime.

Based on the majority of scheme elements described in Table 1.1, Table 1.2 below summarises the key factors of a potential model market for nitrogen water quality trading in a catchment draining into the GBR Lagoon. Table 1.2 summarises how the market provisions recommended in the literature have been incorporated into the market simulation model used in this investigation to test the cost-efficiency of the approach.

Table 1.2: Elements of a Great Barrier Reef water quality trading program and implementation in market simulation

Scheme Element	Potential GBR Market Model	Implementation in Market Simulation
Establishment of a Regulatory Cap on Pollution	The overall regulatory cap can be based on targeted end-of-system nitrogen loads (tonnes per catchment) with initial allocations to individual entities estimated on a per hectare basis consistent with the overall cap target (kg per hectare).	The market simulation model will constrain total emissions to ensure they do not exceed the overall regulatory cap. The maximum limit on total emissions remains in place at all times, before and after trading.

Identification of Pollutants to be Traded	Pollutant trading will be achieved through trading initial per hectare nitrogen allocations ('nitrogen permits'). Input N-application rates are used for purposes of regulatory simplicity and because N-application rate is the key variable associated with the level of pollutant export (Sing and Barron 2014).	The model uses an N-application rate of 170 kgN/ha as a baseline, roughly approximating to the '2009 baseline' in the Wet Tropics WQIP. Market trading is then simulated for successive tightening of the overall cap starting from initial allocations of 150, 120, 90 and 60 kgN/ha. Initial allocations are allocated free of charge to each participant.
Recognition of Differential Costs among Polluters	The viability of the trading approach is based on the fact that the costs and effectiveness of reducing pollution are different for each productive land parcel, based on its soil properties and location in the catchment. Permit sellers will be those who can economically lower their pollution levels below the permitted cap.	The model simulation uses relationships from the literature to predict gross margins ($/ha) and DIN losses (kg DIN/ha) as functions of N applications (kg N/ha) on different soil types in the modelled catchment (Roebeling et al. 2007a, drawing on Armour et al. 2009). Knowing how gross margins and DIN losses vary with N- applications across the catchment, the model predicts buyer and seller trading behaviours under different cap scenarios.
Establishment of Geographic Scope of Program	Trading programs are traditionally based on catchment boundaries.	The cane growing area of the Tully catchment is used as the basis for spatially-specific model simulation. Findings from spatially-specific simulation in the Tully are then applied to infer the likely operation of a trading market in the Lower Burdekin, allowing for key differences between the two catchments.
Development of Trading Rules	Trading rules should be designed to be simple and encourage the most efficient use of nitrogen allocations. Trading rules should also encourage and facilitate appropriate land use changes including conversion to wetlands.	The simulation model is based on a 'smart market' concept, involving a multi-lateral online trading system. Trading of permits is subject to compliance constraints and an overall end of catchment DIN load constraint. An initial set of market simulations only consider reductions in N-applications. A

		second set of simulations extend the trading to include wetland conversion at appropriate locations.
Institutional Structures	A single central buyer and seller of nitrogen credits is suggested in an independent structure, following similar practice to the Lake Taupo system.	The model simulates centralised web-based trading between buyers and sellers. A linear program is used to clear the market by optimising the gains from trade. Market optimisation is achieved by sourcing nitrogen permits from sellers who are willing to release N-permits at low cost and then selling these permits on to buyers who are willing to pay the most to obtain extra permits. In this way, limited by the overall cap, nitrogen applications are moved from lower value uses to higher value uses.
Development of Trading Ratios	Trading ratios are not recommended in this non-point program and a simple 1:1 trading ratio is used, although allowances will be required for differences in N-transport down the catchment. Trading ratios are more suited to a point-to-non- point trading scheme where cost differentials are large with greater perceived risks and uncertainties.	N-allocation permits bought and sold at different locations within the modelled catchment are traded at a 1:1 ratio, moderated by small allowance for differences in N-transport between emission source locations and the estuary. When wetlands are introduced, wetland N-credits are traded on a 1:1 basis with N-permits. A small allowance for N-transport down the catchment is again applied

The fundamental consideration for the introduction of a trading scheme is whether or not it leads to a more cost-effective outcome than a conventional command-and-control approach. The command-and-control alternative to an N-trading market would be a mandatory, uniform non-tradable limit on N-applications, for example a fixed application limit of one of 150, 120, 90 or 60 kgN/ha.

To test whether a trading scheme is more cost-effective than the command-and-control alternative, the following sections of this report use high resolution data from the cane growing areas of the case study catchments to implement a spatially-specific model of market operation at (approximately) paddock resolution. The modelled market contains 4020 250m x 250m (6.25ha) grid cells, each trading as a separate entity.

Market simulation mimics the N-allocation and trading decisions which a landowner might undertake for each of their paddocks, recognising that N-application requirements will likely differ between paddocks depending, primarily, on the underlying soil type and the current stage of cropping schedule (e.g. cane plant, first ratoon etc.). Simulation outcomes identify spatially targeted cost-effective reductions in nitrogen leakage, minimising the costs that the cane industry incurs in meeting the overall emissions cap imposed on the total annual DIN load at the end of catchment.

2.0 DATA AND CASE STUDY AREAS

2.1 Introduction

This section of the document presents the relevant data that has been used to inform the spatially based market simulation model. Overview data, including relevant GIS layers and descriptions of cane growing activities, soil classes and information on nitrogen losses under various production methods and the overall nitrogen cap are presented.

2.2 The Tully Catchment

Parks, ranging from National Parks to recreational reserves, cover 68% of the catchment. Similar to other catchments in the Wet Tropics NRM region, the Tully River is prone to flooding. Annual average river flow is estimated to 3,448,088ML (Terrain 2015). Land mainly used for agricultural production (195 holdings) makes up 20% of the catchment. Sugarcane growing (126 holdings) is the most common agricultural activity, most of which is located around Tully and along the lower stretches of the Tully River. Some horticulture (47 holdings) and beef cattle grazing (55 holdings) are also present (ABS 2010).

Major towns within the catchment are Tully, Tully Heads and Wongaling Beach. Within the Wet Tropics management area the Tully catchment is the second largest source of DIN load (Terrain 2015). Horticulture, which is dominated by cane growing, occupies 19% of the catchment and is estimated to be the source of 85% of the nitrogen pollutant load (Brodie et al. 2008).

Nitrogen losses from catchments in the Wet Tropics are a major cause of concern regarding Reef health and condition (e.g. McKergow et al. 2005, Kroon et al. 2012). The Tully and Tully-Murray catchments have been a particular focus of scientific, economic and interdisciplinary research regarding nitrogen losses from agriculture (e.g. Armour et al. 2009, Bainbridge et al. 2009, Roebeling et al. 2007a, Roebeling et al. 2007b, Schroeder 2009, Skocaj et al. 2012, van Grieken et al. 2013a, van Grieken et al. 2013b, van Grieken et al. 2014, Webster et al. 2012). This research has produced a comprehensive set of data from which linkages have been established between N-fertiliser applications (kg N/ha), soil type (4 categories), DIN losses (kg DIN/ha) and gross margins ($/ha) (Armour et al. 2009, Roebeling et al. 2007a).

Given the concern surrounding cost-effective mechanisms for reducing nitrogen losses from the Wet Tropics catchments and the ready availability of these key linkages in the literature, the Tully catchment was chosen as the setting for spatially-specific modelling of the operation of an N-trading market in cane lands. The following sections describe the spatial, environmental and economic data compiled to implement a spatially-specific model of an N-trading market in the cane lands of the Tully catchment. The design and operation of the N-market model itself is described in Chapter 3.

2.2.1 GIS data collation for the Tully cane lands

GIS-derived, spatially-specific data form the basis for implementing a spatially-specific model of N-market operation in the Tully cane lands. Spatial data detailing:

- Sugarcane area
- Soil class
- Distance through drainage network to the estuary at Tully Heads
- Type and extent of existing wetland

were collated from appropriate GIS sources. GIS processing was undertaken with ArcGIS 10.1 software. All layers were projected to GDA_1994_MGA_Zone_56. Key data sources are identified in Table 2.1.

A 250m x 250m dimension was chosen as the basic grid cell size for modelling N-market trading in the Tully cane lands. This dimension was determined by inspecting visual imagery from Google Earth and 2.5m resolution orthophoto mosaics from the Queensland Department of Natural Resources and Mines. The 250m x 250m grid cell dimension was chosen for the study because it provided a rough approximation to 'paddock scale' sugarcane management (Figure 2.1).

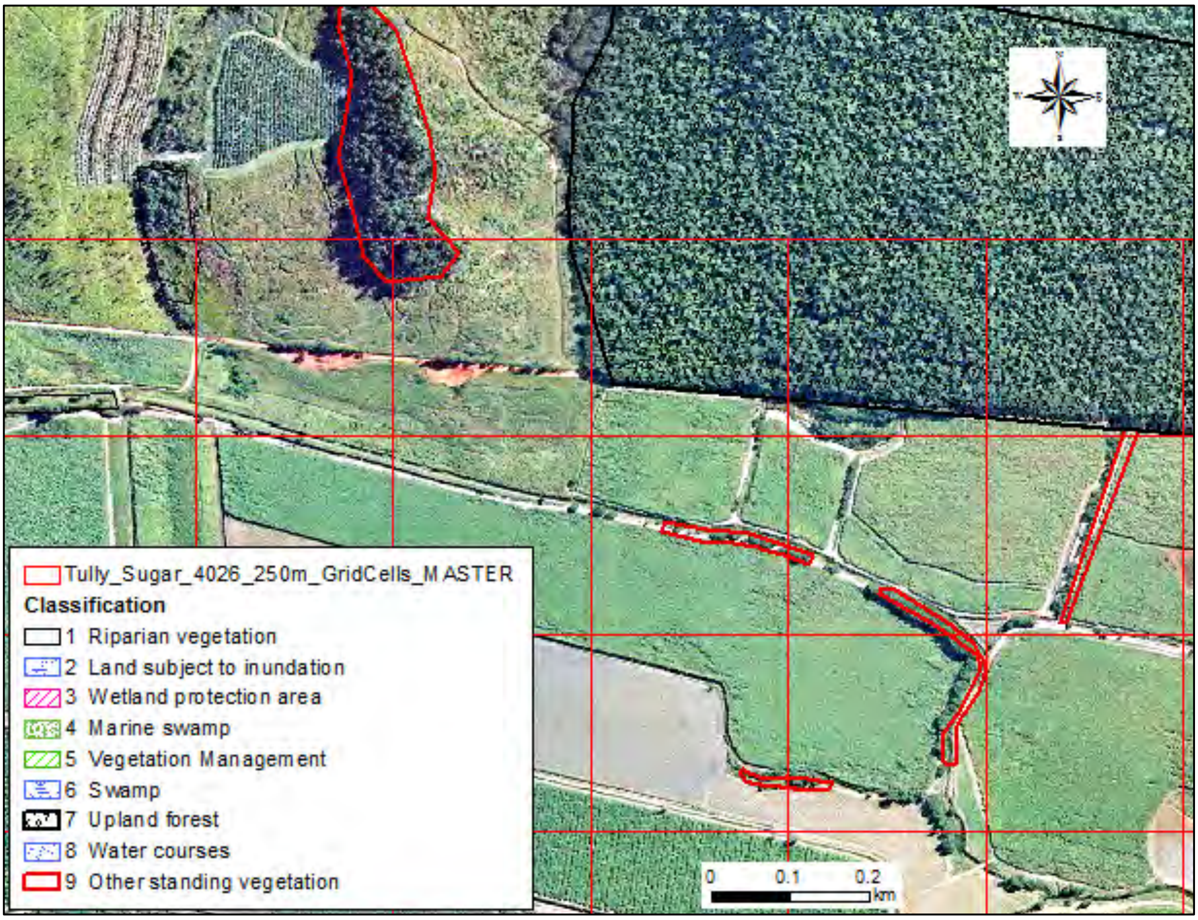


Figure 2.1: 250m x 250m grid cells overlaid on a 25m-resolution orthophoto, indicating that 250m x 250m grid cells roughly approximate to 'paddock scale' decision units.

Table 2.1: Key sources for GIS data

Item	Data	Purpose	Source
1	Land Use QLUMP Current	Areas mapped as sugarcane production were extracted from the QLUMP Current dataset. The Tully catchment was mapped in 2009 at a scale of 1:50,000.	Department of Science, Information Technology and Innovation for the State of Queensland (DSITI). Qld Government QSpatial Spatial Data Catalogue (QSpatial).
2	Wet Tropics 25m Digital Elevation Model (DEM)	Used to derive slope and hill shade rasters	QSpatial
3	Landsat Australia 2002	Visualise land surface across the study region; to measure approximate area of cane fields	Geoscience Australia
4	25 000 Orthophoto mosaic	Mosaiced orthophotos with 2.5m pixel captured in 2004; used to visualise and digitise riparian vegetation and ponded water.	Qld Government Department of Natural Resources and Mines (DNRM)
5	Google Earth online imagery	High resolution imagery from 2014 and 2015; used for digitising riparian vegetation from an eye height of ~ 1km at a scale of ~ 1:10,000	2015 Google Inc.
6	Soils_wet_tropical_coast_study_Cardwell_Tully_Innisfail_area	Mapping of 70 soil series at 1:50,000 scale; classified into 4 categories depending on potential for plant growth being limited by soil drainage	DSITI, QSpatial
7	Tully-Murray soil map from Roebeling et al 2007	To visualise the 4 soils classes used in previous CSIRO research	Scanned from Roebeling et al 2007 and georeferenced for use in GIS
8	Tully drainage basin	To define the extent of the Tully drainage basin, as defined by Australian Water Resources Management Committee (WRMC).	DNRM, created using information owned by Federal Government Agencies. QSpatial
9	Watercourse areas	To define the width and length of major waterways	DNRM, QSpatial
10	Watercourse lines	To define minor watercourses	DNRM, QSpatial
11	Canals	To define canals draining sugarcane fields	DNRM, QSpatial
12	GBR_WATERPATHWAY	Data relating to inherent properties of the landscape	DNRM, QSpatial

2.2.2 Cane area

The 250m x 250m grid cells were produced by merging cells from the 25m DEM (10 cells by 10 cells) covering the Tully Catchment. Grid cells covering the whole catchment were overlaid onto the sugarcane production areas mapped by QLUMP in 2009. 4026 grid cells containing land mapped as sugarcane production were selected as the basis for the spatial framework for this investigation. Six of the 4026 250m x 250m cane grid cells were later discarded due to data anomalies. The remaining 4020 250m x 250m grid cells were the basic 'decision making units' modelled in the spatially-specific N-market simulation model for the Tully cane lands (Figure 2.2).

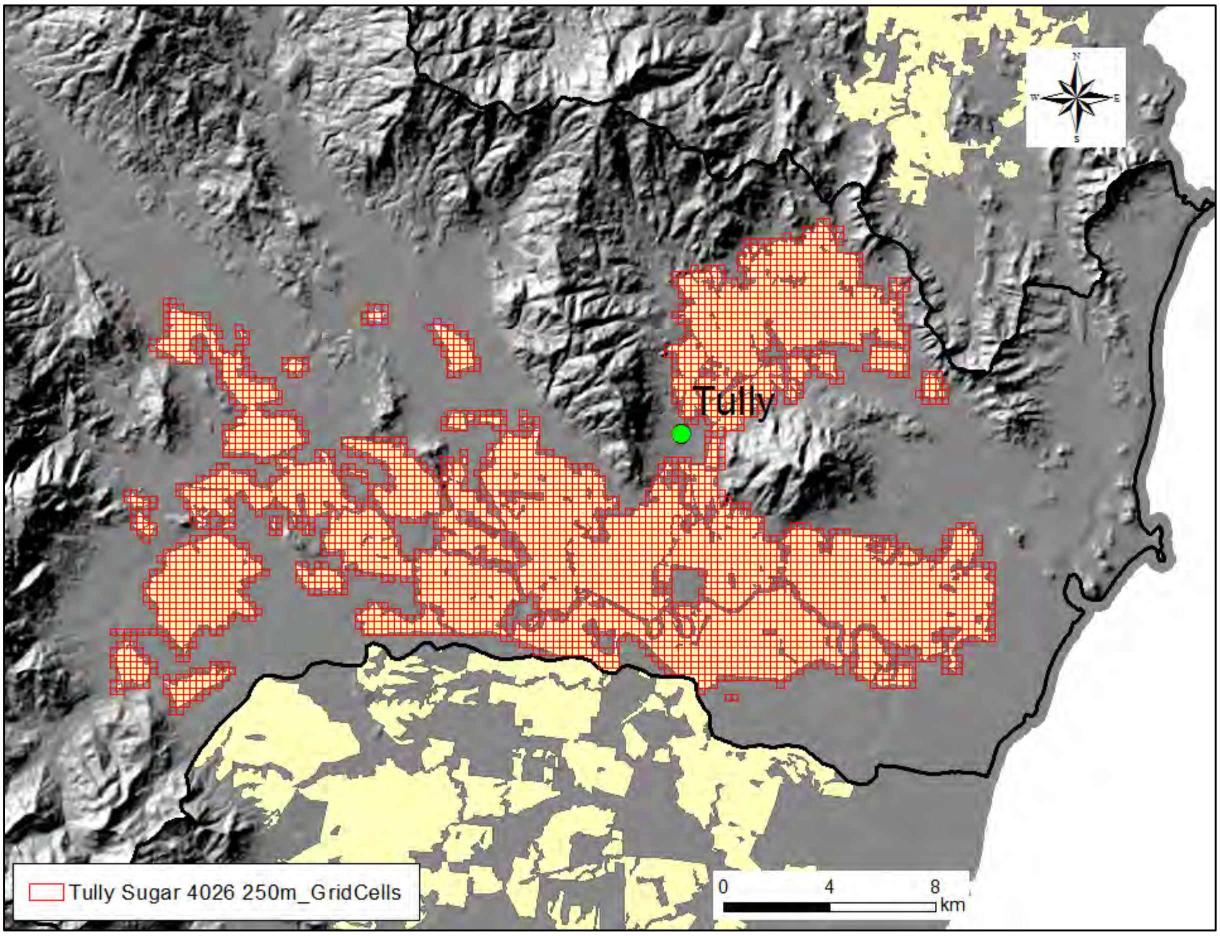


Figure 2.2: Sugarcane production (yellow area) in the Tully and Murray catchments as mapped by QLUMP in 2009. Overlay shows the 250m x 250m grid cells used for spatial analysis and spatially-specific market modelling of N-trading. The Tully catchment is bounded by the thick black line.

2.2.3 Soil Class

Roebeling et al. (2007a) developed ***soil-type-specific*** relationships between N-fertiliser application rates (kg N/ha) and (i) gross margins from cane production ($/ha), and (ii) DIN losses (kg DIN/ha). The spatially-specific N-market model uses these ***soil-type-specific*** relationships to predict the gross margins and DIN losses which would result from particular fertiliser application rates for each of the 4020 sugarcane grid cells. A soil map layer was therefore constructed as a key input for the spatially-specific N-market model for the Tully cane lands. Soil categorisation in this map used the broad soil classifications described by Roebeling et al. (2007a), and proceeded as follows.

Referring to Cannon, Smith & Murtha (1992), Murtha (1986) and Murtha & Smith (1994), digitised 1:50,000 scale maps from DSITI (Table 2.1, Item 6) of 70 soil series were amalgamated into the four classes of Table 2.2, (the same descriptions used by Roebeling et al. (2007a Sec 2.1.1 p3)). This produced the 4-class soil map of Figure 2.3. The soil classes in Figure 2.3 were used as the basis for calculating gross margins and DIN losses from each of the 4020 sugarcane grid cells at particular N-application rates, via the soil-type-specific relationships published by Roebeling et al. (2007a).

Table 2.2: Criteria used for classification of soil types in the Tully cane lands

Classification	**Criteria with morphological description (from Roebeling et al. 2007a)**
S1	Well drained sandy loam soils from granitic origin
S2	Well drained medium to heavy clay soils from alluvial origin
S3	Slowly drained gradational or duplex textured
S4	Poorly drained loam soils from alluvial origin

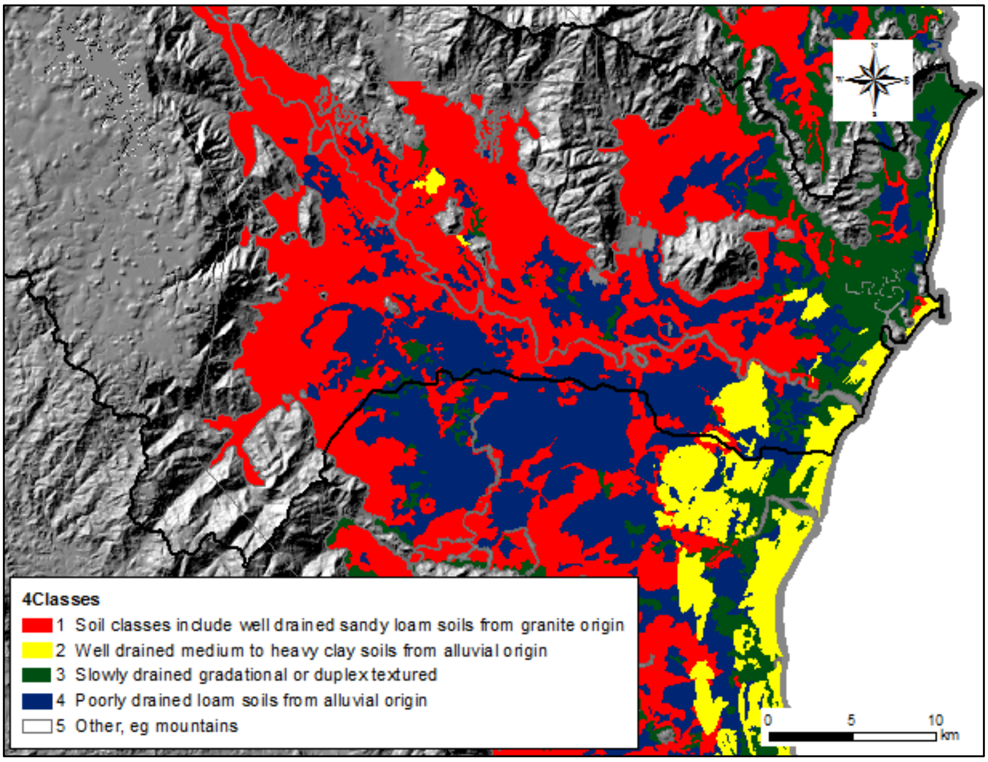


Figure 2.3: Soil classification for the Tully cane lands according to the criteria of Table 2.2.

2.2.4 Distance through drainage network to Tully Heads

Roebeling et al's soil-type specific relationships between N-fertiliser applications and DIN losses, together with the soil map of Figure 2.3, allow DIN losses to be predicted for each of the 4020 grid cells for given fertiliser application rates. This produces spatially-specific predictions of DIN loss at each of the 4020 grid cell locations. The N-trading market will operate within a given overall cap on the total DIN load at Tully Heads. Modelling should therefore include a term to represent the potential DIN load reduction produced by denitrification as DIN is transported through the drainage network and down the catchment. The modelled DIN load reduction depends on the transport distance from the ‘source’ grid cell to Tully Heads. The length of the flow path through the drainage network from each of the 4020 grid cells to Tully Heads was therefore calculated as follows.

The ArcGIS hydrology toolset was used to calculate the number of 25m DEM cells that “digital water” passed through from the upper catchment to the coastline, or the edge of the data represented by the digital elevation model. The centre point of each 250m grid cell was used to sample the flow distance to the Tully Mouth calculated using the 25m DEM. Figure 2.4 shows the features connected to form the drainage network.

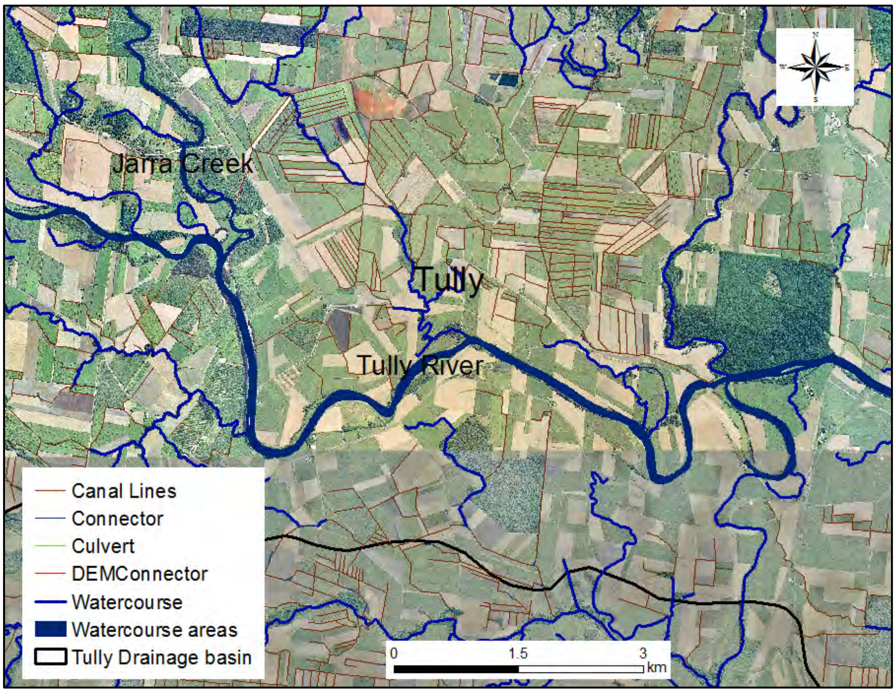


Figure 2.4: Features included in the modelled drainage network in the Tully catchment.

Minor complications arose because of extreme flatness in parts of the lower Tully flood plain. The digital elevation model indicated that the drainage path to the sea for approximately 7% of the 4020 grid cells did not flow via the main trunk of the Tully River. The drainage distance to the sea for these cells was therefore calculated to the mouth of a creek approximately 4km along the coast from Tully Heads. For modelling purposes, DIN loads from these cells were still regarded as part of the overall DIN load cap at Tully Heads. Calculated distances from each of the 4020 grid cells through the drainage network to Tully Heads are shown in Figure 2.5.

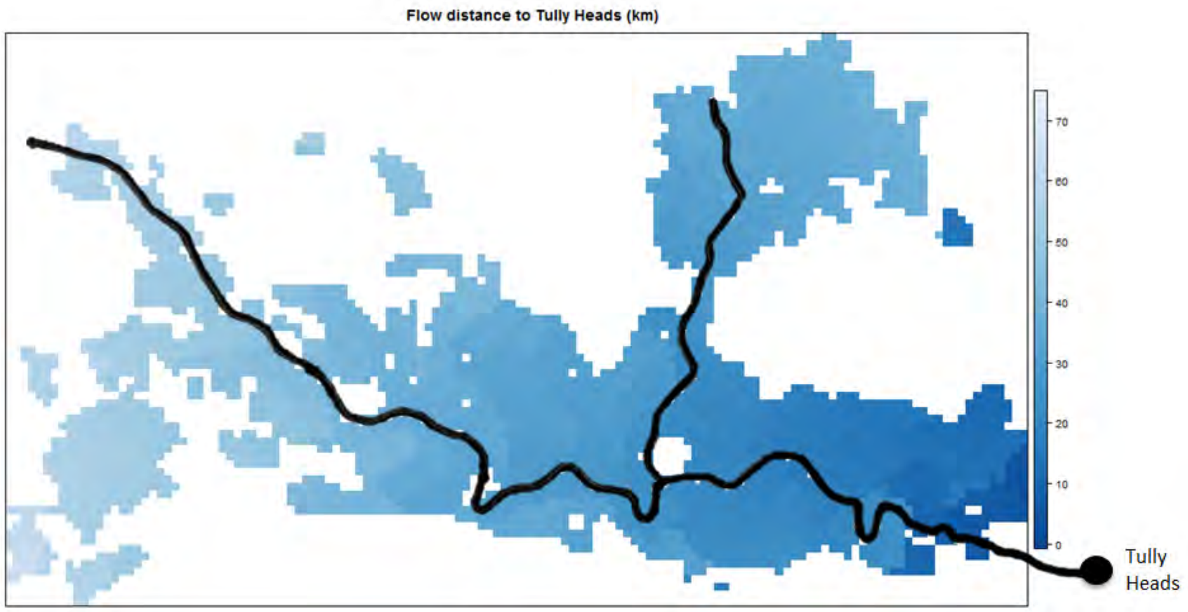


Figure 2.5: Distance through the drainage network from the 4020 sugarcane grid cells to Tully Heads.

2.2.5 Sugarcane production and fertiliser management in the Tully catchment

A sizeable and consistent body of literature has investigated the linkages between cane production, fertiliser management, economic returns and DIN losses from sugarcane production in the Tully catchment, and in the neighbouring Murray.

Van Grieken et al's recent Tully-Murray study (2013b) models environmental and economic outcomes from combinations of fertiliser, fallow and tillage practices (van Grieken et al. 2013b, Table 1). Van Grieken's et al's 2014 report explores outcomes from a similar, but broader, set of combinations. Both of these studies model sugarcane production via APSIM (Keating et al. 2003) and nutrient transport via SedNet/ANNEX (Wilkinson et al. 2004). Catchment-scale outcomes from APSIM and SedNet/ANNEX modelling of the nutrient losses from sugarcane production in the Tully-Murray under different simulated management practices are presented in Armour et al. 2009 and van Grieken et al. 2013a,b.

Roebeling et al. (2007a) present APSIM-derived simulation results which predict how (i) gross margins from sugarcane production ($/ha), and (ii) DIN losses (kg DIN/ha) in the Tully-Murray vary across the 4 different soil classes of Table 2.2 as the following management practices are switched between defined levels:

- nitrogen application rates
- tillage practice
- fallow management practice
- nitrogen application method
- herbicide application rate
- trash management
- harvest strategy

Roebeling et al's results show that, within a particular soil class, nitrogen application rates are the major driver of gross margins and DIN losses (Roebeling et al. 2007a, Section 3.1); the influence of the other modelled management practices on these outcomes is much smaller by comparison.

Variation in gross margins and variation in DIN losses across the 4020 sugarcane grid cells are the primary factors which will dictate trading activity within the N-trading market. N-market simulation was therefore based around the five step-wise levels of N-fertiliser application (kg N/ha), shown in Table 2.3. These steps are within the range of N-applications modelled by Roebeling et al. (2007a), and are representative of N-application rates in the management practice combinations used by Armour et al. (2009) and van Grieken et al. (2013b, 2014).

Van Grieken et al. (2013b) reported usage of the Table 2.3 management classes in the Tully-Murray as Class B 40%, Class C 53%, Class D 7%. This matches the levels of adoption reported for the Tully in the most recent Wet Tropics WQIP (Anon. 2015, Table 3.11, p53). We will therefore consider the Class C N-applications (N150: 150 kgN/ha) as the starting position for simulating operation of the N-trading market.

Table 2.3: Steps in N-fertiliser application used in simulating N-market trading in the Tully

N-application (kg N/ha)	Descriptions	References
N170	Class D ('Dated') practice Typical of historical management; Used to set baseline total DIN load from which 50% and 80% reduction targets will be measured	Armour et al 2009 Anon. 2015 van Grieken et al. 2013b Webster et al. 2012
N150	Class C ('Common') practice Older industry standard; Used as the starting point for N-trading simulations	Calcino 1994, referenced in van Grieken et al. 2013b
N120	Class B ('Best') practice Six-Easy-Steps recommendations	Skocaj et al. 2012 van Grieken et al. 2013b
N090	Class A ('Aspirational) practice N replacement	Thorburn et al. 2004 Skocaj et al. 2012 van Grieken et al. 2013b
N060	Low rate of N application	

2.2.6 Overall DIN load cap at Tully Heads for the N-market model

The simulated N-market for the Tully will allow N-trading between grid cells within an overall cap on the total DIN load discharged from Tully Heads. Market operation will be modelled as the overall DIN cap is tightened progressively from approximately the current situation (represented by Class C N-applications of 150 kgN/ha) down to the DIN load limits set in the Wet Tropics Water Quality Improvement Plan (Wet Tropics WQIP) for the longer term (Anon. 2015).

The Wet Tropics WQIP sets two different targets for reducing DIN loads from the Tully. Both of these targets express DIN load reductions relative to a baseline DIN load of 667 tonnes for the Tully in 2008/09 which was derived from monitoring data (as opposed to APSIM-based modelling) (Kroon et al. 2010, Table 3.1 p 12). The WQIP DIN reduction target derived from Reef Plan 2013 requires a 50% reduction from the 2008/9 baseline to be achieved by 2018 (Anon. 2015, Section 3.3.1 & Table 3.7), whereas the WQIP's ecologically-relevant target (Brodie et al. 2014) requires an 80% reduction from the same baseline by 2035 (Anon. 2015, Section 3.3.2 & Table 3.7).

Using APSIM and SedNet/ANNEX modelling, Armour et al. (2009) predicted a total anthropogenic DIN load of 1055 tonnes from the Tully-Murray. This is very similar to the total 2008/09 baseline anthropogenic DIN load for the Tully-Murray combined [1065 tonnes] established by Kroon et al. (2010, Table 3.1 p 12). Approximately 84% of Armour et al.'s anthropogenic DIN load came from sugarcane cultivation, for which Armour et al. assumed an N-fertiliser application rate of 170 kg N/ha (Armour et al. 2009, p1092). As the DIN loss estimates produced by our N-market simulation model are also derived from APSIM and SedNet/ANNEX, via Roebeling et al's soil-type-specific N-application:DIN loss relationships, **we use the predicted DIN losses from the N-market simulation model with a uniform N-fertiliser application rate of 170kg N/ha as the model's 'baseline'**.

The ability of the N-market to deliver the WQIP's target 50% and 80% reductions from this baseline will be reviewed and discussed later in the report. Note that by using Class C N-applications (N150: 150 kgN/ha) as the starting position for simulating operation of the N-trading market (for the reasons explained in the preceding section) implies that some progress has already been made towards the target 50% / 80% reductions from the 170 kgN/ha baseline.

2.2.7 Fertiliser application and DIN losses in the Tully

Roebeling et al. (2007a) used APSIM modelling to determine soil-type-specific relationships between fertiliser application rates (kg N/ha) and DIN discharges (kg DIN/ha) for standard cane production practice in the Tully[1]. These relationships are reproduced here as Figure 2.6.

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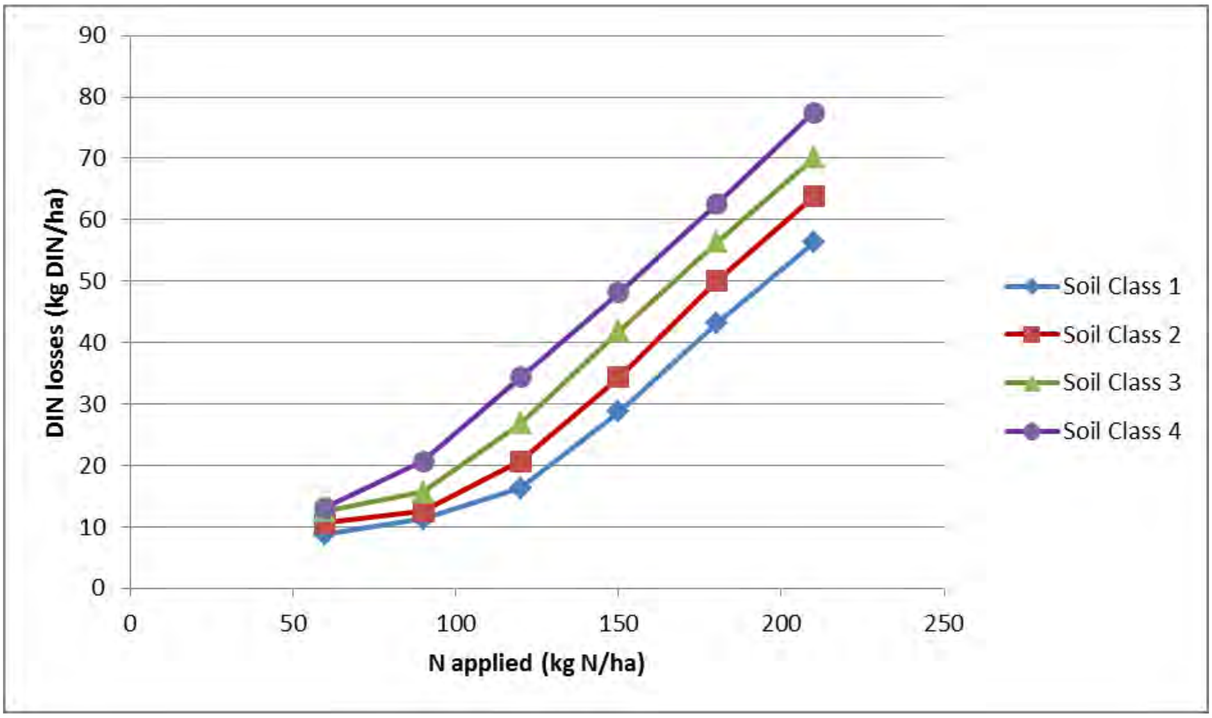
[1] In Roebeling et al's 2007a modelling, standard practice comprised: a bare fallow for 6-months between the final ratoon crop and cane replanting, an N-application rate on plant cane which was 75% of the rate applied to ratoon cane, and green cane trash blanketing.



Data source: Roebeling et al. 2007a, Figure 6, p17.

Figure 2.6: Average annual DIN delivery for nitrogen application rates of 60, 90, 120, 150, 180 and 210 kg per hectare per year for sugarcane production in the Tully catchment on the soil classes of Table 2.2.

The variation in DIN loss in Figure 2.6 across the N-application rates commonly encountered in the Tully (N120 to N170, classes B, C, D in Table 2.3, and van Grieken et al. 2013b) are reasonably consistent with the variation in nitrate-nitrogen[2] (NO_3-N) lost via deep drainage and runoff[3] reported by van Grieken et al's for equivalent fertiliser application rates in the same catchment (van Grieken et al. 2014, Figures 19, 20 & 27, p60 & 62).

The N-market simulation model uses the Figure 2.6 relationships to predict the DIN loss (kg) from each sugarcane grid cell, knowing the area of sugarcane in the grid cell, its soil class mix and an N-application rate. Applying N-fertiliser at a particular rate (kg N/ha) on a particular grid cell (containing a known area (ha) of sugarcane) will produce a particular DIN loss (kg DIN). This allows market trading to be framed in terms of N-applied (kg N-applied), whilst the overall load cap at Tully Heads is set in terms of DIN (tonnes DIN). In the market simulation, tradable N-permits confer the right to apply a specified N-application (kg N/ha) onto the soil at a particular location (modelled as a particular grid cell) in a given year. In practice, this would translate to the right to purchase and apply a specified quantity of fertiliser for application at that particular location.

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[2] Dissolved inorganic nitrogen (DIN) comprises ammonium-N (NH_4^+-N) and oxidised nitrogen (NO_x-N). DIN losses from sugarcane are predominantly in the form of oxidised nitrogen (Bainbridge et al. 2009 Figure 3, p1087).

[3] Van Grieken et al's modelling shows that for the Tully catchment the majority of DIN loss to the catchment is via deep drainage (van Grieken et al . 2014, Figure 27, p64)

2.2.8 DIN transport down the catchment to Tully Heads

DIN transport down the catchment from any particular grid cell to Tully Heads could result in DIN removal via denitrification processes in groundwater, surface runoff and passage through the surface water drainage network. The N-trading model does not allow for any DIN removal in groundwater or in surface runoff but does allow for DIN removal down the drainage network to Tully Heads.

The mechanisms and extent of DIN removal through the drainage network are not fully characterised, but Armour et al's (2009) SedNet/ANNEX predictions indicate that DIN losses down the Tully drainage network are likely to be relatively modest (Armour et al. 2009, Table 4, p1094). SedNet/ANNEX modelling was not available to the project team, so a simple linear reduction in DIN load was introduced proportional to the length of drainage network between a source grid cell and Tully Heads as determined by GIS modelling (Section 2.2.4 and Figure 2.5). A DIN loss of 25% was set for the longest transport distance through the network (64.9 km), and transport losses from cells with shorter transport distances were scaled down proportionally. Simple on/off sensitivity analysis confirmed that inclusion of these DIN losses from transport down the drainage network had very little impact on the overall results. This is because the variation in transport losses across grid cells is much lower than the variations in gross margins and at-source DIN losses arising from cell-specific changes in the soil class mix.

2.2.9 Fertiliser applications and gross margins in the Tully

Roebeling et al. (2007a) present APSIM-derived simulation results which predict how annuity gross margins from sugarcane production ($/ha) in the Tully-Murray for the 4 soil classes of Table 2.2 as N-application rates are varied across the range 210 kgN/ha to 60 kgN/ha in steps of 30kgN/ha.

Annuity gross margin (A) is the annualised equivalent of the total net present value (NPV) delivered over the full cane cycle (fallow – plant cane – ratoon cane x 4 – fallow):

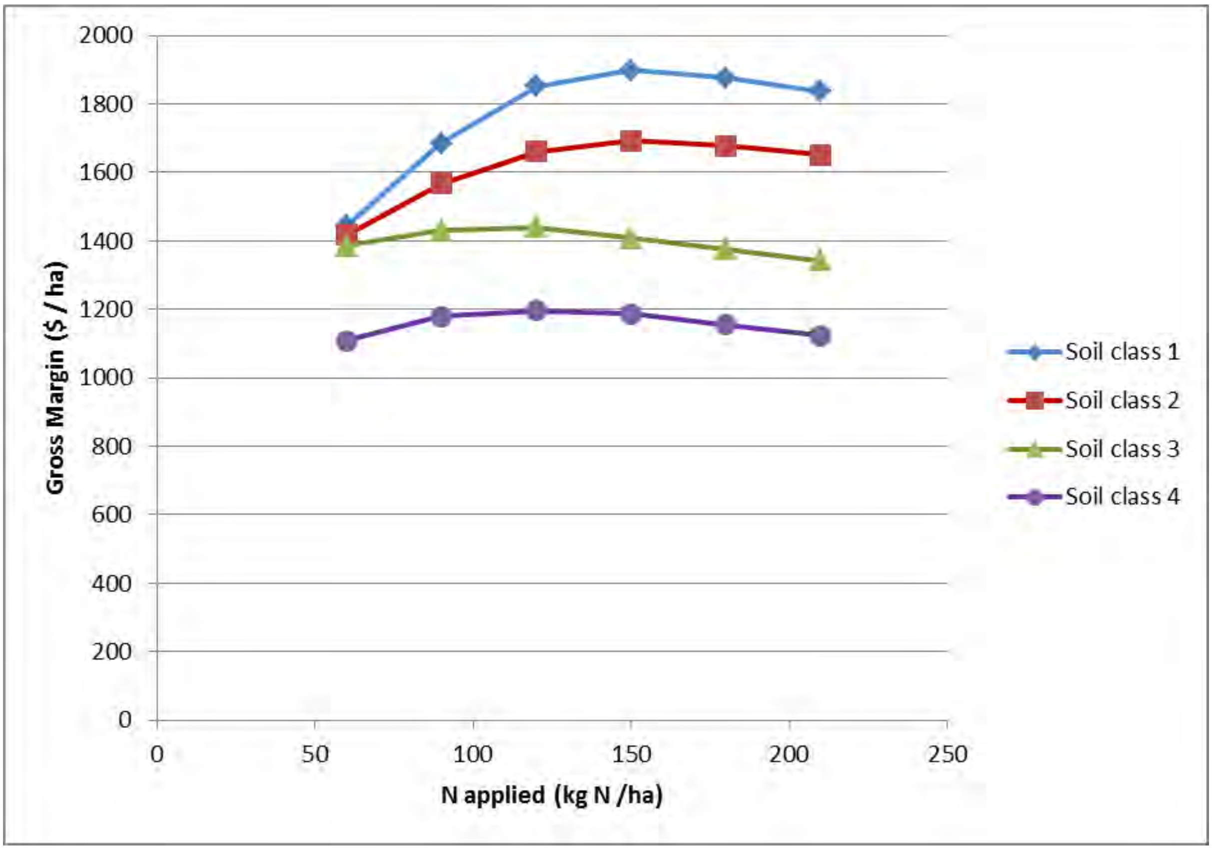
$$A = NPV\left[\frac{r}{1-(1+r)^{-T}}\right]$$

with

$$NPV = \sum_{t=0}^{T}\frac{B_t}{(1+r)^t} - \sum_{t=0}^{T}\frac{C_t}{(1+r)^t}$$

where r is the time discount rate (Roebeling et al. 2007a used 5% per annum), T is the duration of the cane cycle (in years), t denotes individual years, B_t is the $ benefit arising in year t, and C_t is the $ cost incurred in year t. For full details see Roebeling et al. 2007a, Section 2.3 p10-11.

Roebeling et al's annuity gross margins are reported in 2005 $, and were calculated for 2005 market conditions. Roebeling's annuity gross margin results were converted to financial year 2014/15 $ using consumer price index inflation data from the ABS (ABS 2015) for use in this study, but gross margins were not adjusted to reflect changes in the relative prices of farm inputs and outputs. Changes in the International Polarity Scale (IPS) sugar price and local cane prices between 2005 and 2014/15 are considerable (Smith 2015, Figures 18 & 19, p 62-63) and likely to have increased Roebeling's annuity gross margins, even allowing for increasing fertiliser prices over the same time period.



Data source: Roebeling et al. 2007a, figure 4, p16.

Figure 2.7: Modelled annuity gross margins ($/ha) for sugarcane production nitrogen application rates of 60 – 210 kg N/ha for each soil class in the Tully catchment. Annuity gross margins derived from Roebeling et al. 2007, but expressed in FY 2014/15 $.

This concludes the description of the key data used to model N-market trading in the Tully catchment. Data used to infer the likely operation of an N-market in the lower Burdekin cane lands are presented in the following Section. The methodology used to model spatially-specific N-trading in the Tully is described in the next Chapter.

2.3 The Lower Burdekin catchment

The Lower Burdekin drainage basin (1,047,740ha) comprises 0.6% of the State of Queensland. Land use is dominated by grazing on natural or modified pastures. 12% of the land area is used for intensive agriculture (mostly irrigated sugar production), while around 9% is set aside for conservation and minimal use (DEHP 2016). The Lower Burdekin is the largest floodplain system on the Australian east coast. It has a diverse assemblage of coastal ecosystems, including one of the greatest concentrations of wetlands in the Great Barrier Reef catchment (GBRMPA 2013).

Sugarcane production dominates the floodplain ecosystem in terms of area and biophysical processes. The Burdekin River delta and floodplain supports one of Australia's most intensively cultivated and productive agricultural areas with over 80,000 ha of irrigated crops, sugarcane being by far the predominant. The Burdekin cane industry produces some of the highest quality and quantity cane yields in Australia (Mitchell et al. 2008). Nitrate is considered to be the key nutrient pollutant in the Lower Burdekin Area (NQ Dry Tropics 2009).

Although only 300km of the Bruce Highway separate Ayr in the Burdekin Delta from the town of Tully, sugar production in the two catchments differs considerably. A major reason for this is the difference in climate. Tully, in the Wet Tropics, receives an annual average rainfall of around 3500mm (BoM – rain gauge at Tully Sugar Mill), whereas Ayr in the Burdekin Delta in the Dry Topics receives only 1050 mm annually on average, with particularly low rainfall during May – October (BoM – rain gauge at Burdekin District Council in Ayr). Consequently, sugarcane production in Tully is rainfed whereas in the Burdekin production is irrigated. The two major production districts in the Lower Burdekin draw on different irrigation sources. The Burdekin Delta (Delta) region predominantly relies on groundwater, whereas the Burdekin River Irrigation Area (BRIA) uses surface water supplied from the Burdekin Falls Dam. Irrigation applications in the Delta region range between 1000 – 3500 mm per crop (Charlesworth et al. 2002; Stewart et al. 2006, cited in Thorburn et al. 2011a). Irrigation allocations in the BRIA are somewhat lower, Thorburn et al. report 600 – 800 mm per crop per hectare from the irrigation schemes, augmented by runoff capture. Irrigation is typically applied via furrow irrigation. In general, Thorburn et al. (2011a) note that cane yields and N-fertiliser applications in the lower Burdekin are 'the highest in GBR catchments' (Thorburn et al. 2011a, p2).

A wide range of soil types occur in the lower Burdekin cane production area (see for example, Bryant et al. (2012), Figure 21, p44)), with silts common in the Delta and medium clays common in the BRIA. Considerable complexity is evident on soil maps however, with major areas of vertosols, chromosols and sodosols in the BRIA, and dermosols, ferrosols, tenosols and kandosols in the Delta (DERM 2012, cited in Bryant et al. 2012). Differences in soil type were major drivers of variation in the response of gross margin and DIN losses to N-applications in the Tully. Thorburn et al. report that soil types will likely affect cane yield, N-surplus and N-losses via leaching and runoff in the lower Burdekin, although these relationships are further complicated by potential variations in the volume and timing of irrigation applications (Thorburn et al. 2011a).

N-fertiliser applications in the lower Burdekin are considerably higher than in the Tully. Historical recommendations were around 220 kgN/ha (Calcino, 1994), with current industry recommendations around 180 kgN/ha (Schroeder et al. 2010) and paddock-specific recommendations ranging between 130 – 180 kgN/ha (Thorburn et al. 2011b). Cane yields and gross margins are also considerably higher. Van Grieken et al. (2014) report gross margins for medium sized cane farms in the BRIA and Delta which are around 1.8 and 3.2 times higher than those for similarly-sized farms in the Wet Tropics (van Grieken et al. 2014, Figures 7, 8 & 9 p 32 – 33). Smith estimates that current levels of adoption of D, C, B, A-level management practices for DIN and tillage amongst cane farms are 18%, 58%, 18% and 6% for both the BRIA and Delta (Smith 2015, Table 7, p39).

Van Grieken et al. (2014) and Thorburn et al. (2011a) also report a major difference in N-loss pathways; in the Tully and the Burdekin Delta N-loss is predominantly via deep drainage, whereas in the BRIA deep-drainage and surface runoff account for proportions – but total N-loss is dominated by denitrification (van Grieken et al. 2014, Figures 19, 20, 23, 24, 25, 26, 27, 29 & 30 on p 60, 62, 63, 64 & 65).

Kroon et al. (2012) reported a 2009 baseline annual DIN load of 800 tonnes for the Burdekin.

3.0 METHODOLOGY FOR MODELLING A NITROGEN TRADING MARKET

3.1 Regulatory frameworks for nitrogen management

Command-and-control (C&C) approaches to environmental regulations represent a paradigm shift from voluntary-based mechanisms to a mandatory compliance framework. C&C approaches such as fixed discharge licences, mandatory use of technologies or prohibitions on particular actions at specific times and locations have been used to control point and non-point sources of pollution in many countries over recent decades. However, de Vries and Hanley (2016) conclude that incentive-based policy instruments are a more efficient means of achieving environmental goals. Incentive-based policy instruments that have received extensive attention in the literature are direct taxes on pollutant emissions (‘emissions taxes’), taxes on the inputs which give rise to pollutant emissions (‘Pigouvian taxes’) and tradable emissions permits (‘tradable permits’). De Vries and Hanley (2016) provide a succinct review of the main developments in the literature, with a particular focus on the design features of alternative incentive-based policy mechanisms.

An alternative approach to pollution taxes is tradable emissions or discharge permit (TDP). The main idea behind TDP systems is to allocate emissions rights and make them tradeable. This results in a market for the right to pollute and consequently in the emergence of a market price for this right. If the permit market is competitive and all possible gains from trade are realised, this market minimises the cost of achieving a given pollution abatement target (de Vries and Hanley 2016).

Under a TDP system, emitters are allocated a certain number of emission permits, each one of which entitles its owner to emit one unit of emissions. The permits are transferable; they may be bought and sold by anybody that is allowed to participate in the permit market, at whatever price that is agreed upon by the two participants.

The first step in a TDP system is for the regulatory agency to decide on the aggregate quantity of emissions to be allowed and convert the aggregate emissions into a fixed number of permits. Permits are then distributed among emitters. Assuming that the total number of permits is less than the current total emissions, some or all emitters will receive fewer permits that their current emissions. As noted by Field and Field (2009), the emitting firm has three choices:

1. Reduce emissions to the level covered by the initial allocation of permits;
2. Buy additional permits and emit at levels higher than the initial allocation; or
3. Reduce emissions below the initial allocation and sell any excess permits.

The theoretical cost-effectiveness of the emissions trading approach to pollution control was formally developed by Baumol and Oates 1971 and Montgomery 1972. Montgomery (1972) provides a rigorous proof that a TDP system could deliver cost-effective pollution control, and that the least-cost outcome could be achieved for any initial allocation of permits. High transaction costs, however, may lead to reduced trading and increased abatement costs, thereby reducing the cost-effectiveness of a TDP scheme. Numerous authors have addressed the importance of transaction costs in TDP markets (e.g. Hahn and Hester 1989, Tripp and Dudek 1989, Hung and Shaw 2005, Prabodanie et al. 2010, Pinto et al. 2013 and Prabodanie et al. 2014).

Prabodanie et al. (2010) propose a pollution offset system for trading water pollution permits between non-point sources. Under Prabodanie et al.'s system, trading outcomes are optimised via a common-pool online market which is centrally managed. This optimised, centralised market system reduces transactions costs compared with the bilateral trading which is common in buyer-to-seller offset-based systems. Prabodanie et al. (2010, 2014) show that an online market system can reduce transaction costs and maximise the gains from trade in the management of water pollution from non-point sources. Pinto et al. (2013) show how the same system could also be applied to manage sediment discharge from a landscape containing a number of different land classes (native forest, urban, pine plantations and pasture). An online trading system based around centralised marketplace is generally referred to in the literature as a 'smart market' (McCabe et al. 1991). Smart markets are currently applied in the electricity (Hogan et al. 1996) and gas industries (McCabe et al. 1991), and have been proposed for managing surface water quality (Murphy et al. 2009), ground water quality (Raffensperger et al. 2009), impervious cover (Raffensperger and Cochrane 2010), nitrate pollution (Prabodanie and Raffensperger 2007, Prabodanie et al. 2010) and, more recently, air pollution under regulatory tiering (Willet et al. 2015).

This feasibility study develops a spatially-specific application of Prabodanie et al's (2010) pollution trading concepts between non-point DIN emitters in a sugarcane catchment draining into the Great Barrier Reef. Combining physical, economic and climate data within a linear programming framework enables spatially-specific simulation of a centrally mediated, multilateral N-trading system in the Tully catchment. The preceding chapter described the data which were assembled to enable N-market simulation. This chapter describes the rationale and methodology behind the optimised smart market. The next chapter will present the results of several spatially-specific N-trading simulations.

3.2 N-trading via an online smart market

This section focuses on the design and operation of a smart market for N-trading between non-point sources, using the principles described by Prabodanie et al. (2010, 2014) and Pinto et al. (2013).

Spatially-specific N-permits are the commodities which would be traded in an N-trading market for the Tully cane lands. One N-permit gives the permit holder the right to apply one unit of nitrogen per hectare (1 kgN/ha) to a sugarcane paddock in specific location in the catchment. A landholder would have to hold the relevant number of N-permits to cover their intended N-applications at that location (e.g. 150 permits would be required if the intended N-application rate was 150 kgN/ha). A given N-application rate (e.g. 150 kgN/ha) on a particular paddock would produce a corresponding DIN loss, depending on the soil type (e.g. applying 150 kgN/ha would produce an annual DIN loss of 28.8 kg DIN on soil class 1, 34.4 kg DIN on solid class 2, 41.9 kg DIN on soil class 3 or 48.2 kg DIN on soil class 4 [refer back to Figure 2.6]).

In economic terminology, these N-permits are 'spatially-specific loading permits' because they confer the right to 'load' a specified amount of nitrogen onto a particular paddock. The N-permits come bundled with the appropriate quantity of DIN load rights at Tully Heads. Tully Heads is the 'load receptor' at which an overall cap on the DIN load will be enforced.

On market startup, each landholder will receive – free of charge - an initial, equal per hectare allocation of N-permits (e.g. 120 kgN/ha). If a landholder chooses not to trade in the N-market, then N-applications on their paddock will be limited to their initial permit allocation (120 kgN/ha in this example). The initial allocation would be calculated carefully to ensure that if all landowners used their full initial allocations then the estimated overall DIN load at Tully Heads would match the intended overall load cap.

With an N-trading market, landholders can enter bids to buy extra N-permits from the smart market, to add to their initial allocation. Alternatively, they could enter offers to sell some unused N-permits from their initial allocation to the smart market. Landowners' (bidding + buying or offering + selling) exchanges with the smart market are illustrated in Figure 3.1.

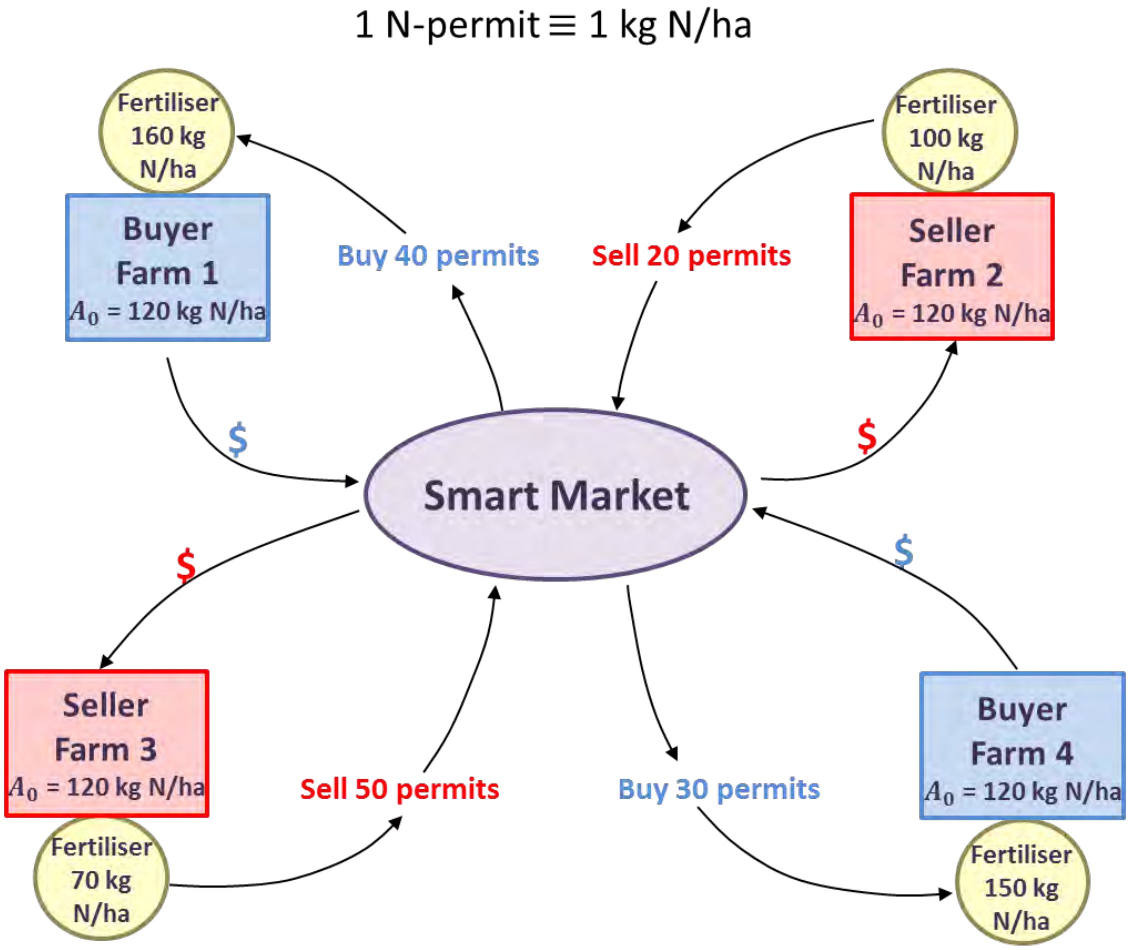


Figure 3.1: Buying and selling N-permits on the centralised smart market, with a uniform initial allocation (A_0) of 120 kg N/ha.

All buying and selling transactions are managed through the smart market; **<u>not</u>** negotiated one-on-one between permit buyers and permit sellers. This centralised smart market provides two key advantages. Firstly, it automatically manages permit sales and permit purchases so that the outcome after trading will not breach the overall DIN load cap set for Tully Heads.

This is possible because the N-permits are spatially-specific, i.e. they relate to a particular paddock (or ‘grid cell’ in the simulation model). The paddock’s location in the catchment is known, so its soil type is known, as is the transport distance from the paddock through the drainage network to Tully Heads. With this information, the smart market manager will use the relationships between N-applications and soil type to predict DIN loss from the paddock (refer back to Figure 2.6, and will then allow for DIN removal through the drainage network to calculate the effect of those N-applications on the total DIN load at Tully Heads. These calculations will be applied to prospective permit purchases (which will increase DIN load at Tully Heads) and prospective permit sales (which will decrease DIN load at Tully Heads). The smart market manager can choose which bids (to buy additional N-permits) and offers (to sell unused N-permits) they accept. This allows the market manager to accept a set of bids and offers which will exactly balance out in terms of their impact on the total DIN load at Tully Heads, thus ensuring that the total DIN load cap at Tully Heads still holds after trading.

The second key advantage of the smart market again arises because the market manager can choose which bids (to buy additional N-permits) and offers (to sell unused N-permits) to accept. The market manager will accept the combination of bids and offers which maximises the overall gains that landholders make from their N-permit trades. This works as follows; if some landowners know that they can significantly increase their gross margins by applying more nitrogen, they will lodge high bids with the market manager to **purchase** extra N-permits. Conversely, if other landowners know that additional nitrogen applications will only increase their gross margins by a modest amount, they will lodge relatively modest offers with the market manager to **sell** some of their N-permits on the N-market – hoping to make more profit by selling their N-permits on the market than they would by applying that nitrogen to the cane paddock.

The ‘smart’ action of the smart market accepts the modestly-priced offers to supply N-permits and then sells those permits to the buyers who entered high bids for N-permit purchases. This matches overall N-permit supply with N-permit demand (Figure 3.1), whilst still ensuring that permit trading does not infringe the overall load cap at Tully Heads. In this way N-permit purchasers are able to buy additional N-permits at the lowest price consistent with securing an adequate supply of permits from N-permit sellers. The N-permit sellers also gain from trading because they will receive the highest price consistent with matching their supply of N-permits to permit purchasers’ demand for N-permits.

3.3 Linear program for optimising N-permit purchases and sales

The market manager uses a linear program to optimise market clearing (i.e. match demand for and supply of N-permits) by accepting bids (for N-permit purchases) and offers (for N-permit sales) such that the overall gains from market trading are maximised, whilst also ensuring that the overall DIN load cap at Tully Heads is not breached.

To allow the market manager to maximise the gains from trading, landowners will have to submit a set of bids and offers to the market manager for purchases and/or sales of N-permits across a spectrum of N-prices. This assumes that the landowner knows the gross margin which they would expect to make by applying particular N-rates to their paddock, and that they also know their initial N-allocation.

The following example illustrates the thinking which a landowner might follow to calculate how much they would be willing to pay for additional N-permits to add to their initial allocation, and how high a price they would require in order to sell some N-permits from their initial allocation.

Imagine that landowners receive an initial allocation of 120 kg N/ha. On soil classes 1 & 2, gross margin could be increased by increasing N-applications to 150 kg N/ha (Figure 2.7). On soil class 1, increasing N-applications from 120 to 150 kg N/ha would increase gross margin by around \$47 per ha (Figure 2.7; Soil class 1). However, an extra 30 N-permits would be required to cover the additional 30 kg N/ha of nitrogen application. Consequently, in this situation a landowner on Soil class 1 would be willing to pay no more than \$1.57 per N-permit to cover this change[4].

From the same 120 kg N/ha initial allocation, a landowner on Soil class 4 would see their gross margin reduce by around \$19/ha if they sold 30 N-permits from their initial allocation and reduced their N-applications to 90 kgN/ha. Consequently, the Soil class 4 landowner would be willing to sell these permits provided that they received a price of least \$0.63 per N-permit to cover this change[5].

In this example the Soil class 1 landowner would place a bid to purchase 30 N-permits per ha, provided that the N-permit price was not more than \$1.57 per permit, and the Soil class 2 landowner would place an offer to sell 30 N-permits, provided that the N-permit price was at least \$0.63 per permit[6].

Landowners would repeat these calculations to determine their desired purchase quantities and maximum acceptable purchase prices for switching to higher N-applications (N150, N170, N200), or to determine their available offer quantities and minimum acceptable sale prices for switching to lower N-applications (N090, N060), from an initial allocation of 120 kgN/ha. The list of purchase prices and purchase quantities, together with sale prices and sale quantities would be submitted to the market manager before market trading started. In economic terminology, this list is called a ‘bid and offer schedule’[7].

The optimisation model which is used to maximise the gains from trade in the N-market, whilst also ensuring that the DIN load cap at Tully Heads is not breached, is developed from the linear programming implementations described by Prabodanie et al. (2010, 2014). A mathematical description of this linear program is provided in Appendix 1. The linear program was coded for the spatially-specific N-market in the Tully using the lp_solve (Mixed Integer

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[4] $\frac{\text{additional gross margin}}{\text{extra permits purchased}} = \frac{47}{30} = 1.57$ \$ per N-permit

[5] $\frac{\text{reduced gross margin}}{\text{permits sold}} = \frac{19}{30} = 0.63$ \$ per N-permit

[6] In this example, there is a clear possibility for trading. However, before accepting the trades, the market manager would consider the potential impact on the DIN load at Tully Heads and also check whether other landowners were prepared to pay a higher price for permits or were prepared to sell permits at a lower price.

[7] The calculation of the bid and offer schedule described here ignores the effects of risk aversion.

Linear Programming) solver, accessed via the lpSolveAPI package in R (R Core Team 2013). The results of N-market simulation are presented in the following Chapter.

3.4 Extending the N-trading market to include wetland credits

Sections 3.5-3.10 of this chapter described how less-productive sugarcane land in the Tully could potentially be converted to constructed (treatment) wetlands. Constructed (treatment) wetlands could remove some of the DIN released from up-stream cane land, and so generate N-credits which could be sold on the N-trading market. The smart market can be extended to include N-credits from constructed wetlands alongside purchases and sales of N-permits. Figure 3.2 shows how a smart market would operate with wetland credits.

As the DIN load cap at Tully Heads is reduced, the market-clearing price for N-permits rises. This is because of increased demand for the reduced total allowable DIN load. Higher N-prices under tight DIN load caps might be sufficient to persuade landowners to convert their less-productive cane paddocks to constructed (treatment) wetlands. Figure 3.2 depicts a situation where the DIN limit at Tully Heads has been tightened significantly such that the initial allocation of N-permits is 60 kgN/ha. In this situation, Farmer 3, facing a high permit price, would find it more profitable to convert their cane paddock to a wetland. Their potential treatment wetland is estimated to remove 140 kgN/ha of DIN, and together with an initial allocation of 60 kgN/ha, this would enable Farmer 3 to sell a total of 200 credits to the common pool smart market. Farmer 2 on the other hand, finds it more profitable to purchase an additional 90 permits from the market so they can apply 150 kgN/ha of fertiliser on their paddock. Farm 4's land is not suitable for treatment wetland conversion, and with the 60 kgN/ha initial allowance, Farmer 4 finds it more profitable to exit sugarcane altogether. Exiting from sugarcane production would allow Farmer 4 to sell all of their initial allocation of permits. In the Figure 3.2 example, a total of 260 permits plus credits are bought and sold, and the market clears. Results from simulating N-trading with wetland conversion are presented in the next chapter.

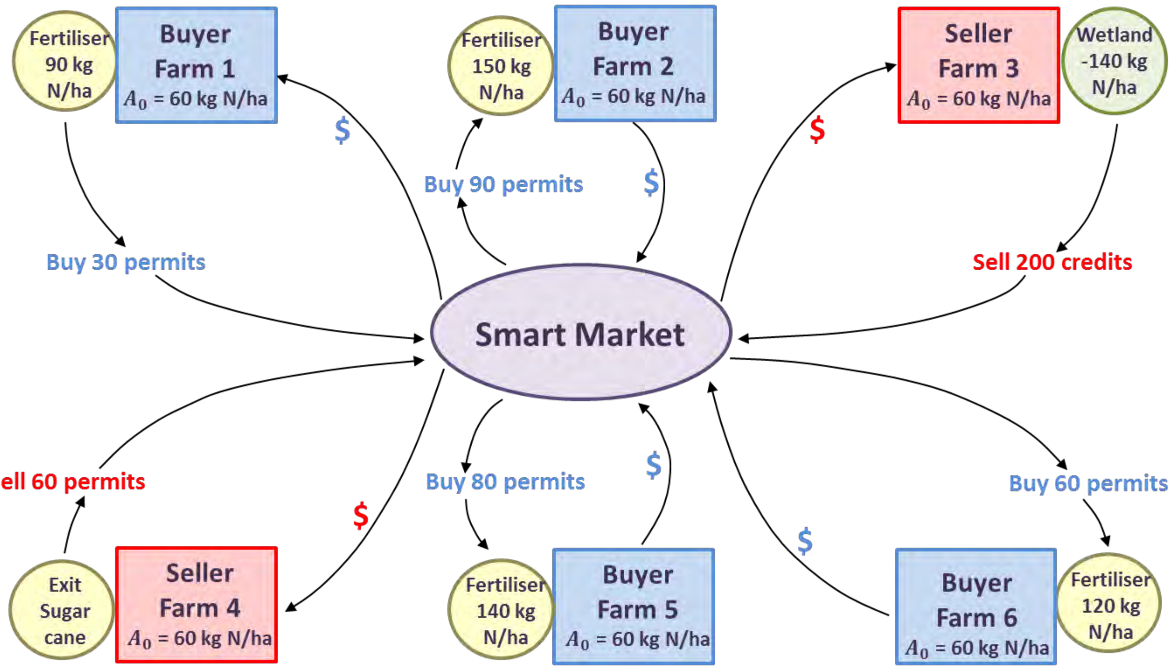

Figure 3.2: Buying and selling N-permits and N-credits from constructed (treatment) wetlands on the centralised smart market, with a uniform initial allocation ($\boldsymbol{A_0}$) of 60 kg N/ha.

3.5 Wetlands as a potential source of DIN credits

The use of constructed wetlands to treat water pollutants, such as nitrogen and phosphorus, from agricultural runoff has been trialled as a mechanism for abating pollution from diffuse sources in a range of studies. A feasibility study of a nutrient trading program for the Big Bureau Creek watershed in the US has considered the potential inclusion of wetland treatment systems on farm land (The Wetlands Initiative 2014). Pollutants removed by wetlands can be regarded as a source of credits within a nutrient trading framework (Raffini and Robertson 2005). Properly designed and sited wetlands to remove nutrients and other pollutants from agricultural runoff have the potential to provide a cost-effective pollution reduction option (Kadlec and Knight 1996, quoted in Department of Employment, Economic Development and Innovation 2011, p52).

Vegetated systems, such wetlands, are a natural feature of floodplain of GBR catchments where intensive agricultural activities are primarily undertaken. This is the situation in the Tully catchment. Recognising the potential ability of wetlands to reduce DIN loss from sugarcane production[8], this study extends the smart nutrient trading framework to make a preliminary investigation of the feasibility of including constructed (treatment) wetlands within market trading as a mechanism for reducing DIN loss and generating DIN credits – which would have market value.

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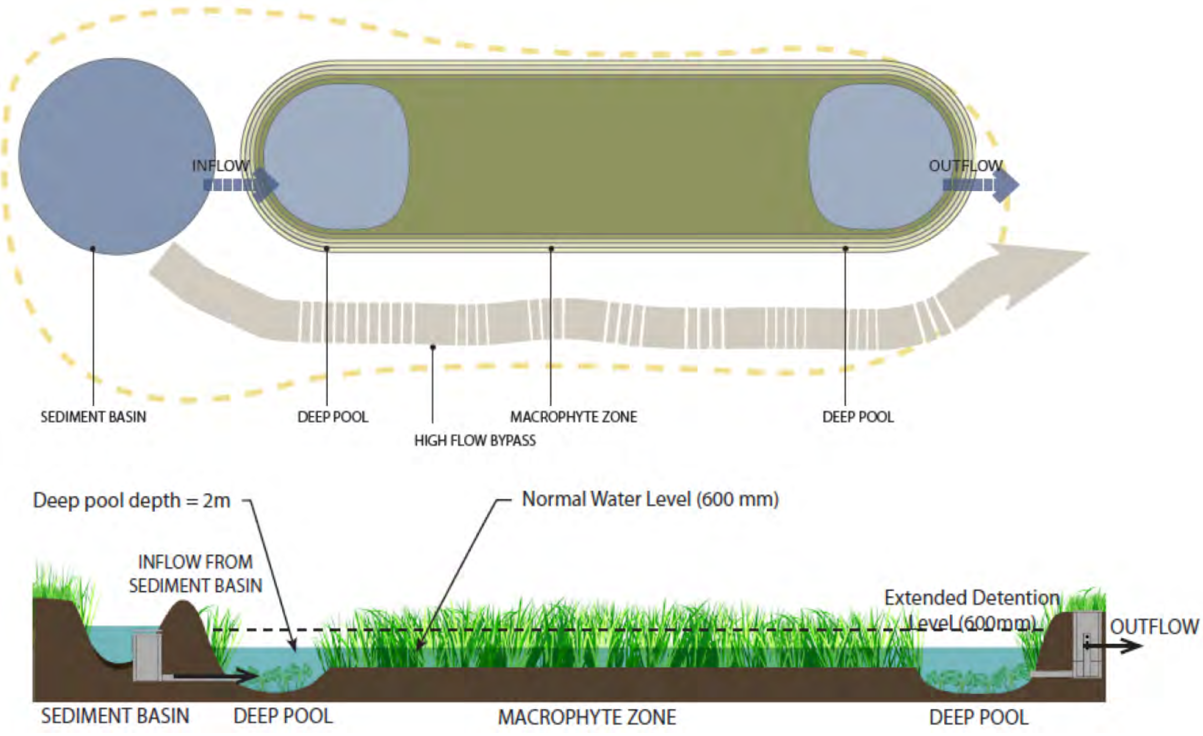
[8] Floodplain wetlands are well known to deliver a range of other benefits in terms of flood mitigation, sediment removal and biodiversity. This study focuses only on the value which wetlands deliver via DIN reduction. Subsequent studies could investigate wetlands' role in linked markets for reducing other Reef stressors in addition to DIN.

Candidate wetland locations within the 4020 grid cells in the Tully cane lands were identified using the Queensland Government's guidelines on wetland management, referred to as 'the Handbook' in this report (Department of Employment, Economic Development and Innovation 2011), combined with GIS digital elevation model (DEM)-derived data on upstream drainage areas and BoM-derived data on average rainfall. These candidate wetlands are 'hypothetical' in the sense that this study only includes those existing sugarcane lands that are deemed suitable for conversion to constructed (treatment) wetland, based on the criteria outlined in the Handbook.

The potential wetland treatment systems considered in this study are surface-flow or free-water wetlands which provide an appropriate water management and DIN treatment option for sugarcane (Department of Employment, Economic Development and Innovation 2011). In these potential wetlands, influent water flows predominantly across the soil surface into a pond where it is retained for several days to allow sufficient time for the biological, chemical and physical processes including denitrification which converts nitrate to nitrogen gas. The treated water is then released slowly through the outlets. The (hypothetical) wetlands considered in this study are assumed to comply with the design recommendations outlined in the Queensland Wetlands Program fact sheets (Fact sheets 2014). These wetlands consist of four functional elements located within the farm run-off treatment train (Figure 3.3):

- sediment basin
- deep pools
- macrophyte zone
- high flow bypass channel

The sediment basin traps sediments and controls water flow into the wetland. The deep pools and macrophyte zone together form the area where water is retained and treated. Finally, the high flow bypass channel ensures that the wetland only receives flows up to its designed capacity from a given rainfall event. This high flow bypass prevents the macrophyte zone from being washed out by floodwater.



Source: Queensland Wetland Program – constructed (treatment) wetland factsheet.

Figure 3.3: Wetland plan view and cross section

3.6 Identification of suitable sites for wetlands

As an example of how constructed (treatment) wetlands could generate DIN credits within a nutrient trading program, potential locations for constructed wetlands with the following design specifications were identified in the Tully catchment:

- 5 days retention period for the runoff from a 30mm rain event[9]
- average depth of macrophyte zone 1.8m

Wetland locations within the Tully catchment which satisfied these design specifications were identified by following a two-step process which used a set of standard calculations, many of which are taken from the Handbook. The two steps comprised:

- a preliminary screening of the potential wetland area within a sugarcane 250m x 250m grid cell as a proportion of the cell's upstream drainage area

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[9] Five days residence time is considered to be the minimum required for efficient denitrification processes in treatment wetlands (Kadlec and Knight 1996, quoted in DeBose et al. 2014, p37). BoM daily rainfall data at station number 32042 (Tully Sugar Mill) over the period of 1926 to 2016 indicates the following key information: (i) there are on average 167 rain days/year (i.e. days on which rainfall is non-zero); (ii) the distribution of the rainy days shows that a 30mm rainfall event lies between 75th and 90th percentile (27.4mm at 75th percentile, 60.2mm at 90th percentile, 95.3mm at 95 percentile and 196mm at 99th percentile); (iii) when data on all days are included, i.e. including days with no rain, a 30mm event stands at just under the 90th percentile of the rainfall distribution.

- for grid cells which passed the preliminary screening, detailed calculation of the wetland size required to provide 5 days' retention of runoff from a 30mm rainfall event in the cell's upstream drainage area.

3.7 Preliminary wetland sizing

For the purposes of this preliminary study, the analysis focussed only on denitrification processes as a mechanism within the wetlands to remove nitrogen. It is acknowledged that other processes, such as plant assimilation of nitrogen, may also play a role. As recommended in the Queensland Wetland Management Handbook, preliminary screening of potential wetland locations identified sugarcane grid cells for which the area of cane which could be converted into constructed wetland comprised between 2 and 5% of the cell's upstream drainage area. The rule-of-thumb operating here is that sugarcane areas which comprised less than 2% of the upstream drainage area would not be able to provide adequate retention time for denitrification, whereas cane areas which comprised more than 5% of the upstream drainage area would be unlikely to receive sufficient nutrient loading to make wetland construction worthwhile. In this case, the existing sugarcane area within a 6.25 ha grid cell is taken to be the maximum potential area that could be taken out of sugarcane production and converted to wetland.

Upstream drainage areas for each of the 4020 sugarcane grid cells were calculated using runoff modelling from a 25m x 25m DEM. Each of the 4020 250m x 250m sugarcane grid cells contains 100 25m x 25m DEM cells. The upstream drainage areas of the 100 DEM cells within any particular 250m x 250m sugarcane grid cell will typically differ from one another. These differences can be considerable, for example if the main Tully River flows through part of the 250m x 250m sugarcane grid cell. For this reason, the upstream drainage area of a 250m x 250m sugarcane grid cell was taken to be the mean upstream drainage area of the 100 DEM cells within that sugarcane grid cell.

Preliminary screening based on sugarcane area relative to upstream drainage area identified those sugarcane grid cells for which sugarcane area (i.e. potential wetland area) comprised 2 – 5% of the cell's upstream drainage area. Applying this preliminary screening, 100 sugarcane grid cells were identified as potentially suitable locations for constructed (treatment) wetlands in the Tully catchment (Figure 3.4).

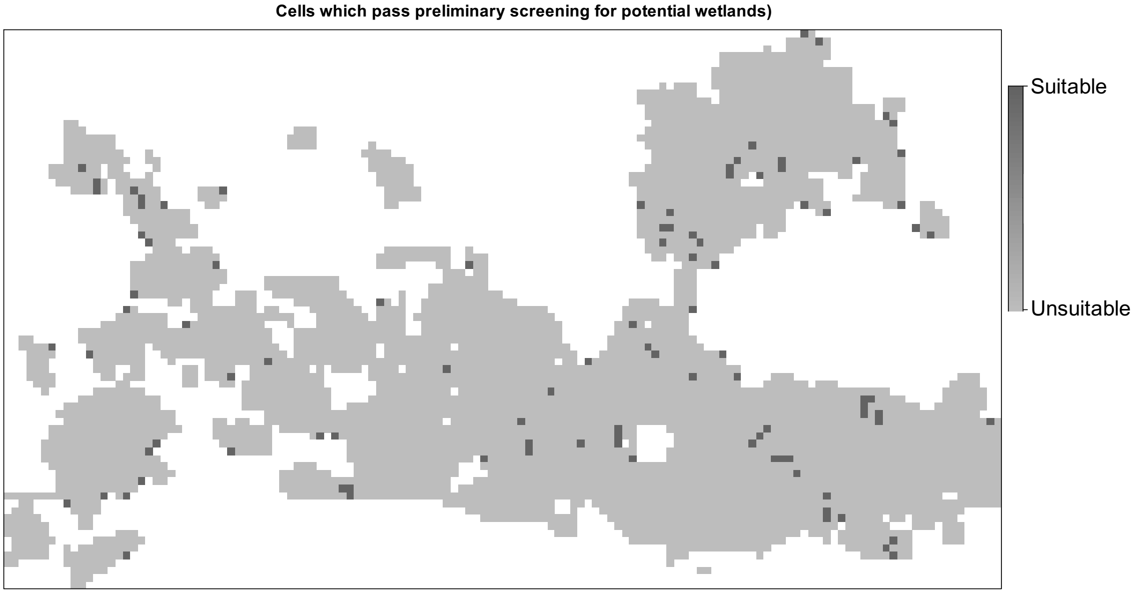

Figure 3.4: 100 sugarcane grid cells which passed preliminary screening for wetland suitability based on "2-5%" rule

3.8 Wetland sizing for a 30mm rainfall event

More detailed calculations of wetland sizing requirements were undertaken for the 100 potentially suitable locations identified by preliminary screening.

To provide wetland designs appropriate for indicating the potential role of wetlands as a source of DIN credits in a DIN trading program, wetlands were designed to provide 5 days' treatment of the runoff from a 30mm rainfall event. This aims to treat DIN lost during 'first flush' events in the wet season (Department of Employment, Economic Development and Innovation 2011). The volume of runoff generated by a rain event of a particular size depends on catchment variables such as soil type, existing moisture present in the soil and evaporation. The following formula, from the Handbook was used to calculate cell-specific net runoff:

$$\text{Net runoff (litres)} = \text{upstream drainage area } (m^2) \times \text{rainfall event size (mm)} \times C_v$$

where: C_v is a soil-type-specific volumetric runoff coefficient

The volumetric runoff coefficient figures from the Handbook were matched to the four soil types used in this study to produce net runoff values for rain events of different sizes (Table 3.1).

Table 3.1: Typical single storm event volumetric runoff coefficients (C_v) for the different soil types

Rainfall event (mm)	Soil Hydrologic Group			
	Group A Sand	Group B Sandy Loam	Group C Loamy clay	Group D Clay
	Soil S2	Soil S1	Soil S3	Soil S4
10	0.02	0.10	0.09	0.20
20	0.02	0.14	0.27	0.43
30	0.08	0.24	0.42	0.56
40	0.16	0.34	0.52	0.63
50	0.22	0.42	0.58	0.69
60	0.28	0.48	0.63	0.74
70	0.33	0.53	0.67	0.77
80	0.36	0.57	0.70	0.79
90	0.41	0.60	0.73	0.81
100	0.45	0.63	0.75	0.83

Reproduced from: Wetland Management Handbook: Farm Management Systems (FMS) guidelines for managing wetlands in intensive agriculture (Department of Employment, Economic Development and Innovation 2011).

Knowing cell-specific soil type mixes, cell-specific net runoff can be calculated for a 30mm rain event. The wetland volume required to provide 5 days' retention for this runoff can then be calculated. Assuming an average depth of 1.8m for the macrophyte zone (Department of Employment, Economic Development and Innovation 2011), allows a minimum wetland surface area to be calculated to provide at least five days' retention time, as recommended in the literature (Kadlec and Knight 1996 quoted in Debose et al. 2014, p37). If we assume that the wetland will be constructed on land currently used to produce cane, this calculation provides a minimum required sugarcane area in the grid cell in order to provide 5 days' retention of the runoff from a 30mm rain event in the cell's upstream drainage area.

Using this process, of the 100 grid cells shown in Figure 3.4, 62 grid cells were identified as exceeding the minimum required cane area for construction of a wetland which would provide the desired 5 days' retention time for DIN removal (Figure 3.5). Across these 62 cells, average constructed wetland size was 3.11 ha, (minimum 0.18 ha, maximum 6.25 ha – i.e. the full grid cell area).

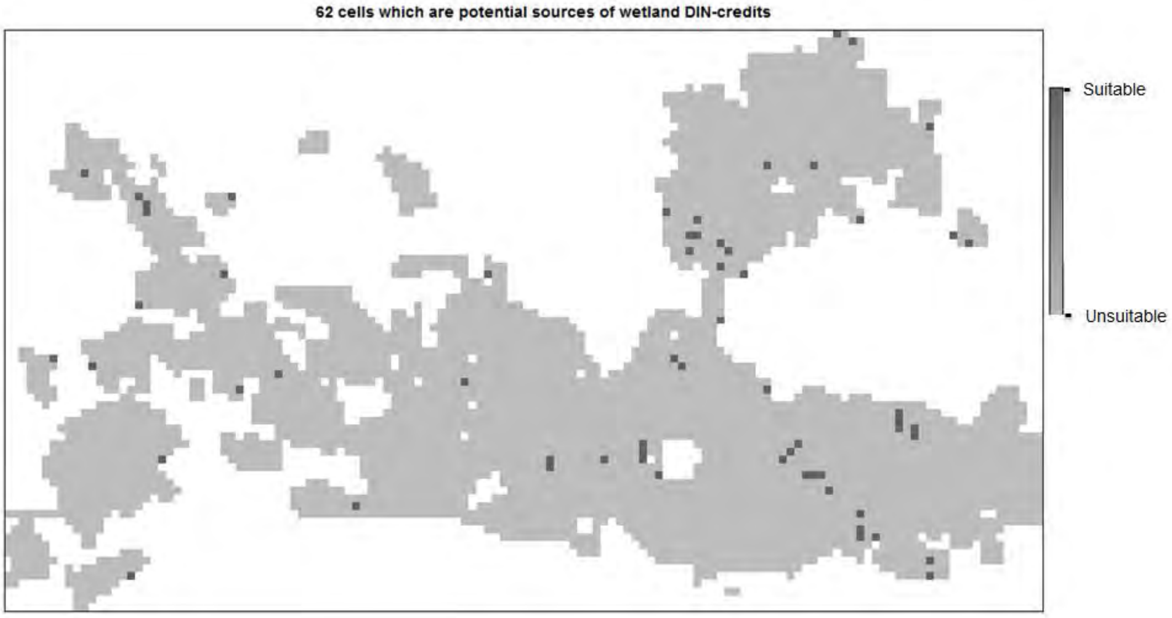

Figure 3.5: 62 grid cells which are candidates for wetland conversion and inclusion as credit sources in the DIN trading program

Subsequent calculations estimate the number of DIN credits which would be produced from each of these 62 grid cells, under particular conditions.

3.9 Estimating DIN removal

The amount of nitrate removed from a wetland depends on the wetland's hydraulic loading rate. The focus was on nitrate as this is the dominant runoff from sugarcane fields (Bainbridge et al. 2009) and analysis of 7 years of historical water quality data collected by Queensland Department of Science, Information Technology and Innovation (DSITI) showed that 90±11% of the DIN in the lower Tully River was nitrate (data collected 17km from mouth at Bruce Highway bridge, Andrew Moss, Queensland DSITI, pers. com.). Annual hydraulic loading rate (AHL) is given by the volume of water discharged annually from the wetland's upstream drainage area divided by the area of the wetland itself (Crumpton et al. 2006, Tomer et al. 2013, The Wetlands Initiative 2014).

To estimate the volume of water discharged annually from the upstream drainage area of each grid cell, a representative runoff per m^2 of upstream drainage area is calculated because actual cell-specific data on runoff are not available. This calculation is challenging because of the highly variable rainfall patterns in the Tully catchment, evident in historical rainfall data from the BoM rain gauge at Tully Sugar Mill. In the Tully catchment, the majority of annual rainfall comes in intense rain events during the wet season (December - April). Furthermore, the proportion of rainfall that runs off from sugarcane land varies depending on the:

(i) size of rainfall event, and
(ii) soil type

Historical data on daily rainfall between March 1926 and February 2016 from the BoM rain gauge at Tully Sugar Mill (Bureau of Meteorology, www.bom.gov.au) were used to calculate the average number of days for which a rainfall event of particular size would be expected per year e.g. from historical data, a 30mm rainfall event is expected to occur on average during 12.56 days per year; whereas a 70mm rainfall event is expected to occur on average during 2.89 days per year (Figure 3.6).

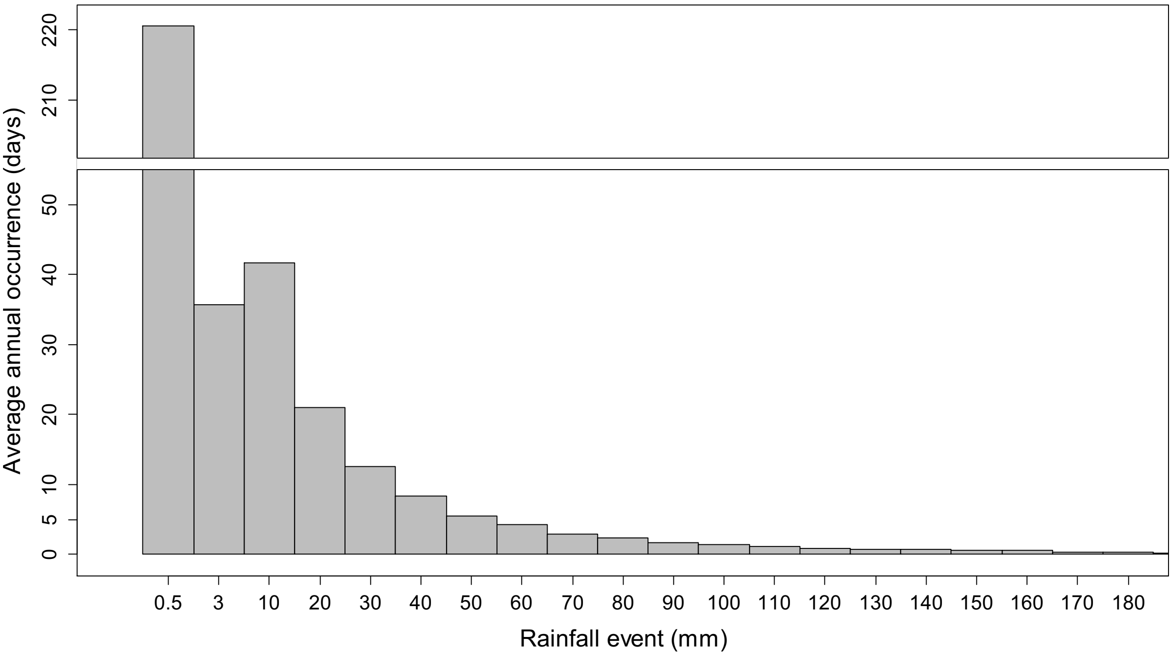

Figure 3.6: Average annual occurrence of rainfall events of increasing size, from daily rainfall data from the rain gauge at Tully Sugar Mill Mar 1926 – Feb 2016 (BoM data)

Knowing the expected occurrences of particular sizes of rainfall event per year, the amount of rainfall which those events contribute to total annual rainfall in the Tully catchment can be calculated. For example, (refer to Figure 3.6) on average, 30mm events contribute (12.56 x 30) = 377mm of rainfall annually; on average, 70mm events contribute (2.89 x 70) = 202mm annually. Once the average annual contribution of rain events of particular sizes is known, the soil-specific volumetric runoff coefficients ($C_{v_{soil}}$) from Table 3.1 can be used to convert average annual rainfall contributions from particular sizes of rain events into runoff contributions on a known soil type, using equation (1):

$$TAR_{soil} = \sum_{i=1}^{H} \left(EventSize_i * ExpEventSize_i * C_{v_{soil}} \right) \qquad (1)$$

where:

$EventSize_i$ is a rainfall event of size i (0.5mm, 3mm, 10mm, 20mm, 30mm ….. 610mm)
$ExpEventSize_i$ is the expected annual occurrence of an event of size i (Fig. 4)
[e.g. a 30mm rainfall event is expected to occur 12.56 days per year]
$C_{v_{soil}}$ is the volumetric runoff coefficient for a particular soil type (from Table 1)
H indicates the total number of sizes of event in the data set
TAR_{soil} is the total annual runoff from a particular soil type

One further complication is taken into account. As explained previously, the minimum surface area required for treatment wetlands was calculated based on five days' retention time for the runoff generated from a 30mm rain event in the wetland's upstream drainage area. If runoff from a large rain event exceeds the storage capacity of the candidate wetland, excess runoff will be discharged, untreated, via the overflow bypass channel. This overflow runoff will not contribute to the wetland's annual hydraulic loading. For this reason, the $(EventSize_i * C_{v_{soil}})$ products in equation (1) for large rain events are capped at a maximum of five days' runoff from a 30mm event on the relevant soil type. The assumption here is that runoff in excess of this volume will be discharged via the overflow bypass.

These calculations produce total annual runoff predictions for each soil type in the Tully catchment. The final step is to produce an average total annual runoff per square metre of the Tully cane lands, weighted by the proportions of each soil type:

$$TAR_{avg} = \sum_{i=1}^{4} TAR_{soil} * (Proportion\ of\ soils\ in\ Tully\ caneland) \qquad (2)$$

TAR_{avg} approximates the volume of water discharged per square metre of a wetland's upstream drainage area. Multiplying by the upstream drainage area produces the annual discharge volume which is required to calculate the wetland's annual hydraulic loading (AHL).

Once the AHL is known, the amount of nitrate removed by each potential wetland can be calculated using the relationship developed by Crumpton et al. 2006, subsequently used in other studies (Tomer et al. 2013, The Wetlands Initiative 2014):

$$\%NR = 103 \times AHL^{-0.33} \qquad (3)$$

The average composition of nitrogen losses from sugarcane cultivation in the Tully-Murray is reported in Figure 3 of Bainbridge et al (2009). Bainbridge et al.'s results indicate that oxidised nitrogen (NO_x-N) comprises the vast majority of DIN losses from cane in the catchment. Consequently, we use the percentage nitrate removal predicted by Equation (3) as a conservative estimate of the percentage of DIN removed by a constructed (treatment) wetland in a candidate grid cell.

The DIN load delivered to a candidate wetland is calculated by multiplying its upstream drainage area by the average DIN load export (kg DIN/ha) for cane lands in the Tully. Average DIN load export will vary depending on the predominant N application rate (e.g. 210, 180, 150, 120, 90 or 60 kg N/ha), and by soil type. Figure 6 in Roebeling et al 2007a [reproduced earlier as Figure 2.6] shows soil-type-specific relationships between N applications (kg N/ha) and DIN losses (kg DIN/ha).

Knowing the soil type mix in each of the 4020 grid cells, the relationships from Roebeling et al. (2007a) enable a totalling, and then the average DIN loss per hectare to be calculated for the Tully cane lands under assumed N application rates of 210, 180, 150, 120, 90 or 60 kg N/ha. These average DIN losses (kg DIN/ha) are reported in Table 3.2. Average DIN losses from Table 3.2 are multiplied by upstream drainage area to calculate the DIN load into a candidate wetland (at a particular N application rate).

Table 3.2: Average DIN losses (kg DIN/ha) for different N application rates in the Tully-Murray cane lands; drawing on the N applications to DIN loss relationships per soil type shown of Roebeling et al. (2007a) [Figure 2.6]

Management practice (N applied: kg N/ha)	Average DIN loss across all cane land (kg/ha)
N210	64.2
N180	50.4
N150	36.0
N120	23.0
N090	14.7
N060	10.4

Knowing the percentage DIN removal rate (from equation 3) and the incoming annual DIN load (under an assumed N application rate) for a candidate wetland i, the annual DIN removal by wetland i can be calculated simply by multiplication. The number of DIN credits which a particular wetland would be able to generate in the smart trading market would equal the kg DIN which the wetland removed annually. DIN removal (in kg), and thus the number of credits generated, depends on the incoming DIN load. Incoming DIN load varies with the predominant N application rate. As an example, estimated DIN removal (kg DIN) under a predominant N application rate of 180kg N/ha for the 62 candidate wetland grid cells is shown in Figure 3.7.

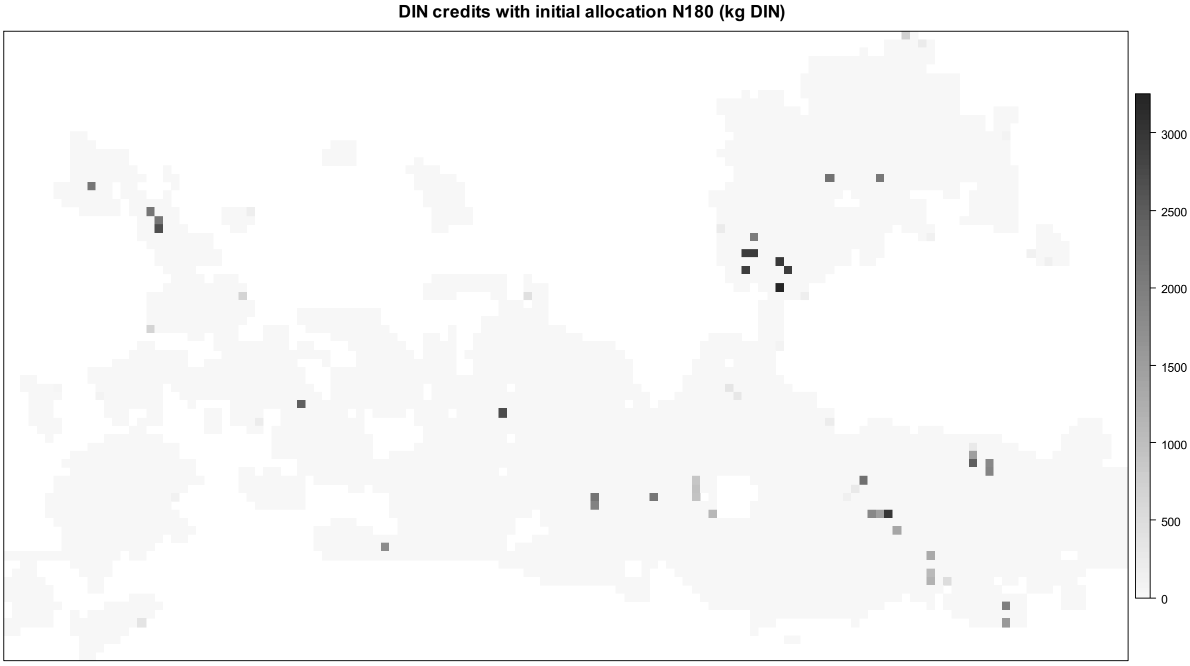

Figure 3.7: Predicted DIN removal from candidate wetland cells (kg DIN) when the predominant N-application rate is 180 kg N/ha.

3.10 Economic analysis of wetland construction and maintenance

Several studies have attempted to estimate the construction costs of wetlands both in agricultural and urban catchments (Byström 1998, The Wetlands Initiative 2014, Roebeling et al. 2011, Roebeling et al. 2009, 2011, 2015). Roebeling et al. (2011) compiled wetland construction costs and wetland operation and maintenance cost data from published papers and reports and used these data to estimate wetland cost as a function of DIN removal. Given the diverse data sources, timeframes and objectives of these studies, it is not surprising that estimated cost functions in the literature vary widely. They may therefore not provide an accurate approximation to the actual cost of wetland construction in Queensland. Discussions with industry and professional bodies involved in wetland construction in Queensland indicated that construction costs are currently typically between \$30k - \$40k per ha, depending on the nature of the terrain, access and design purpose (Eadie 2015, pers. com.). Construction costs of \$30k/ha and \$40k/ha have therefore been used as an upper and lower estimate of construction cost for treatment wetlands in this indicative N-market study.

For a candidate grid cell in which a given sugarcane area could be converted to constructed (treatment) wetland, the total cost of construction is calculated by applying either a \$30k/ha or a \$40k/ha construction cost to the sugarcane area in that cell. This one-off construction cost per candidate grid cell is then annualised over a 10-year period using the annualisation formula:

$$C_c = A_i \left(\frac{r}{1 - (1 + r)^{-T}} \right) \qquad (4)$$

where C_c = annualised cost of construction
A_i = construction cost for grid cell i, given by $A_i = 30000 \times sugararea_i$
r = discount rate
T = number of years cell i stays as a wetland

A constructed wetland is assumed to remain as a wetland (i.e. taken out of cane production) for a period of 10 years. A 5 % per annum discount rate is assumed. The annual operating and maintenance costs are assumed to be 2 %[10] of the initial construction cost (A_i). Summing annualised construction costs and operation and maintenance costs produces the annual total cost of wetland construction and operation (C_t):

$$C_t = C_c + C_{om} \qquad (5)$$

C_t values are cell-specific because they vary with the area of the candidate wetland. These costs comprise part of the input data for the extended linear program which simulates operation of a trading market including both reductions in N-applications and – for candidate grid cells identified by the process described above - conversion of cane land to a constructed (treatment) wetland which generates DIN credits for sale on the market. This market model is described in the following chapter.

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[10] Taylor (2005) summarized cost-related information on best management practices in structural stormwater quality from the literature, and quoted annual maintenance costs ≈ 2% of construction cost.

4.0 RESULTS

4.1 Introduction

This chapter presents results from spatially-specific simulations of N-trading in the Tully cane lands, and then draws on findings from those results to reflect on the potential operation of an N-trading market in the Lower Burdekin – taking account of key differences between sugarcane production in the two catchments.

The spatially-specific N-trading simulations apply the market modelling methodology of Chapter 3 to spatially-specific data from the Tully. Outcomes from operation of a basic N-permit market, as illustrated in Figure 3.1, are described initially. Market simulations are then extended to include constructed (treatment) wetlands as potential sources of N-credits.

4.2 Spatially-specific N-market simulations in the Tully

Section 2.2.5 described how outcomes under a uniform N-application rate of 170 kgN/ha would provide a baseline for market simulations in the Tully consistent with the 2009 DIN-load baseline in the Wet Tropics WQIP. The Wet Tropics WQIP sets two long-term targets for reducing total DIN load at Tully Heads: a 50% reduction from the baseline load by 2018 ('the Reef Plan target') and an 80% reduction from the baseline load by 2035 ('the ecologically-relevant target'). Section 2.2.5 also described how a uniform N-application rate of 150kgN/ha is an appropriate starting point for simulating current N-management in the Tully catchment; market simulations therefore begin from this position.

The first subsection below establishes the baseline DIN load for our N-market simulations. Subsequent subsections then compare and contrast outcomes from the N-trading market and outcomes under uniform mandatory N-application limits, as the DIN load cap at Tully Heads is tightened progressively towards the 50% and 80% reduction targets.

4.2.1 Baseline outcomes

Figure 4.1 and 4.2 show the spatial variation in predicted DIN losses (kg DIN/ha) and gross margins ($/ha) from uniform baseline application of 170 kgN/ha across the Tully cane lands. Gross margins are higher and DIN losses lower under baseline conditions on soil classes 1 and 2, compared with soil classes 3 and (particularly) 4.

The predicted baseline total DIN load at Tully Heads is 748 tonnes[11]. This is 12% higher than the 667 tonnes baseline DIN load for the Tully in the Wet Tropics WQIP (Kroon et al. 2010, Table 3.1 p12). This difference could have arisen because N-application rate, total sugarcane area, the areas and locations of the four soil classes and/or denitrification through the drainage network are likely to differ somewhat between our spatially-specific model and the actual conditions that produced the monitoring results which Kroon et al. report (Kroon et al. 2010). To ensure internal consistency in our market simulations, we use the 748 tonnes

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[11] As explained in Section 2, this assumes 25% DIN removal through the drainage network for the maximum transport distance of 64.9 km. DIN removal from cells with shorter transport distances through the drainage network is scaled down proportionally.

baseline DIN load prediction from our model as a reference point. **From this baseline, the 50% and 80% DIN load reductions produce target DIN loads of 374 tonnes and 150 tonnes, respectively, at Tully Heads**. Table 4.1 reports key outcomes at the simulated baseline.

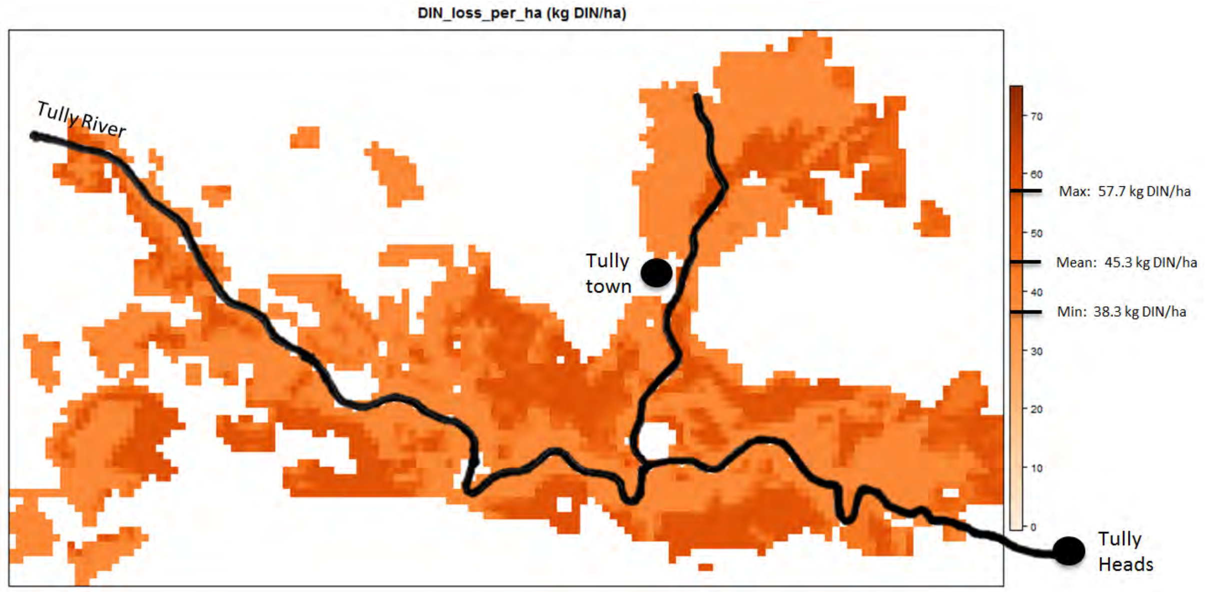

Figure 4.1: Predicted DIN losses from individual paddock-scale grid cells in the Tully cane lands under baseline conditions: uniform N-applications of 170 kgN/ha.

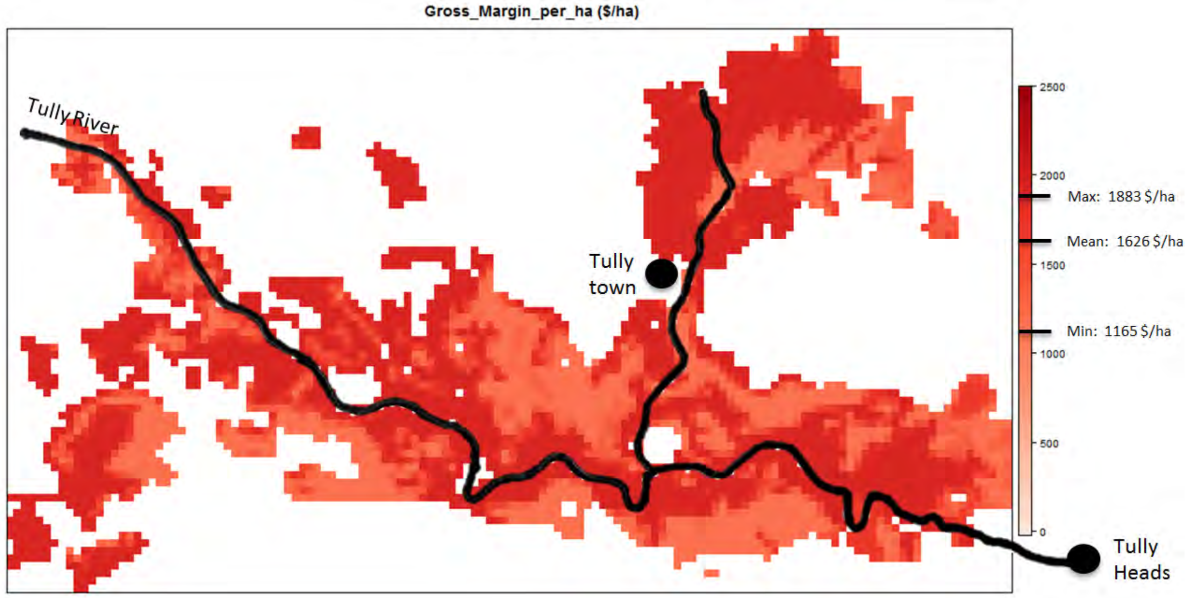

Figure 4.2: Predicted gross margins from individual paddock-scale grid cells in the Tully cane lands under baseline conditions: uniform N-applications of 170 kgN/ha.

Table 4.1: Predicted outcomes in the Tully cane lands under baseline conditions: uniform N-applications of 170 kgN/ha

Parameter	Predicted baseline outcomes
Total DIN load at Tully Heads	748 tonnes [baseline]
Total N applied	3186 tonnes
Total DIN losses at source	855 tonnes
Total gross margin from cane	30.2 M$
Total cane production area	18,742 ha

4.2.2 Results from N-market trading (without wetlands)

4.2.2.1 Results under progressive tightening of the DIN load cap: standard N-market

Tables 4.2, 4.3, 4.4 and 4.5 report simulated outcomes which arise from setting DIN load caps at Tully Heads which correspond to uniform N-application limits of 150, 120, 90 and 60 kgN/ha, respectively. Outcomes are reported separately when the DIN cap is enforced via (a) a mandatory uniform N-application limit, and (b) an N-trading market.

Table 4.2: Predicted outcomes with a DIN load cap of 591 tonnes at Tully Heads, under (a) a mandatory uniform N-application limit of 150 kgN/ha, (b) N-market trading from an initial N-permit allocation of 150 kgN/ha.

	Outcomes	
Parameter	(a) N-application limit 150 kgN/ha	(b) N-trading
Total DIN load at Tully Heads	591 tonnes [21% reduction from baseline]	525 tonnes[12] [30% reduction from baseline]
Total N applied	2,811 tonnes	2,649 tonnes
Total DIN losses at source	675 tonnes	601 tonnes
Total gross margin	30.57 M$	30.63 M$
Total cane production area	18,742 ha	18,742 ha
Extra gross margin from trading	-	60 k$

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[12] DIN load reduces under the market because gross margins on Soil classes 3 & 4 can be increased by reducing N-applications from the initial allocation of 150 kgN/ha to 120 kgN/ha.

Table 4.3: Predicted outcomes with a DIN load cap of 377 tonnes at Tully Heads, under (a) a mandatory uniform N-application limit of 120 kgN/ha, (b) N-market trading from an initial N-permit allocation of 120 kgN/ha.

	Outcomes	
Parameter	(a) N-application limit 120 kgN/ha	(b) N-trading
Total DIN load at Tully Heads	377 tonnes [50% reduction from baseline]	377 tonnes [50% reduction from baseline]
Total N applied	2,249 tonnes	2,266 tonnes
Total DIN losses at source	431 tonnes	433 tonnes
Total gross margin	30.11 M$	30.28 M$
Total cane production area	18,742 ha	18,742 ha
Extra gross margin from trading	-	170 k$

Table 4.4: Predicted outcomes with a DIN load cap of 241 tonnes at Tully Heads, under (a) a mandatory uniform N-application limit of 90 kgN/ha, (b) N-market trading from an initial N-permit allocation of 90 kgN/ha

	Outcomes	
Parameter	(a) N-application limit 90 kgN/ha	(b) N-trading
Total DIN load at Tully Heads	241 tonnes [68% reduction from baseline]	241 tonnes [68% reduction from baseline]
Total N applied	1,687 tonnes	1,758 tonnes
Total DIN losses at source	275 tonnes	278 tonnes
Total gross margin	28.08 M$	29.02 M$
Total cane production area	18,742 ha	18,742 ha
Extra gross margin from trading	-	939 k$

Table 4.5: Predicted outcomes with a DIN load cap of 171 tonnes at Tully Heads, under (a) a mandatory uniform N-application limit of 60 kgN/ha, (b) N-market trading from an initial N-permit allocation of 60 kgN/ha

	Outcomes	
Parameter	(a) N-application limit 60 kgN/ha	(b) N-trading
Total DIN load at Tully Heads	171 tonnes [77% reduction from baseline]	171 tonnes [77% reduction from baseline]
Total N applied	1,125 tonnes	1,277 tonnes
Total DIN losses at source	195 tonnes	197 tonnes
Total gross margin	24.80 M$	25.13 M$
Total cane production area	18,742 ha	17,307 ha
Extra gross margin from trading	-	329 k$

Figure 4.3 shows how participation in N-market trading varies as the initial permit allocation varies. Market participation exceeds 50% in all situations. For the lowest initial permit allocation of 60 kgN/ha, corresponding to a DIN cap which provides a 77% reduction from the baseline, 283 permit sellers (grid cells) exit cane production completely.

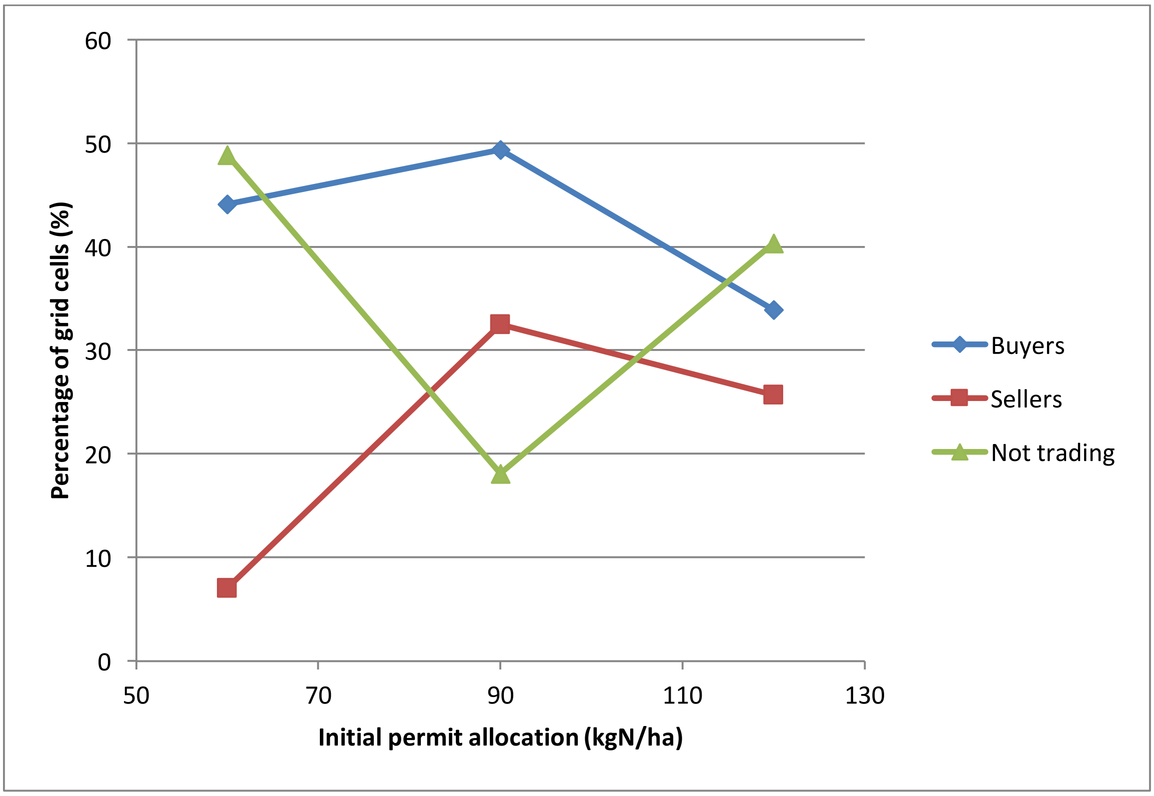

Figure 4.3: Market participation in the N-trading market for different initial N-permit allocations

Figure 4.4 shows the variation in DIN prices across grid cells after market clearing for different initial permit allocations.

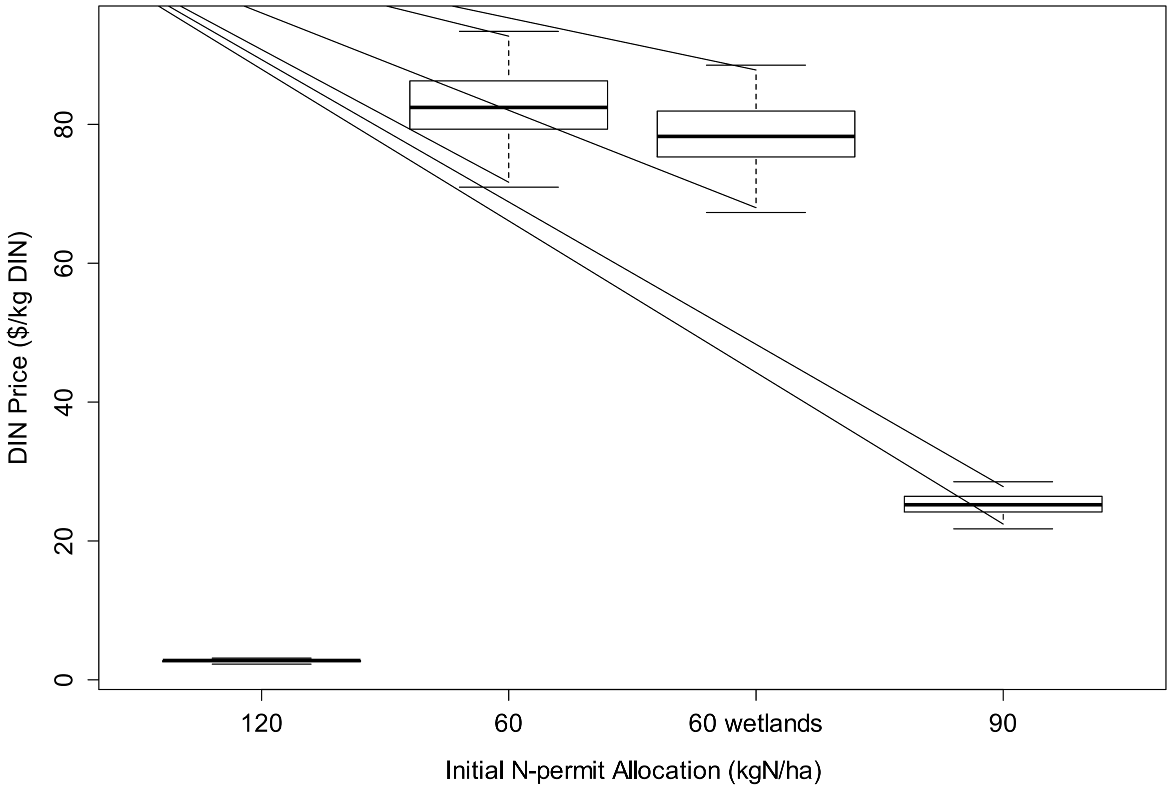

Figure 4.4: Variation in DIN prices across grid cells for different initial N-permit allocations. Bold line shows the median, edges of box show interquartile spread, whiskers show 1.5 time interquartile spread from the median.

4.2.3 Results from N-market trading with wetlands

N-market operation was also simulated with wetlands. In this market landowners with suitably-located land could, if they wished, convert a grid cell from cane production to a constructed (treatment) wetland. This option would only be chosen if the market price for DIN was high enough to cover the foregone gross margin from cane production plus the annualised cost of wetland construction and maintenance.

Simulation results from the N-market with wetlands were identical to those from the market without wetlands for the DIN caps at Tully Heads corresponding to initial N-permit allocations of 150, 120 and 90 kgN/ha. Outcomes from the N-market with wetlands were considerably different, however, under the tightest of the modelled DIN caps – corresponding to an initial permit allocation of 60 kgN/ha and a 77% reduction on baseline DIN load.

4.2.3.1 Results under the 60 kgN/ha DIN load cap: N-market with wetlands

Table 4.6 reports outcomes from the N-market with wetlands under a DIN load cap of 171 tonnes at Tully Heads, corresponding to a uniform N-application limit of 60 kgN/ha. Outcomes are reported separately when the DIN cap is enforced via (a) a mandatory uniform N-application limit, and (b) an N-trading market.

Table 4.6: Predicted outcomes from the N-market with wetlands under a DIN load cap of 171 tonnes at Tully Heads, with (a) a mandatory uniform N-application limit of 60 kgN/ha, (b) N-market trading with wetlands from an initial N-permit allocation of 60 kgN/ha

	Outcomes	
Parameter	(a) N-application limit 60 kgN/ha	(b) N-trading
Total DIN load at Tully Heads	171 tonnes [77% reduction from baseline]	171 tonnes [77% reduction from baseline]
Total N applied	1,125 tonnes	1,277 tonnes
Total DIN losses at source	195 tonnes	211 tonnes
Total DIN credits from wetland at source	0	15 tonnes
Total gross margin	24.80 M$	26.28 M$
Total cane production area	18,742 ha	18,380 ha
Extra gross margin from trading	-	1,475 k$

Table 4.7 reports trading activity in the N-market with wetlands from initial permit allocations of 60kgN/ha, and a DIN load cap of 171 tonnes at Tully Heads.

Table 4.7: Trading activity from initial allocations of 60 kgN/ha in the N-market with wetlands

No. grid cells buying permits	1787
No. grid cells selling N-permits or supplying N-credits	103
No. grid cells not trading	2130
No. grid cells exiting cane production	47
No. grid cells converting to wetland	56
Median price for DIN trades ($/kg DIN)	78.26 $/kg DIN

A total of 56 grid cells (from a maximum possible 62) are now converting to wetlands and exiting cane production completely. A further 47 grid cells are exiting cane production completely without converting to wetlands. The number of N-credits generated by wetland conversion is typically higher than the number of N-permits released when exiting cane production. Hence fewer grid cells are required to convert to wetlands or exit cane production in order to meet the N-demand of grid cells which are aiming to increase their N-applications. The cost of sourcing N-credits from wetland conversion is typically lower than the cost of releasing N-permits by exiting cane production. Consequently, DIN prices with an initial allocation of 60 kgN/ha are lower in the N-market with wetlands, compared with the N-market without wetland N-credits (Figure 4.3 and Table 4.7).

4.2.4 Spatially-specific N-market trading simulations for the Tully

The following figures illustrate operation of the simulated N-trading market in the Tully, using outcomes from initial allocations of 90 kgN/ha as examples. Figure 4.5 shows N-fertiliser applications after trading, Figure 4.6 identifies grid cells as buyers, sellers or non-participants in trading and Figure 4.7 shows changes in gross margins realised through trade.

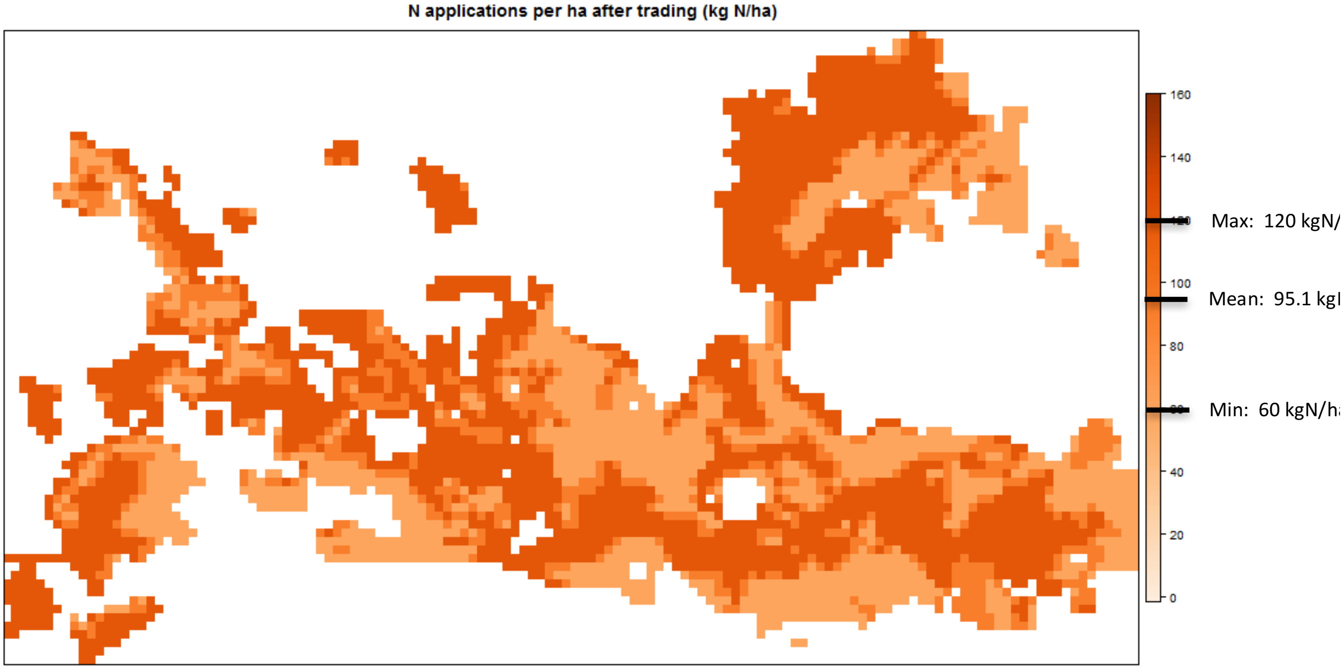

Figure 4.5: Predicted N-fertiliser applications (kg N/ha) after N-market trading, from a starting position with uniform initial allocations of 90kgN/ha.

Note how N-applications have diverged from the uniform 90 kgN/ha initial allocation. Referring back to Figures 4.1 and 4.2, market action has increased N-applications in the more productive, less lossy locations.

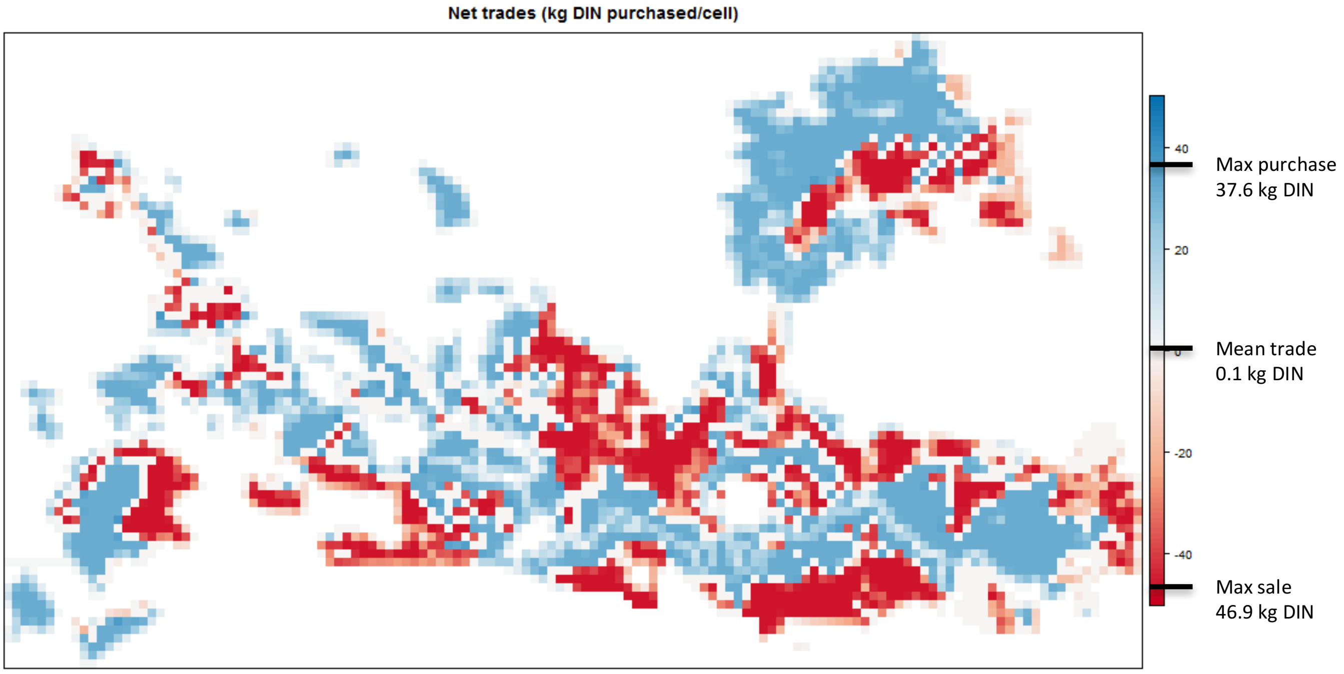

Figure 4.6: N-permit buyers (blue), sellers (red) and non-participants (grey) in N-market trading, from a starting position with uniform initial allocation of 90kgN/ha. In total there are 1986 buyers, 1306 sellers and 728 non-participants.

Note the high level of market participation (82% overall) in Figure 4.6.

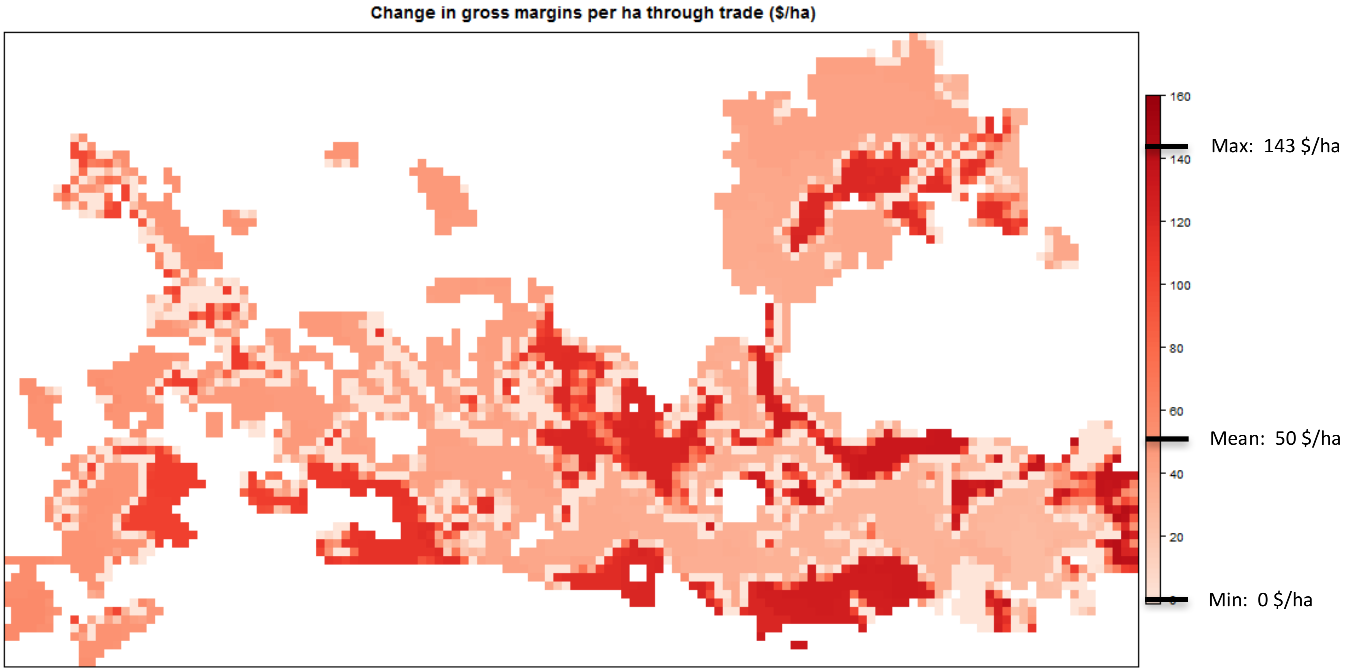

Figure 4.7: Changes in gross margin ($/ha) realised through N-market trading, from a starting position with uniform initial allocations of 90kgN/ha.

Figure 4.7 shows that cell-specific gross margins either increase, or remain unchanged, after market trading. Grid cells which sell N-permits realise the largest gains from trade.

Figures 4.8 - 4.11 contrast net trades and the gains from trade in N-markets without (Figures 4.8 & 4.9), and with (Figures 4.10 & 4.11), wetlands – starting from an initial allocation of 60 kgN/ha.

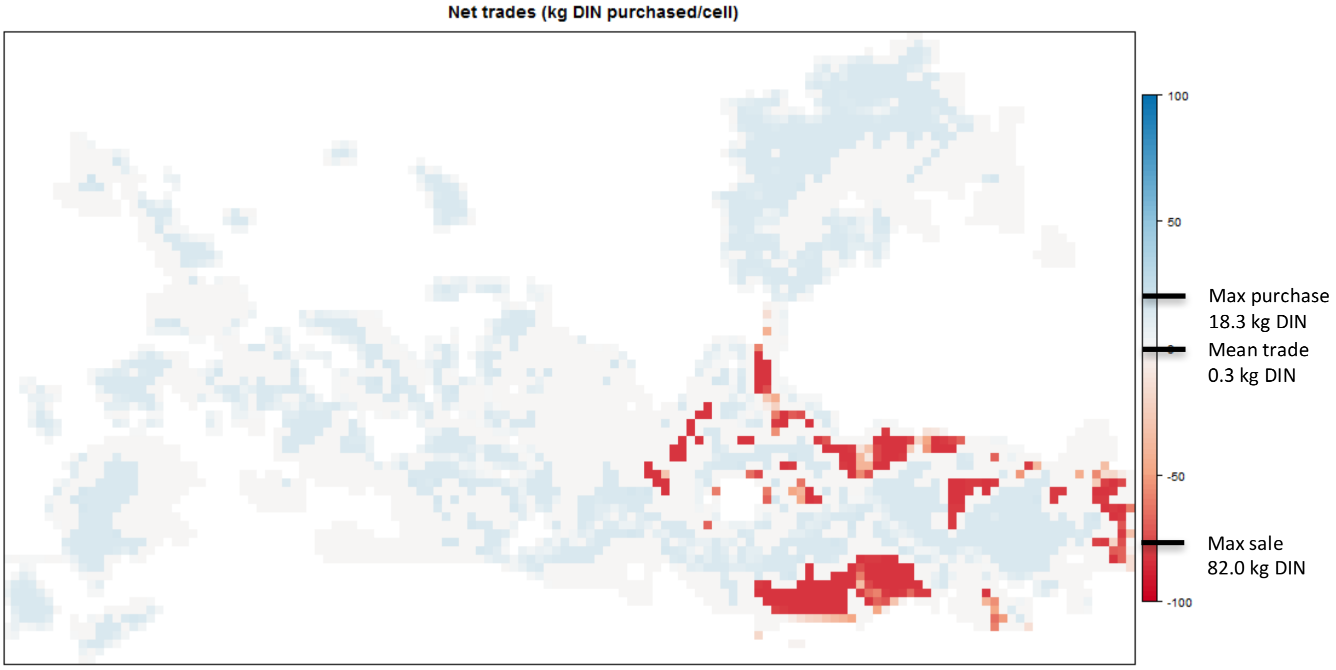

Figure 4.8: N-permit buyers (blue), sellers (red) and non-participants (grey) in N-market trading, from a starting position with uniform initial allocation of 60kgN/ha in an N-market without wetlands. In total there are 1773 buyers, 283 sellers and 1964 non-participants.

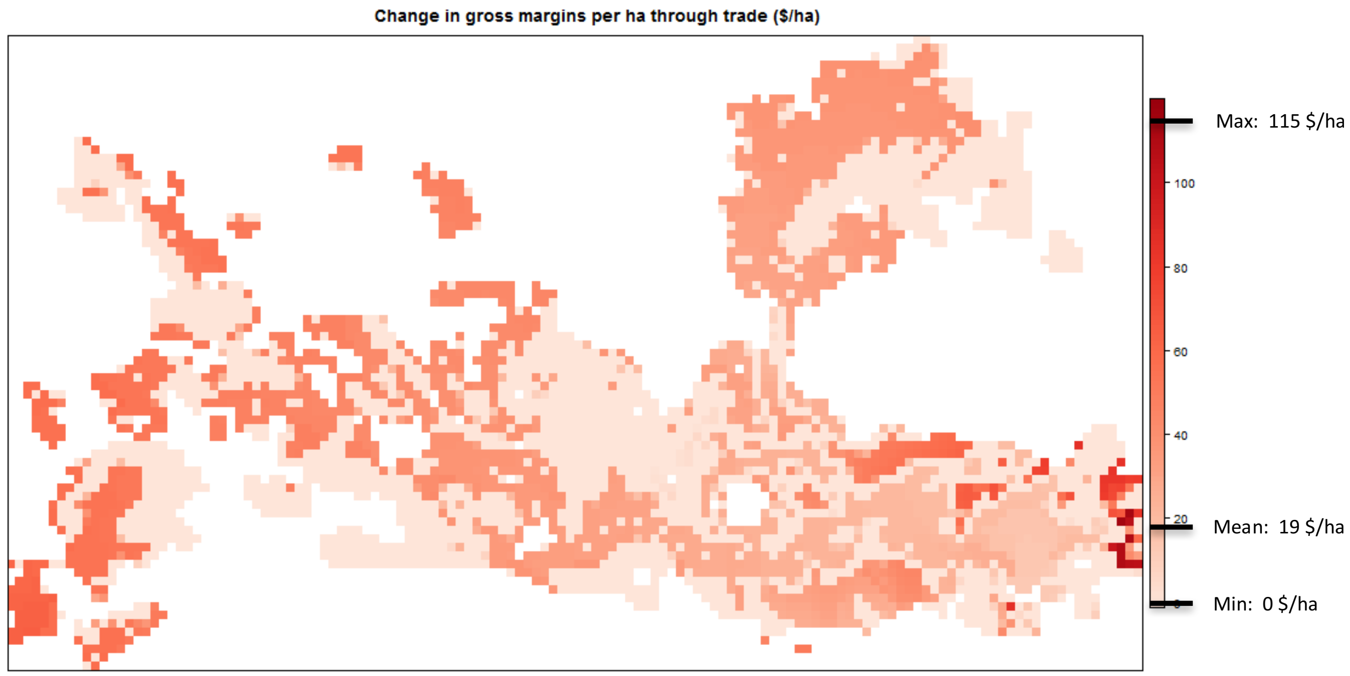

Figure 4.9: Changes in gross margin ($/ha) realised through N-market trading in a market without wetlands, from a starting position with uniform initial allocations of 60kgN/ha.

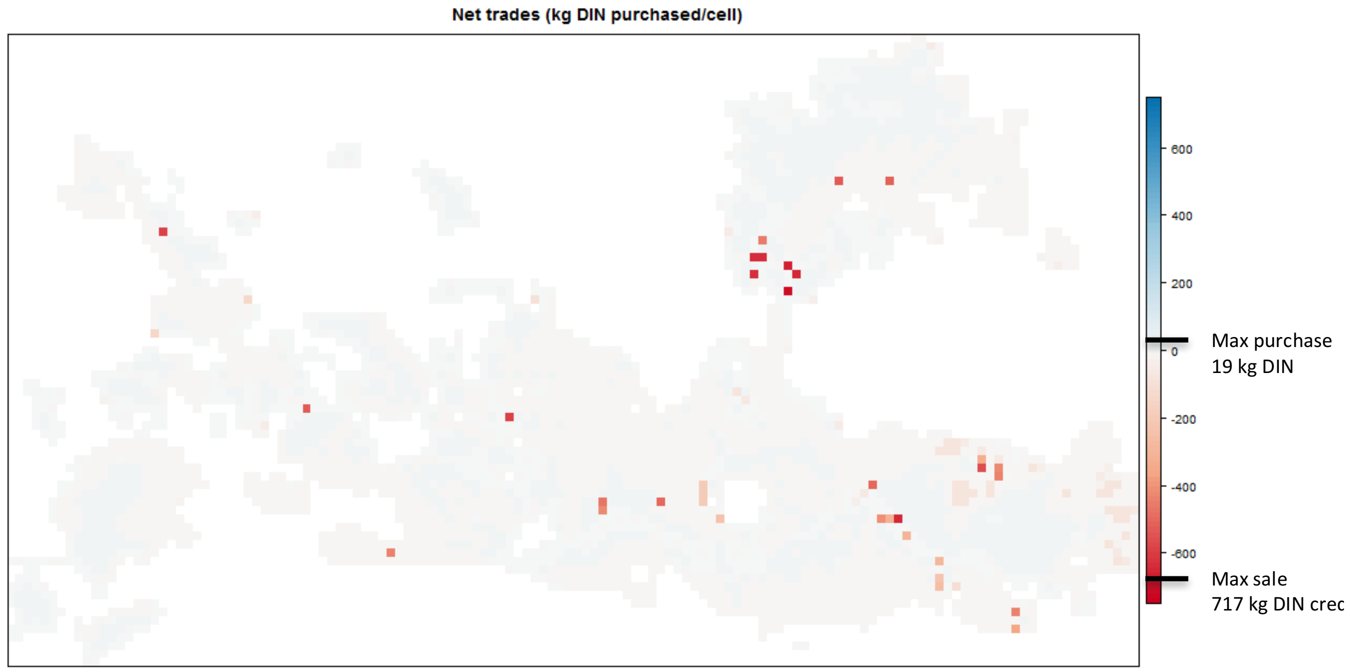

Figure 4.10: N-permit buyers (blue), sellers (red) and non-participants (grey) in N-market trading, from a starting position with uniform initial allocation of 60kgN/ha in an N-market with wetlands. In total there are 1787 buyers, 103 sellers and 2130 non-participants.

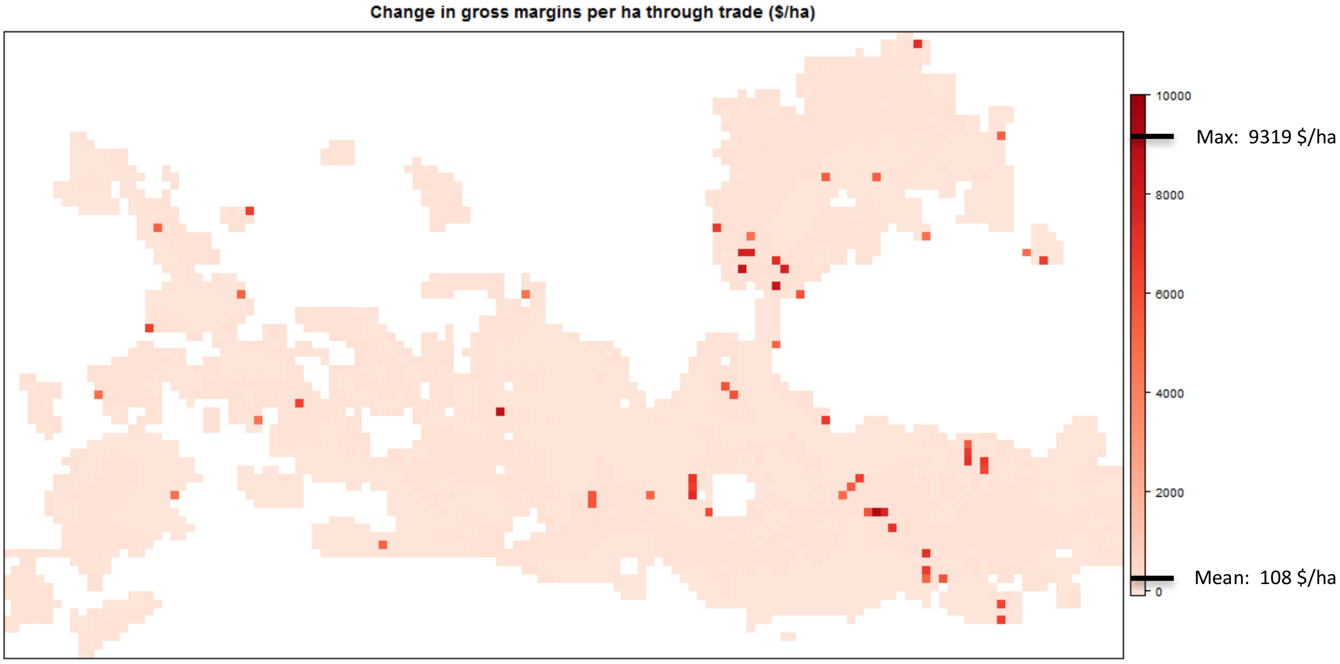

Figure 4.11: Changes in gross margin ($/ha) realised through N-market trading in a market with wetlands, from a starting position with uniform initial allocations of 60kgN/ha.

Figure 4.11 shows that the 56 cells which convert to wetlands all realise gains from trade in excess of $4,500 per ha.

4.2.5 Discussion of Results from spatially-specific N-market modelling in the Tully

Heterogeneity in abatement costs and its consequences for the level of market participation were key issues raised by the Great Barrier Reef Water Science Taskforce when considering the suitability of a nutrient trading scheme for the Great Barrier Reef (State of Queensland 2015). Results from spatially-specific N-market modelling in the Tully show that:

- there is considerable heterogeneity across grid cells in the way in which N-applications affect gross margins
- this heterogeneity is sufficient to drive an active trading market with more than half of the grid cells in all simulations buying or selling N-permits (Figure 4.2).

In common with existing literature (e.g. Roebeling et al. 2009b, van Grieken et al. 2013b), simulation results suggest that reducing N-fertiliser applications to around 120 kgN/ha may be sufficient to achieve the ‘Reef Plan’ 50% DIN load reduction target from the 2009 baseline. Our simulation results also suggest that this level of reduction could be achieved at modest cost; this is again in accordance with existing literature (e.g. Roebeling et al. 2009, van Grieken et al. 2013b). Further reductions in DIN load toward the ‘Ecologically-relevant’ 80% reduction target appear to be more difficult to achieve. Our simulations suggest that a DIN load cap corresponding to uniform N-application at 60 kgN/ha would deliver close to an 80% reduction (Tables 4.5 and 4.6), but a mandatory uniform limit on N-applications is unlikely to be the most cost-effective mechanism for achieving this outcome (Tables 4.5 and

4.6). In these circumstances the additional flexibility provided by an N-trading market becomes particularly attractive.

Figures 4.5 to 4.9 show how market trading acts to redistribute a limited nitrogen pool more cost-effectively across cane production. As the total DIN load cap tightens, and the N-price rises, Figures 4.5. and 4.6 show that landowners on lower yielding, 'leakier' soils can increase their gross margins by selling some of their N-permits to landowners on better soils. Permit buyers obtain a considerable increase in gross margin by applying this additional nitrogen to their own land. Permit buyers' increased gross margins are more than sufficient to cover the reduced gross margins of the permit sellers; this is the basis for market trading. It is clear that permits are predominantly being sold by landowners on soil classes 3 & 4, and predominantly bought by landowners on soil classes 1 & 2. It is the variation in gross margins across soil classes, and – in particular – the steep curvature of the gross margin curves on soil classes 1 & 2 at lower N-applications, which effectively drives the N-trading market in the Tully.

As the DIN load cap is tightened towards the 80% reduction required by the ecologically-relevant target it becomes more expensive to source N-permits. Our model assumes that N-applications below 60 kgN/ha are not really viable for cane production. In this situation, in a conventional N-market, N-permits will only be released for sale if grid cells exit sugarcane production entirely by selling their full initial allowance. The DIN price required to persuade landowners to do this is high (Figure 4.4), because the profits from permit sales must be sufficient to cover the full opportunity cost of exit. Including constructed (treatment) wetlands as a source of N-credits can make a considerable difference in this situation (Tables 4.6 & 4.7, Figures 4.8 - 4.11).

Appropriately-sited constructed wetlands could potentially generate a large quantity of N-credits. Selling these credits on the N-market provides landowners with an alternative source of income, easing their transition out of cane. The N-credits from wetland also benefit the landowners who remain in cane. With constructed (treatment) wetlands acting as DIN-sinks, more fertiliser can be applied in the catchment without infringing the total DIN load limit at Tully Heads. This effectively increases fertiliser supply which, in tandem with the lower costs incurred by supplying N-credits from wetlands instead of sourcing N-permits from exiting cane, leads to a reduction in the market N-price (Table 4.7). A lower N-price makes it less expensive for landowners on better soils to purchase additional nitrogen, so – from all perspectives – outcomes improve. The inclusion of constructed (treatment) wetlands in the N-market appears to provide considerable efficiency advantages (Table 4.7 vs. 4.5).

4.3 Potential N-market operation in the Lower Burdekin

Whist the fundamental principles of N-market operation remain unchanged between locations, differences in key factors such as the variations in gross margins and DIN losses with N-applications across soil types, and differences in climate and use of irrigation are likely to affect how N-markets might function in the Lower Burdekin in comparison to the Tully. Sections 2.2 and 2.3 indicated very considerable differences between the Tully and the lower Burdekin – and further differences between the Delta and BRIA zones within the Burdekin. This section draws on findings from the spatially-specific N-market simulations in the Tully to reflect on the potential operation of an N-market – or N-markets – in the lower Burdekin.

4.3.1 Differences in gross margin as driver of N-market trading

Differences across soil types in the curvature of gross margins at lower N-applications were identified as a key driver of market participation in the Tully. Gross margins in the Tully declined more rapidly with reducing N-applications on the higher yielding, less lossy soils, and less rapidly on lower yielding, lossier soils. This facilitated trading because landowners on the lossier soils could make more by selling their N-permits to landowners on the better soils than they could from applying that nitrogen to their own crops. Lossier soils (classes 3 & 4) covered only around a third of the Tully cane lands. This produced a supply-constrained smart market and delivered higher gains from trade for the landowners on poorer soils. This had important implications for exit opportunities as the load cap was tightened towards the challenging ecologically-relevant target.

There are a wide range of different soil types in the Lower Burdekin, with distinct differences between the main soil groups in the Delta and the BRIA. As a general principle, gross margins would be expected to respond less strongly to reducing N-applications on lossier soils, so it would be expected that the basic ingredient for active market participation would also be present in the Lower Burdekin. However, a spatially-specific grid cell model would have to be overlaid on relevant soil maps to determine whether an N-market in the Delta or the BRIA, or across both regions, would be supply-constrained as it was in the Tully.

Van Grieken et al. reported spreads of gross margins for the Wet Tropics, the Burdekin Delta and the BRIA (van Grieken et al. 2014, Figures 7 – 9, p 32-33). The spread of gross margin relative to its mean is considerably wider for the Tully than for the BRIA, and – particularly – for the Delta. Whilst differences between grid cells in the curvature of gross margins with decreasing N-applications is the key requirement for active market participation, a narrower spread of gross margins across farms may suggest that market trading potential in the BRIA and – particularly – the Delta could be lower than in the Tully.

4.3.2 Farm size

Farm enterprises are typically larger in the Burdekin than in the Tully, and this is particularly so for the BRIA. This is likely to have important implications for market participation as larger enterprises are generally more profit-driven, and are therefore more likely to engage with an N-market if there are gains to be made from trade.

4.3.3 Irrigation

Section 2.3 reported that whilst deep drainage was the major N-loss pathway in the Tully and the Burdekin Delta, denitrification was the major N-loss pathway for the BRIA – where deep drainage and surface runoff accounted for similar (but modest) proportions of total N-loss. This could have important implications for the ability of an N-market to deliver the desired reductions in DIN load at the mouth of the Burdekin. This is primarily a cost-effectiveness issue, rather than a cost-efficiency issue, as it impacts upon the ability of an N-market to deliver its environmental objective.

4.3.4 Opportunities for incorporating constructed (treatment) wetlands

Irrigation during the dry season in the Burdekin is likely to reduce the chances of the macrophyte zone drying out in constructed (treatment) wetlands. This should help to improve overall wetland effectiveness for DIN removal and reduce uncertainty surrounding the calculation of N-credits from wetlands. Uncertainty in DIN removal would typically be addressed by incorporating a trading ratio in the N-market. This ratio would impose an 'exchange rate' of more than 1:1 between N-credits from wetlands and N-permits. The N-credit:N-permit 'exchange rate' could be reduced if there was less uncertainty regarding wetlands' ability to remove DIN. A lower 'exchange rate' would make constructed (treatment) wetlands a more attractive option for the landowner. This would facilitate wetland conversion and assist in delivering the valuable contribution which wetlands can potentially make towards cost-effective DIN management under tight DIN load caps.

4.3.5 One N-market in the Burdekin – or linked markets in the BRIA and the Delta?

As already discussed, there are considerable differences in soil types, DIN loss pathways, gross margins, variation in gross margins and transport distances to the river mouth between cane farms in the Delta and in the BRIA. These differences would have to be considered in full detail when designing an N-trading market for the lower Burdekin. It may be that the combined effect of these differences necessitates operating distinct – but interlinked – N-markets for the Delta and the BRIA. This would form an important component for future study, when the potential design of between-zone and within-zone trading would be addressed. The market optimisation framework developed here for simulating spatially-specific N-trading in the Tully could be adapted to accommodate more sophisticated smart market structures, drawing on the principles outline in Prabodanie et al. 2014.

4.3.6 Regulation and governance

The regulation and governance structures outlined for a potential smart market in the Tully should also be applicable to N-market(s) in the Burdekin. Record-keeping and reporting would likely be perceived as less onerous by larger farm enterprises, so this could potentially facilitate successful governance implementation in N-market(s) in the Burdekin.

5.0 REGULATIONS AND GOVERNANCE

5.1 Introduction

The Great Barrier Reef Water Science Taskforce recommends greater use of market approaches to deliver improved water quality outcomes more cost-effectively (State of Queensland 2015). Nutrient trading was identified as a potential quantity-based instrument that could be implemented in the GBR catchments. According to the Taskforce, the suitability of a nutrient cap and trade scheme for the GBR critically reliant on satisfying the following three requirements:

- Strong regulatory drivers
- Sufficient heterogeneity in abatement costs across participants
- Sufficient number of participants

The market simulation results indicated that there is considerable heterogeneity in abatement costs across potential sugarcane N-market participants, and suggested high levels of participation in the proposed smart market. In simulation at least, these two requirements appear to be fulfilled. The remaining requirement is therefore to suggest an appropriate package of potential regulatory drivers. This issue is addressed in the following subsections.

5.1 Enforcement and monitoring[13]

The proposed smart market would operate within a mandatory compliance framework consistent with the Environmental Protection Act 1994. Figure 5.1 illustrates an example of the regulatory and governance framework for the proposed smart market. Trade agreements would have to be signed and dated by each farmer at the commencement of the program. Within this framework, landholders would have to comply with the maximum kg N application permitted on their land, corresponding to their initial permit allocation adjusted to include any accepted permit purchase bids or accepted permit sale offers after market clearing (Farms 1, 2, 3 & 4 in Figure 5.1). Farmers could choose not to participate in N-trading; N application on their land would then be limited to their initial permit allocation.

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[13] Some of the information in this section is adapted from a US EPA document titled “Water Quality Trading Scenario: Nonpoint Source Credit Exchange” (http://www3.epa.gov/npdes/pubs/wqtradingtoolkit_nps-credit-exchange.pdf, date accessed 11th March 2015).

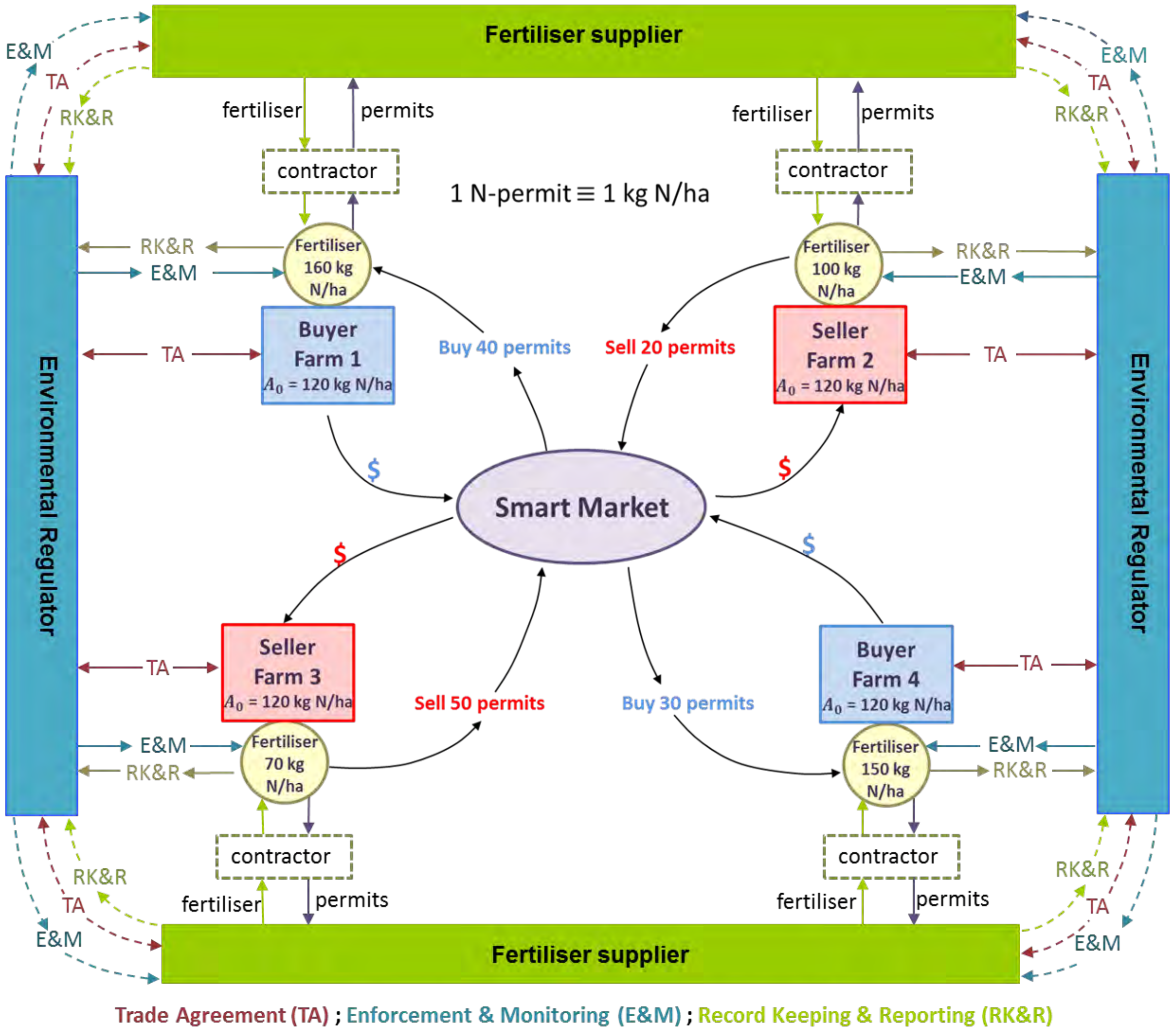

Figure 5.1: Regulatory and governance framework for the proposed smart market

The regulator would have to establish clear enforceable mechanisms consistent with the Environmental Protection Act 1994 to ensure legal accountability for the N-permits traded. These mechanisms could be incorporated into Queensland state regulations, market trade agreements or both. Inclusion of these accountability provisions would make each farmer or landholder legally responsible for their N management on the paddock. Legally binding provisions would require that the regulator had the authority to enforce and monitor actual N application on the paddock.

The terms in the trade agreement between farmers and the regulator would need to detail specific issues such as:

- Initial allowance of N-permits
- Location at which permits are valid
- Duration for which permits are valid
- Procedures for submitting bids to buy permits and offers to sell permits
- Monitoring and reporting requirements
- Procedures for random checks and inspection by the regulator

- Procedures regarding breach of trade agreements and their implications
- Monitoring of water quality by the regulator at specific points on the Tully river (ambient monitoring) – to check that reductions in N-applications are having the desired effect
- Sharing of anonymised trade data on aggregate permit prices and aggregate purchase and sale quantities among participants

An online portal (and information sheets) would provide landholders with information regarding the number of permits required for different combinations of best management practices on their land – and the corresponding impact on DIN load at Tully Heads. This information would be made available to the landholders well in advance of trading.

Landholders would be required to monitor and report their N-applications by appropriate record keeping to comply with the terms in the N-trading agreement. Monitoring and reporting could, for example, be backed up by random spot checks on record keeping and N-applications.

Contractors' fertiliser applications will be GPS-linked[14] so that they can be geo-checked against permit validity. Fertilizer suppliers/contractors should be allowed to accept the permits from farmers and only apply the required amount of fertiliser as given by the number of permits for that particular land.

The smart market accepts bids to purchase additional N-permits from those participants who value N-applications most highly, and accepts offers to sell un-used N-permits from participants who offer to sell them most cheaply. The market price offered for permit purchases and sales will be similar for all farmers, with a modest price spread reflecting differences in DIN transport from the paddock to Tully Heads. These features ensure that both buyers and sellers will receive the maximum possible gains from market participation, within the constraints imposed by the DIN load cap at Tully Heads. This outcome of the smart market minimises the incentive for farmers to re-sell the permits outside the market, because the smart market solution has already matched buyers who are willing to pay the most for additional N-permits with sellers who are willing to sell their un-used N-permits most cheaply. This maximises the gains for both buyers and sellers because the additional permits bought deliver an additional (sugarcane) gross margin which is bigger than the revenue which could be obtained from selling the same permits to another farmer.

5.2 Converting cane land to wetlands or other alternative income streams

Within the smart market program, farmers have the option to convert their sugarcane land into other land uses. The market simulations considered the possibility of conversion to constructed (treatment) wetlands for N-removal. Other land uses for alternative income opportunities could also be considered e.g. aquaculture, although these have not been modelled in the initial feasibility study. The progressive tightening of the DIN load limits will

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[14] This is already common practice

drive the price of permits up as landowners compete to buy permits from a smaller pool. As the DIN load cap tightens and the market N-price rises, farmers in appropriate locations might find it more profitable to sell their entire initial allocation and convert their sugarcane into constructed (treatment) wetlands so that they obtain an alternative income stream from the N-credits generated by the wetland. In this situation landowners would sign a wetlands agreement with the regulator. The regulator would provide guidelines to potential wetland owners on the maintenance required to ensure that the wetland continued to be effective in removing DIN. These guidelines would contain information similar to that in the wetland management handbook (Department of Employment, Economic Development and Innovation 2011). The wetlands agreement would require the wetland owner to:

- retain the land as a wetland for an agreed duration (e.g. 10 years)
- carry out periodical maintenance of the wetland as detailed in the Handbook

To encourage farmers to convert their land into a constructed (treatment) wetland, government could consider providing a subsidy or an interest-free loan towards wetland construction costs.

The government may also wish to consider offering conversion assistance for transitioning to low-N alternative income opportunities for owners of cane land which is not suitable for wetland conversion.

5.3 Education and information initiatives and community involvement[15]

Introduction of a smart market for N-trading would have to be supported by a vigorous and accessible program of education and information initiatives. Issues addressed could include:

- information campaigns (government or industry associations)
- Off-site training in N management
- On-site training in N management (which may be subsidised)
- Information from fertiliser suppliers and fertiliser manufacturers
- Soil and DIN monitoring
- Recognition of low impact fertiliser usage via certification and/or awards (green credentials)

5.4 Extending the scope of smart trading markets

The smart market framework could be extended to include other entities within the catchment, and/or other relevant entities which discharge nitrogen into the same section of the Reef Lagoon. The smart market modelled in this research addressed DIN losses on land parcels growing sugarcane in the Tully catchment. In the simulations, only DIN losses from sugarcane production contributed to the total DIN cap at Tully Heads. However, other

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[15] This section draws on the set of possible options for education and information initiatives to address diffuse pollution in agriculture, as outlined by Gunningham & Sinclair (2005)

anthropogenic DIN sources within the catchment should also be included within this cap. The non-point to non-point smart market could be expanded to include these other sources, such as horticulture and grazing on improved pastures. The smart market could also be expanded to include point sources of DIN such as sewage treatment works and urban stormwater runoff. The scope of smart market governance would have to be extended appropriately to encompass point and non-point sources in combination. Figure 5.2 illustrates a variety of the potential regulatory and governance framework permutations that are possible. Potential points of regulation in the market and the potential smart market participants could be varied as the geographic extent of the smart market increased. The basic framework of Figure 5.2 may be useful for determining the relevant participants in the governance and advisory structures that will allow the market to function effectively. Ultimately, the scope of the smart market could be extended to include all point and non-point sources, which affect water quality in the adjacent section of the Reef Lagoon.

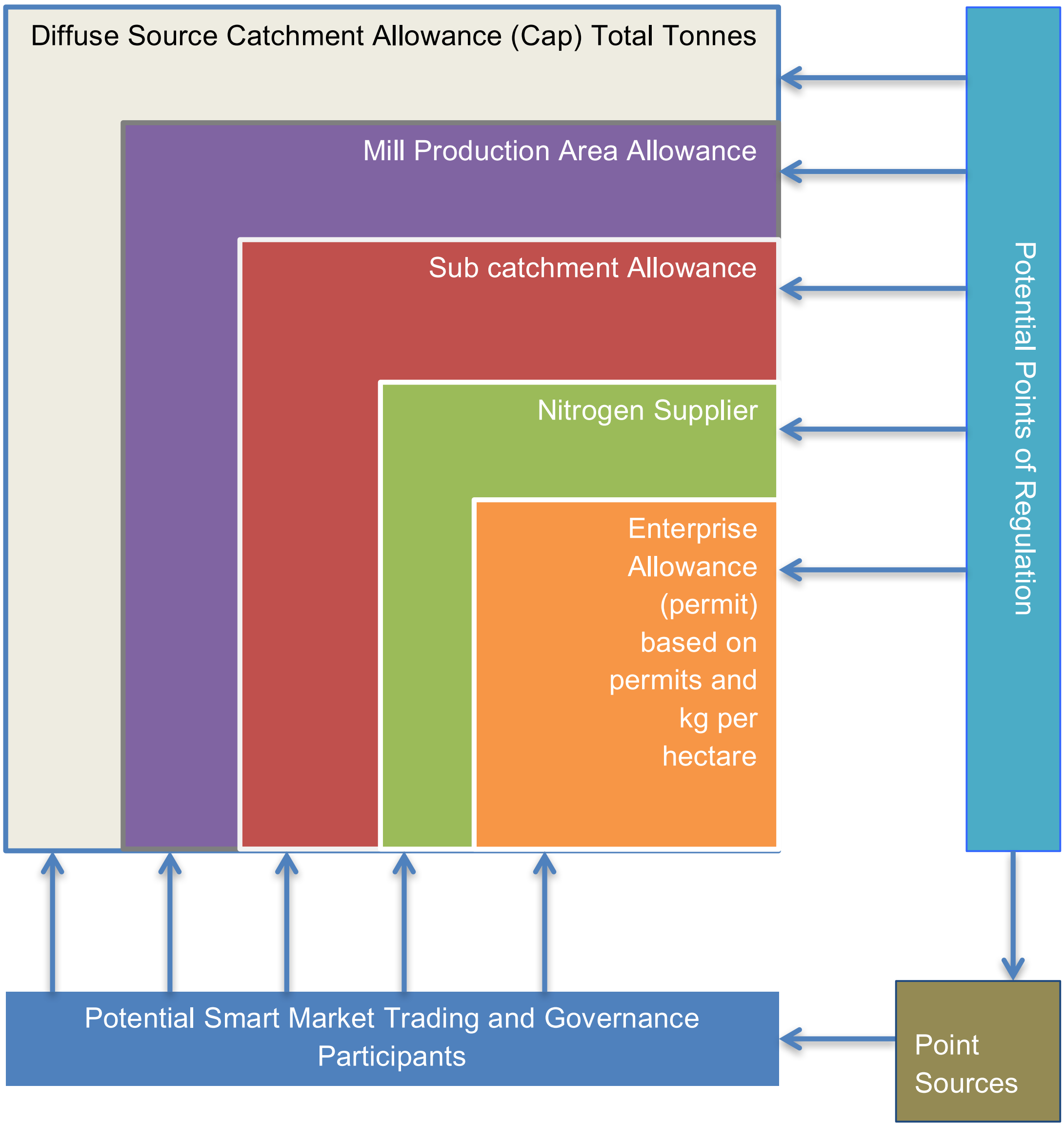


Figure 5.2: Extending the scope of smart market governance

6.0 RECOMMENDATIONS AND CONCLUSION

6.1 Key Conclusions

The purpose of this scoping study was to identify the potential for a cap and trade program based on a non-point-to-non-point trading scheme to be implemented to meet nitrogen reduction targets in the Great Barrier Reef. The fundamental threshold issue examined if the cap and trade approach was more economically efficient than a simple command and control approach. The outcome of spatially-specific modelling in a case study catchment indicated that a degree of economic efficiency is to be gained.

Under the cap and trade approach it is possible to get close to the targeted 80% reduction using a per hectare application cap of 60kg. In the market simulation as the cap is gradually tightened the market price for nitrogen increases and under the tighter cap conversion of marginally productive cane land in key locations to wetlands becomes economically viable.

The market simulation found that trading reduces the total cost impact on the cane growing section of the industry to achieve nitrogen reduction targets. The ability to trade nitrogen savings and reductions into the smart market meant no growers were economically worse off.

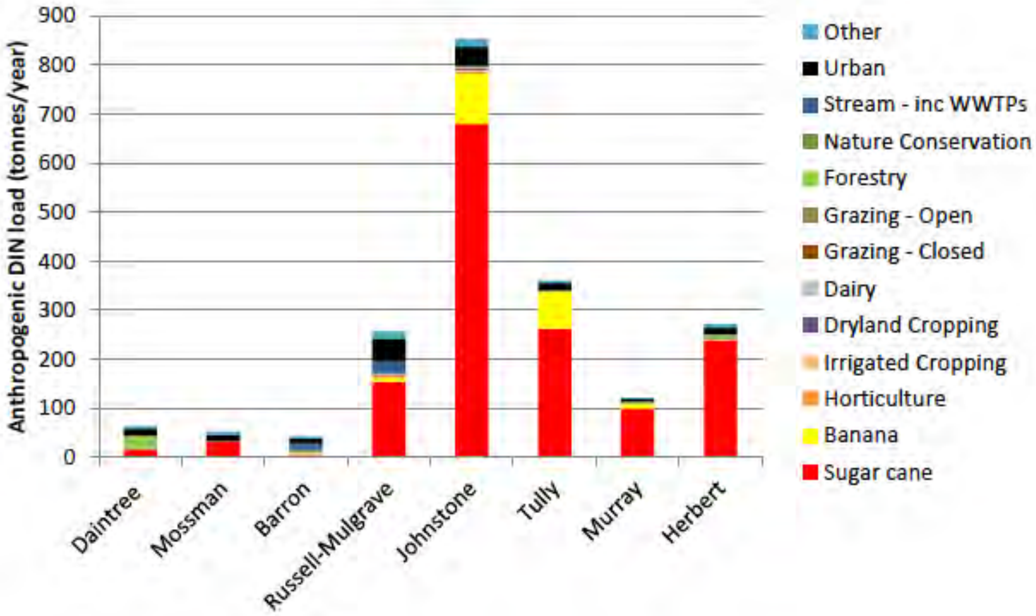
Overseas experience shows that setting up a cap and trade water quality improvement scheme is a potentially costly, controversial and time-consuming exercise. In this instance the modelled economic gains from a non-point-to-non-point trading approach rather than a simple command and control approach are modest. Full investigation of the cost of implementing a cap and trade scheme was beyond the parameters of this scoping study.

Beyond economic efficiency arguments, there are a number of other reasons that a cap and trade scheme should be considered. The approach will put the onus on the industry to meet the targets and to innovate. It will reward growers who can most effectively reduce their nitrogen pollution and maximise production on better soils. The trading approach will help incentivise innovation and implementation of existing best management practice and new approaches. Conversion of land to nitrogen-intercepting wetlands was one innovation modelled, though there may be many others that could be potentially included in the trading framework such as edge-of-field bioreactors.

The flexibility involved in the cap and trade scheme may make the introduction of a nitrogen cap more palatable for the industry rather than an inflexible command and control regulatory approach.

Implementation of a non-point-to-non-point trading scheme is a long-term undertaking requiring significant courage, investment and leadership. In the shorter term, this study has identified that the costs to cane growers of reducing nitrogen pollution is comparatively low. The Great Barrier Reef Water Science Taskforce identifies that the regulatory focus must be on ensuring that any future development does not undo water quality outcomes associated with addressing the legacy of past development (State of Queensland 2015). The 'no worsening' approach to future development highlights a significant future opportunity for a stage one water quality-trading program focused on point to non-point trading.

Point to non-point trading is the major form of water quality trading operating elsewhere. Under the model, major point sources such as sewage treatment plants and stormwater sites trade with diffuse sources such as agriculture to reduce overall compliance costs.



Source: Terrain NRM (2015) Wet Tropics Water Quality Improvement Plan

Figure 6.1: Anthropogenic DIN load in the Wet Tropics

While urban centres are a minor proportion of the total DIN load in most catchments, they do provide a potentially significant future revenue stream. Significant urban population increase is expected within the Great Barrier Reef Catchments. According to population projections by Queensland Treasury the population across the major urban centres of Townsville, Cairns, McKay and Gladstone is expected to increase by approximately 370,000 people by 2036. To meet the current license regulatory provisions for wastewater treatment and water sensitive urban design in new urban centres an estimated investment of approximately $900 million will be required[16].

With the recommended implementation of 'no worsening' provisions, the costs of point source regulatory compliance will rise significantly. Built asset solutions to meet this new standard will make cost-effective water supply difficult. Current regulation allows flexibility in meeting license conditions and Queensland Urban Utilities has undertaken a pilot in South East Queensland. Therefore there is significant scope for the investigation of opportunities for point to non-point trading involving urban centres and cane growers.

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[16] Based on industry expert assessment of approximately $1000 per person for advanced sewage treatment and $1500 per person for water sensitive urban design provisions in new estate developments, Edie M (2015) pers com

6.2 Recommended Future Research

In order to more accurately model the potential gains from water quality trading there is a need for more up to date economic data on costs and yields per hectare under various management scenarios. Knowledge of the effectiveness of wetlands in removing DIN and the processing capacity of in-stream and estuary systems would also be beneficial.

Water quality trading has significant potential for maximising the outcomes of investment to reduce nutrient loads both across and within sectors. Recommended trading-based research is as follows:

- Potential for point to non-point trading of nitrogen in key catchments and among urban, industrial and agricultural sectors. This would involve an analysis of the cost and location of required built asset solutions to meet current and future regulatory conditions, an analysis of nitrogen offsets through agricultural reductions and identification of key institutional barriers and constraints to implementation.

- The capacity of landholders to participate in nitrogen and other reef stressor trading is not well understood. Shortle (2013) identifies that many of the failures of early water quality trading schemes were caused through little or no participation by eligible participants. The extent to which cane farmers will participate in a nitrogen-trading scheme, whether it be non-point to non-point or point to non-point, remains unknown and is outside the scope of this study. However, given the potential for cost-effective nitrogen reduction, a choice modelling experiment with a representative sample of farmers to quantify potential incentives and barriers to market participation would provide a key piece of intelligence. Experimental and behavioural studies would improve the understanding of factors that influence whether and how agents of various types participate in markets with the objective of improving the choice architectures of these markets (Shortle 2013). Such a research program could effectively reveal regulatory and price drivers and barriers to participation in nitrogen and other reef stressor reduction trading approaches and thus refine the development of the market framework. It would also contribute to the bottom up approach recommended for effective market development.

- Potential for point to non-point trading of sediment reductions in key infrastructure (port) locations and among agricultural sectors. This would involve an analysis of the cost and location of required asset solutions to meet current and future regulatory conditions, an analysis of sediment offsets through agricultural reductions and identification of key institutional barriers and constraints to implementation.

- The opportunity for a broader trading approach that involves multiple reef stressors from point and non-point sources. The application of such an approach would involve trading between stressors and sectors to maximise the outcomes from investment.

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APPENDIX 1: MARKET SIMULATION – LINEAR PROGRAM

A.1 Linear Program

A linear program is used to solve for prices and permit allocations such that total joint benefit accruing to buyers and sellers from market participation is maximised, subject to the maximum allowable DIN load at Tully Heads, and given the initial permit allocation. This N-permit allocation problem is modelled for a single time period and it is assumed that farmers submit bids and offers which truly represent their own best interests (Prabodanie et al. 2010). The following mathematical model is developed from the descriptions provided by Prabodanie et al. (2010, 2014). In this model, it is assumed that DIN delivery from separate grid cells combine linearly to produce the overall DIN load at Tully Heads, i.e. the model does not account for potential non-linearities between DIN load emissions from grid cells and denitrification through the drainage network to Tully Heads.

Indices

$i = 1,..,N\ participants\ or\ traders$

$k = 1, \ldots, K$ bids or offer steps

Parameters

$A_i =$ initial allocation to trader i

$d_i =$ increase in DIN load at Tully Heads, from one unit DIN loading at source i

(d_i is the transport coefficient, $0 \leq d_i \leq 1$)

$L =$ the maximum DIN load at Tully Heads (the cap)

$U_{ik} =$ upper bound on k^{th} bid step placed by participant i

($U_{ik} > 0$ for buy steps, $U_{ik} < 0$ sell steps

$P_{ik} =$ price of associated with k^{th} bid step placed by participant i

Decision variables

$b_{ik} =$ number of permits bought or sold by partipant i at k^{th} bid or offer step

$q_i =$ maximum DIN load allowed for participant i.

(q_i is also the total number of permits held by participant i after market clearing).

$\mu_i =$ price for one permit for participant i, given in terms of shadow price of contraint 2 below.

Objective function for the N-market overall

$$\text{Maximise} \quad \sum_{i=1}^{N} \sum_{k=1}^{K} P_{ik} b_{ik} \ , \quad \text{subject to}$$

Upper bounds on bids and offers from market participants

$$\text{If } U_{ik} \geq 0, 0 \leq b_{ik} \leq U_{ik}\ , \ \text{ else } \ U_{ik} \leq b_{ik} \leq 0$$
$$\text{for all } i = 1, \ldots, N \ \text{ and } \ k = 1, \ldots, K \qquad (S1) : \theta_{ik}$$

Compliance constraints on each grid cell

$$q_i - \sum_{k=1}^{K} b_{ik} = A_i \qquad \text{for all } i = 1, \dots, N \qquad\qquad (S2) : \mu_i$$

Water quality constraint at Tully Heads

$$\sum_{i=1}^{N} d_i q_i \le L \qquad \text{for all } i = 1, \dots, N \qquad\qquad (S3) : \delta$$

In accordance with the optimisation problem stated above, the linear program maximises the joint total surplus (or net benefit) to buyers and sellers from participating in the N-trading market. The coefficients P_{ik} in the objective function indicate how much each block of DIN load is worth to the buyer/seller (Prabodanie et al. 2014). The objective function maximises total gains from N-permit trading. This ensures that the maximum net benefits will be achieved from market trading if the bid and offer schedules are true indications of the economic outcomes to cane farms (Prabodanie et al. 2014, 2010).

An upper bound on each bid/offer (S1) ensures that the quantity of permits cleared is within the maximum quantity specified by each participant. The compliance constraint (S2) specifies the relationship between the quantities of bids/offers accepted, the maximum DIN load allowed at Tully Heads and the initial allocation of DIN load permits. The maximum DIN load allowed, net of bids and/or offers accepted, must match the initial permit allocation for each participant i. The water quality constraint (S3) ensures that the DIN load limit at Tully Heads is not violated. DIN load from each grid cell i is weighted by grid cell i's transport coefficient to account for DIN removal by denitrification in the drainage network from the grid cell to Tully Heads.

The variables shown to the right of the constraints ($\theta_{ik}, \mu_i,$ and δ) are the associated shadow prices. The shadow price for the compliance constraint for each participant (μ_i) indicates the change in total net benefit from market trading (i.e. the change in the value of the objective function) which would arise if participant i were to receive another unit (kg) of DIN allowance. An additional kg of DIN given to participant i would increase DIN load at Tully Heads by d_i kg, where the total DIN load (L) is binding. At the optimum, the total value of the objective function will be reduced if participant i is given another kg of DIN allowance. Shadow price μ_i thus indicates the cost which would be imposed on market outcomes by increasing participant i's DIN allowance by an additional 1 kg. This result is based on the theory of marginal cost pricing (Prabodanie et al. 2010). Consequently, this μ_i is therefore the price that the market manager should charge participant i for the right to discharge an additional 1 kg of DIN from their paddock. The shadow price δ on the water quality constraint at Tully Heads (S3) represents the marginal change in the value of the objective function (i.e. the change in the total net benefit realised from market trading) which would result if the DIN load cap at Tully Heads were to be relaxed by 1 kg.

The dual formulation of the LP problem shows that participant i's price is given by $\mu_i = d_i\delta$. This indicates that the price paid for permits supplied to, or the price paid for permits bought from, participant i is adjusted by the linear program according to the impact which participant

i's DIN emissions have on the binding total DIN load constraint at Tully Heads. Permit prices need not be equal across market participants because DIN emissions from different grid cells have different impacts on DIN load at Tully Heads, depending on denitrification through the drainage network. It can also be shown from the dual formulation of the linear program that μ_i is at least equal to, or less than, the offer price for bids accepted from permit buyers, or μ_i is at least equal to, or more than, the reservation price for offers accepted from permit sellers.

A.2 Linear program with wetland credits

The linear program described above can easily be modified to incorporate N-credits from constructed (treatment) wetlands alongside purchases and sales of N-permits. This is implemented by adjusting the cell-specific compliance constraints and the water quality constraint at Tully Heads appropriately to accommodate N-credits. In other respects, and in interpretation, the linear program with wetland credits operates in a similar way to the linear program without wetland credits.

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