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Modelling environmental risk and land management tradeoffs in the Great Barrier Reef catchment

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We develop a catchment scale modeling framework to identify cost-effective strategies for joint onsite abatement and offsite mitigation of land-based pollution from agricultural activities that pose a risk to water quality in the Great Barrier Reef (GBR). An illustrative example of the Barron catchment in north Queensland is used to demonstrate an approach to specify social planner's problem for non-point source pollution management as a cost minimisation model to meet a specified reduction in land-based pollution emissions at the receiving waters of GBR. We focus on the tradeoffs between onsite pollution control and offsite pollution mitigation under a collective contract for nutrient reduction at a sub-catchment level and discuss implementation options.

Key words: non-point source pollution, water quality, land use, cost-effectiveness, coastal zone management

[*] The views presented in this paper, drawn from preliminary work in progress, are those of the authors and do not represent the official view of ABARE or the Australian Government

Introduction

The Great Barrier Reef World Heritage Area (GBR) is a multiple use resource with an estimated annual economic benefit of around $5.8 billion in 2004/05 to the Australian economy (Access Economics 2005). With the increasing value being placed on the environmental amenity of this natural resource by all users, particularly over the past three decades, greater emphasis is being placed on managing the environmental risks associated with land use in its catchments. This emphasis means that the marine and terrestrial resources in the GBR region are treated as a collective resource that is managed to maximise social welfare from a range of production and conservation activities. One of the most pressing public interest issues confronting the region is minimising potential water quality impacts on the GBR from land based pollution. Recent estimates suggest that around 80 per cent of marine pollution that enters the Reef as sediments, nutrients and chemicals originates from land based activities (Australian Government and the Queensland Government 2005). Grazing and cropping represents a major source of sediment and nutrients delivery to the GBR, while urban infrastructure development, agriculture, tourism and mining are also important drivers of land use change. While the exact impacts remain uncertain (Larcombe and Woolfe 1999), it is generally accepted that inshore reef areas are under threat and a reduction in land based pollution may reduce this risk and increase the resilience of the reef system to cope with other ecological threats.

The Reef Water Quality Protection Plan (the Reef Plan), introduced in 2003, has a goal of halting and reducing the decline in water quality entering the Reef, within ten years. This is to be achieved through actions that reduce the load of pollutants from diffuse sources entering the Reef, and by rehabilitating and conserving areas of Reef catchment that have a role in removing water-borne pollutants. In a broad sense, meeting these objectives calls for activities to reduce the risk of marine pollution through onsite abatement and offsite mitigation. Moreover, the Reef Plan follows an integrated coastal management framework to manage the risk of diffuse source pollutants entering the reef through catchment waterways. The Reef Plan and the Natural Heritage Trust that supports the activities of the Reef Plan place an emphasis on voluntary environmental management facilitated through science based risk assessment and economic incentives (Reef Plan 2003).

In this paper, we develop a modelling framework to determine cost-effective solutions for water pollution abatement in the GBR catchment. The focus is to determine the tradeoffs between onsite pollution control and offsite pollution mitigation under a collective contract for sediment reduction at a catchment level. We restrict our analysis to management options associated with agricultural land uses, although the analysis may be extended to cover other land uses. The paper begins with a discussion of the diffuse source pollution problem in the GBR and the challenges policy planners face when addressing those issues. The scope for cost-effective mitigation strategies is then discussed. The third section presents the conceptual framework and an illustrative model is then developed to address diffuse source pollution in the GBR as a collective source pollution problem. The paper concludes following a discussion on possible implementation issues.

Non-point source pollution in the GBR

Agricultural non-point source pollution entering the GBR is a production externality. This means individual land users' actions affect well being of the broader community, and these effects are not reflected in the costs or returns faced by land users. Because the polluters can pass the cost of pollution on to others, activities that seek to maximise farm profits, such as extensive grazing, application of fertilisers and agrochemicals that support intensive land uses, may in fact reduce social welfare through water quality impacts downstream. The disparate land users may emit only small amounts of undesirable byproducts, however, collectively, at a catchment or regional scale, they may generate significant levels of harmful material, sufficient to cause environmental damage downstream. Ecosystem damage occurs when the level of pollution exceeds the natural assimilatory capacity of the environment. Although pollution has a positive shadow value to farmers as they receive direct benefits from activities that, inadvertently, contribute to pollution (Chambers and Quiggin 1996), pollution increases costs to reef users, making it desirable to institute environmental protection, provided benefits of intervention exceeds costs.

In complete markets, landholders and reef users would be able to tradeoff the benefits and costs of reef uses with that of activities that may accelerate soil erosion, sediment deposition and nutrient runoff into the GBR. Prices paid, for example by agricultural users to gain access to land and water resources, would reflect the opportunity cost of environmental protection. Private marginal benefits and costs would equal social marginal benefits and costs.

Although markets could provide cost-effective ways of resolving environmental problems as well as providing flexibility to land users, there are a number of impediments. Market failures such as the presence of externalities, lack of clearly defined property rights, and asymmetric and incomplete information do not allow for efficient allocation of resources. For example, if property rights to natural resources such as the use of waterways to pass agricultural emissions downstream are not well defined, natural resources tend to be treated as 'free' goods, and their use often exceeds the social optimum. This is because the costs of using such resources can be passed on, in whole or in part, to other resource users and society at large. Moreover, when assessing the value of a resource, environmental costs or values such as biodiversity and aesthetic values are not determined in market transactions, therefore they are often ignored. Imperfect information on pollution pathways, uncertainties about private costs of pollution and about the response of polluters to policy instruments further complicate the search for market solutions (Borisova 2005), and introduce risks of policy failure.

Policy planner problem

When market failure exists, it may become appropriate for governments to intervene by implementing pollution control strategies. Intervention typically takes one or a combination of three main forms: suasion, direct regulation or market based instruments (MBI).

In determining policy responses, the choice of appropriate policy instruments is crucial to avoid worsening the existing market failure. Therefore, a number of factors need to be taken into account. The first is to identify the source of market failures that have led to resource degradation. Then, practical and workable options for action need to be chosen by assessing the costs of those options that can address the market failures, and determining the likelihood that a chosen option will deliver the desired outcome within the desired time frames and geographic scales. Where achieving a desired outcome is constrained by lack of incentives for individuals to participate, policy mechanisms such as group contracts may prove useful. For example, a team contract for nutrient reduction could be used to tie payments to individual land users based on the collective performance of all land users in a sub catchment.

Exclusive versus non-exclusive

When designing instruments to address externalities such as agricultural pollution, policy makers will need to consider the nature of benefits from mitigating the externality. For example, where the benefits of mitigation are private and exclusive, there will be an incentive for landholders to invest in mitigation, even in the absence of well-defined property rights (ABARE 2005).

There will be little incentive for the beneficiaries of mitigation to invest in mitigation of an externality where the benefits are nonexclusive. For example, an investment to improve water quality will potentially benefit all downstream users. This creates a free rider problem whereby downstream users who do not contribute to the costs of mitigation still gain the benefits from the investment. Under these circumstances, some form of private collective action or government intervention may be required to overcome the incentive to free ride. For example, land users within a sub-catchment may all agree to the introduction of a levy to improve water quality within their sub-catchment, in return for the right to conduct their farming operations. Where the benefits of mitigation are public and nonexclusive government intervention will most likely be needed to achieve the optimal level of investment in pollution mitigation (ABARE 2005).

When dealing with diffuse source pollution the most difficult problem for the policy planner is to identify the origin of pollution. Nutrient runoff from agricultural land, for example, may originate from numerous paddocks across an agricultural catchment. Therefore, it may be difficult to monitor trends over time because runoff conditions may vary across sites reflecting land use patterns and site characteristics. Nevertheless, with technological innovations, such as GIS technologies, it could be traced to a particular geographic extent, such as a sub-catchment, which makes it possible to separate pollution emissions across groups of land users. While this partly addresses the monitoring problems highlighted by Braden and Segerson (1993), for example, application of these technologies is also fraught with challenges (Jacobsen et al. 2001; Yang et al. 2003b).

One of the advantages offered by these technologies is that they offer cost-effective ways for tracing the diffuse source pollution through collective monitoring at a catchment or sub-catchment level, where measures need to be focused on categories of land based activities, rather than on numerous point discharges (Mallawaarachchi et al. 2002). The collective information would allow better design of collective action that can significantly reduce pollution loads at the catchment scale at relatively low cost. This is because, if we can acquire information about costs of abatement, the abatement action can be targeted to those areas where the pollution risk can be reduced most cheaply (Caruso 2001).

In the context of GBR, this is particularly important because studies indicate that 80 per cent of marine pollution, in terms of sediments and nutrients, comes from 30 per cent of the GBR catchment area (Productivity Commission 2003). This information provides the opportunity to target instruments to a group of high impact polluters in a particular catchment for cost-effective treatment of the pollution risk. Many studies have demonstrated the economic advantage in prioritizing the implementation of control measures over areas that generate the highest return for a given management strategy (for example; Dickinson et al. 1990; Lu et al. 2004; Ribaudo et al. 1999). Moreover, the ability to target policy instruments to specific 'hotspots', resembling a sub-catchment or a particular land use, is important to ensure that the benefits of pollution abatement are maximised for a given abatement cost (ABARE 2005; Mallawaarachchi et al. 2002). In this way, the policy planner could minimise monitoring expenditure through technological innovations such as GIS to effectively convert a diffuse source pollution problem to one resembling a point source pollution problem thus minimizing overall costs (Beare and Newby 2005; Mallawaarachchi et al. 2002). Although much of the point source pollution control principles would apply, this class of problems are more appropriately called a *collective source*.

Uncertainty

While the linkage between polluting sources and the ambient load at the receiving environment can be partly identified through technological innovation, for an extensive resource such as the GBR, the changes in ambient load and the consequent damage are unable to be detected with certainty (Brodie et al. 2005), and linking changes in ambient loads to actions taken within a collective source remain illusive. This is because many aspects of the complex interactions between alternative land uses and terrestrial, riverine, estuarine and marine ecosystems connected to the GBR remain poorly understood. For example, while well targeted changes to land use practices to mitigate erosion may reduce the mobilisation of sediment to the river system (Prosser et al. 2002), the timing and impact of any reduction of the negative impact of the pollution on marine ecosystems in the GBR lagoon is largely unknown (Williams et al. 2001). Although recent studies may prove beneficial in establishing the connection between land use change and environmental dynamics (Brodie and Mitchell 2006);(Roebeling 2006), inability to predict environmental responses to management changes makes it difficult to assess the benefits of environmental improvement and determine the required level of abatement effort as well as the potential acceptability of instruments chosen to achieve environmental improvements (Borisova 2005).

From the policy planners' perspective, uncertainty about the outcome of a policy action is particularly important when actions have irreversible consequences. Decisions that are regarded as irreversible typically involve large sunk costs. Large scale land clearing, for example, can be regarded as irreversible because reverting to the prior land use may only be possible over a long time frame. The fundamental asymmetry is that the decision not to undertake an action can be reversed, but once the action has been taken, the costs of reversing the action are usually high. In this instance, it has been argued that a more conservative approach to resource development should be taken (Krutilla and Fisher 1985) by, for example, taking additional time to acquire more information, in order to reduce the level of uncertainty. On the other hand, the longer the time delay between discernible improvement in the marine environment and the actual change in land use practices that determine the level of pollutants entering the reef, the higher the uncertainty that any particular action will yield desired results. For example, if marine ecosystem health falls below a critical level in the GBR, minimum thresholds for a species to reproduce may not be reached and it could become extinct. Therefore changes to environmental policy have often been recommended on precautionary grounds.

While uncertainty does not justify inaction, nor does the precautionary principle that often guides environmental decisions justify immediate actions (Peterson 2006). However, once such action is considered beneficial, such as in the case of the Reef Plan, emphasis needs to be placed on how to reduce the risk of any chosen action not delivering the intended outcome. One approach to managing this risk is to develop a portfolio of policy actions that seek to offset some of the key uncertainties against each other and spread the risk between the parties, because different policy instruments may place different risks on the costs and benefits borne by different parties. For example, regulations and taxes impose a higher cost burden on landholders, whereas subsidies place a greater cost burden on taxpayers and the general public. The nature of the intended benefits may also be important when considering alternative actions with uncertain outcomes. For example, if the benefits of the proposed action are public or non-exclusive, then it is appropriate that society bears the risk if the chosen action did not deliver a better outcome than some other, or no, intervention. On the other hand, if the benefits are largely private or exclusive, those exclusive beneficiaries such as landholders and other resource users ought to bear the risk, rather than the general public.

Setting environmental targets

The next issue concerning the policy planner is to set appropriate environmental targets which are neither overambitious to be achievable or too low to be effective. Focusing on cost effective strategies in setting environmental targets can ensure that environmental targets are not overly costly, and therefore are more likely to be met as well as provide desired environmental improvements.

In a very broad sense, an optimal environmental target is such a level of pollution reduction that is desired by society, being potentially Pareto optimal. The socially efficient level of pollution is typically not zero, as it involves trading off the costs and benefits of pollution abatement. In the absence of transaction costs, an efficient level of pollution will occur at the point where the marginal cost of damage caused by pollution is equal to the marginal cost of abating this pollution (ABARE 2005). In determining the costs it is important to also understand the natural assimilatory capacity of the receiving systems and the incremental change in pollutant loads that result from land use changes.

From the polluter point of view targets should be set at a level consistent with polluters' costs of abatement as determined by relevant technological and resources constraints. In determining appropriate pollution abatement targets, information about bio-physical factors influencing pollution generation and transport, the relationship between land use and pollution emission, costs and benefits of different abatement options as well as information about technological changes and innovation should be investigated.

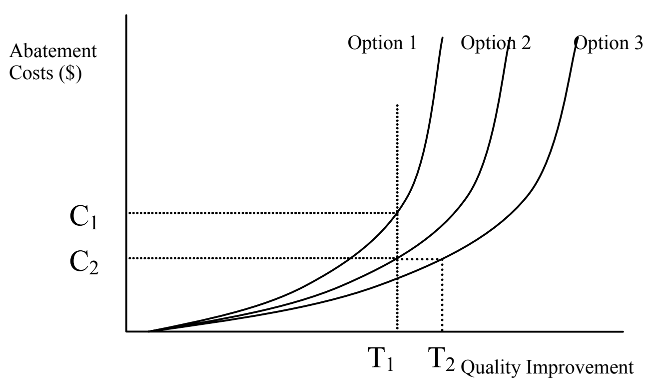
It has been recognized that environmental targets should be dynamic in nature and should change in line with technology changes and innovation (Snower 1982). However, Requate and Unold (2003) argue that the set of available abatement options does not necessarily expand with technological changes and innovation. This is because the adoption of new technology often involves high fixed costs. While future technological change cannot be ascertained *a priori*, the challenge is to set targets that encourage innovations in reducing the overall costs of managing the externality.

Economic analysis that takes into account the parameters of the polluting environment, polluter responses and pollution pathways can help policy planners set targets that are achievable being not overly costly as well as effective because of a high likelihood of environmental improvements.

Determining efficient water pollution reduction

The presence of externalities, heterogeneity of resources and differences in skills and knowledge of land users means that determining a socially optimal resource allocation is at best impractical. The major difficulty that impedes the pursuit of optimality is the issue involved in determining damage functions and evaluating the benefits of environmental policy. While the costs of reducing pollution can be measured with some degree of accuracy, despite advances in non-market valuation techniques the environmental benefits are difficult to quantify and remain controversial. Given the difficulty in measuring environmental net benefits in its entirety, economic analyses mostly focuses on achieving efficiency without optimality. As Baumol and Oates (1988) suggest the information requirement for optimal policy design is beyond grasp, and the recourse is to use standards that serve as targets for environmental quality coupled with fiscal measures and other complementary instruments as means to attain these standards. These measures, when properly designed, can enhance the efficiency of a public program to control externalities.

Figure 1. Cost minimization model.



The analytics of the decision making process is similar to that illustrated in figure 1. In attempting to achieve an externally imposed environmental quality target at least cost, a decision maker has, in this illustration, three different options to choose from. Option 1 represents the situation where onsite pollution abatement control was implemented. Option 2 represents the combined onsite and offsite pollution abatements that may offer lower cost of achieving the environmental target T_1. Option 3 represents the situation where a technological innovation further extends capacity for pollution mitigation to T_2. at the same cost.

In this study, we extend a version of the Mallawaarachchi and Quiggin (2001) land allocation model, to explicitly incorporate onsite and offsite pollution mitigation options. The cost minimization model follows Baumol and Oates (1988) for pollution abatement, using insights from Baresel et al. (2006), Khana et al. (2003) and Yang et al. (2003a).

Identification of costs that matter

The costs of intervention in water pollution mitigation include two types: transaction cost and abatement cost.

Transaction costs

Transaction costs include the cost of acquiring information on the sources and impacts of pollution and on the cost of abatement as well as costs of administering, monitoring and enforcing compliance with a particular policy. The overall transactions cost can be reduced by technological innovation, contract design and facilitation of information networks.

Abatement costs

Abatement cost includes the direct costs of complying with a policy, as well as indirect costs such as an opportunity cost in terms of forgone income. For example, establishing buffer setbacks along rivers and streams to reduce sediment runoff from grazing land will incur an opportunity cost in terms of reduced income due to the exclusion of stock from this land, as well as the direct costs of fencing off the setback and installing water points and pipe. These costs tend to vary across landholders. For example, the opportunity costs of excluding stock from a hectare of land in an area with low carrying capacity are lower in comparison to an area with high carrying capacity (ABARE 2005).

Therefore examination of cost effective options for diffuse source pollution abatement, as proposed in this framework, will include the assessment of best management options and potential investments in technologies with a potential for cost savings. In seeking these cost savings, understanding the production environment, pollution pathways and the broader landscape characteristics would allow greater scope to design efficient mechanisms. For example, in collectively meeting an externally imposed target for water quality improvement at a catchment level, it may be desirable to split the compliance burden between onsite abatement and offsite mitigation.

The core objective of Reef Plan is to reduce sediment and nutrient outflow from GBR catchments. This objective needs to be met through activities that support efficient use of regional natural resources. To this end, a combined onsite abatement and offsite mitigation strategy involving changes to land use and land cover management on farm, and construction of engineering works midstream to capture sediment and embedded nutrients at strategic points along the sediment delivery pathway, could allow a degree of flexibility in balancing environmental risk and economic tradeoffs. In the absence of perfect knowledge to guide efficient allocations, this approach could also offer more cost-effective resource allocations (Beare et al. 2003; Jacobsen and Mallawaarachchi 2002). Moreover, such solutions may offer a quick-fix in generating measurable and certain reductions in pollution outflow in the immediate term, while putting in place measures that are likely to ensure a reduced pollution outflow in the longer term.

If such a split system were in place, individual land users seeking least cost options for pollution abatement will face two types of tradeoffs: namely tradeoffs relating to the choice of land use on farm; and tradeoffs between the level of onsite pollution control and offsite mitigation. While each land user could determine the optimal level of onsite abatement based on own information, the cost of joining an offsite mitigation facility will set a ceiling for the opportunity costs of onsite mitigation. We will revert to this point later in this paper.

Pollution abatement tradeoffs

Onsite tradeoffs

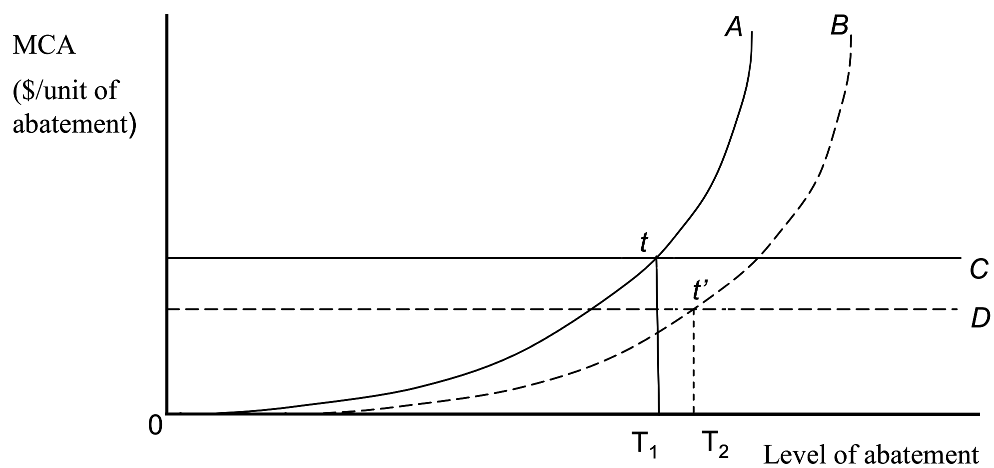
Because agricultural output and pollution emissions are joint products, pollution emission commands its own shadow price at the margin, representing the cost of reducing pollution. Duality theory may then be used to estimate the costs of agricultural pollution reduction and to determine the economically efficient level of abatement.

In determining economically efficient solutions for agricultural pollution abatement, the efficiency conditions that represent economic tradeoffs between farm profitability and pollution discharge include:

- for each polluting *input* on each site, the marginal net private benefit from the use of this input should equal or exceed the expected marginal external damages from the use of the input; (Ribaudo et al. 1999).

- a land should be brought into production as long as returns on this land just exceed the costs of management, including pollution mitigation.

If we assume that a land user's economic goal was to maximise net revenues, with no private benefits from pollution control, he would not have the incentive to reduce pollution emissions on his own. This is because any reduction in pollution emission would result in increasing costs to the land user as reflected by the increasing slope of the marginal abatement curves *A* and *B* (figure 2) for onsite abatement. Imposing a water quality target may necessitate a move away from conventional practices to those using fewer polluting inputs, adding filter strips, and even retiring cropland or investment in offsite abatement technologies. The higher the level of water quality protection sought, the greater is the marginal cost of pollution abatement per unit of abatement effort. A too high a cost of onsite pollution abatement may increase the risk of not achieving the desired pollution reduction target. Therefore, investing in offsite abatement technologies (represented by *C* and *D*) may be one alternative to reduce the overall cost of pollution reduction facing a landholder. This entails consideration of tradeoffs between onsite and offsite pollution mitigation.



MCA = marginal cost of abatement

Figure 2: Onsite and offsite pollution tradeoffs

Onsite and offsite tradeoffs

A policy planner developing pollution management policy faces two basic options. First, land managers can be persuaded to change practices to minimise the creation of the externality, thus encouraging prevention at source. Second, as pollution only becomes a cause of disutility at the receiving environment, action can be taken to mitigate the externality through appropriate treatment offsite, before pollution reaches the receiving environment. Such a split system may allow individual landholders to direct their expenditure on pollution abatement onsite and offsite, thus permitting efficiencies in attaining an overall pollution abatement goal.

The tradeoffs between onsite and offsite pollution abatement is illustrated in figure 2. The schedules *A* and *B* represent the increasing marginal cost of onsite pollution abatement under two technologies. Whereas, the lines *C* and *D* represent the fixed cost of offsite pollution abatement to meet two different water quality targets. The shape of curve *b* implies that higher the level of water quality protection the higher the marginal cost of pollution abatement. In this instance higher water protection targets may encourage alternative pollution abatement methods such as offsite technologies.

A land user seeking to maximise net benefits will choose the option that provides the lowest cost of pollution abatement reflecting farm specific characteristics. The decision rule is that a land user would undertake onsite abatement while the marginal cost of pollution abatement on farm is less than or equal to the marginal cost of offsite pollution abatement. The switching point, where the onsite and offsite pollution control costs of achieving target T_1 are equal, is represented at point *t*.

Moreover, innovation or a technological improvement represented by *B* and *D* may offer grater opportunity for on farm abatement cost reduction. If the innovation reduces the cost of onsite abatement more abatement will occur onsite than offsite, or, alternatively, higher water quality target T_2 can be achieved at the same cost. The innovation in offsite abatement technology, in this case, reduces the overall cost of meeting a more stringent target.

Following a brief description of the study region, in the next section we provide an outline of a model that can be used to determine cost effective pollution abatement strategies for a GBR catchment such as the Barron (figure 3).

Study region

The Barron River catchment located in the Wet Tropics Region of North Queensland has been chosen as a study area for application of the model to examine cost effective pollution management options to meet water quality objectives. The Baron represents an area of about 2,200 km2 (11 per cent of the total Great Barrier Reef catchment area).

Tourism and agriculture are important economic activities in the Baron catchment. The Baron River, flows through forests, agricultural lands, wetlands and the urban areas before entering the Great Barrier Reef lagoon, and is considered one of the wet tropics streams most heavily utilised and impacted by land use change.

Agriculture has been identified as a main source of pollution of the water steams in this catchment. The clearance of inland area for agricultural use, over-grazing, and poor land-use practices, have been identified as risk factors contributing to soil erosion and saltation of rivers and sediment run-off. Moreover much of these sediments are believed to be contaminated with nutrients sourced from fertilisers, crop residues and mill wastes, and pesticide residues going onto coral reefs (Productivity Commission 2003).

Agricultural production occupies almost 45 per cent of the region with grazing taking almost 30 per cent of the catchment and cropping taking up more than 10 per cent. The main agricultural crops in this region are cereals, oil seeds, sugarcane, tobacco and horticulture crops. Grazing is mostly concentrated in the upper catchment while cropping occurs mainly in the middle and lower catchments; protected areas cover 22 per cent of the catchment and are located in the North West part of the region (Barron River Integrated Catchment Management Association Inc. 2006).

The gross value of agricultural production (GVP) in this region was $279 million in 2001 (ABS 2001). In terms of GVP, horticulture industry ranks first in the region, taking up about 40 per cent the regional GVP. The beef, sugar and dairy industries account for 18 per cent and 12 per cent respectively (ABS 2001).

Modelling framework

Consider a catchment subdivided into $m = 1, \ldots, M$ sub-catchments, based on a biophysical model of the stream network that accounts for sediment and nutrient flows that drain into a water body through a single tributary of a river. Each sub-catchment is divided into $k = 1, \ldots, k_m$ land units. Each land unit is homogeneous in its site characteristics and has an area of a_k^m. Each land unit is used for a number of activities including non production activities $j = 1, \ldots, J$; and each activity uses inputs $i = 1, \ldots, I$. The total area used for agriculture in each sub-catchment is A_m.

Thus $$\sum_{j=1}^{J}\sum_{i=1}^{I} x_{ijk}^m = a_k^m \tag{1}$$

$$\sum_{k=1}^{k_m} a_k = A_m \tag{2}$$

where, x_{ijk}^{m} denotes the area allocated to activity *j*.

The sediment flow generated per unit area s_{ijk}^{m} is a function of land management, in this case represented by the choice of input for activity *j*. Assuming all farm activities allow for some on-farm interception of sediments, the proportion of sediments leaving a land unit is denoted by δ_{ijk}^{m}.

The total sediment load generated by agricultural activity in each sub-catchment, S_{m}^{0} is derived from all current agricultural activities (hence subscript *c*) across all land units in that sub-catchment[1]. Therefore;

$$S_{m}^{0} = \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} s_{ij_ck}^{m} . x_{ij_ck}^{m} . \delta_{ij_ck}^{m} \qquad (3)$$

The sediment load is a joint product of agricultural activity *j*. The regulator monitors the levels of agricultural run-off at each sub-catchment boundary from existing land uses denoted j_c. The regulator has no information about sediment loads from individual land units. Information on individual land characteristics is publicly available as well as a set of best management practices that can be used to mitigate sediment discharges from a given land unit. The targeted reduction in sediment discharges from the sub-catchment is $\tilde{\mathrm{T}}_m$, which is to be applied to sediment discharges from current land uses S_{m}^{0}.

The costs involved in mitigating sediment discharges can be defined as the loss in quasi rent, from its current level π_{ij_ck} (revenue minus variable costs) due to changes in agricultural practices. A social planner seeking to achieve a targeted reduction in sediments ($\tilde{\mathrm{T}}_m$) from a given sub-catchment at a particular compliance boundary at least cost, faces the following problem.

Minimise $$\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} \pi_{ij_ck}^{m} x_{ij_ck}^{m} - \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} \pi_{ijk}^{m} x_{ijk}^{m} \qquad (4)$$

Subject to

$$S_{m}^{0} - \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} s_{ijk}^{m} . x_{ijk}^{m} . \delta_{ijk}^{m} \geq \tilde{\mathrm{T}}_m \qquad (5)$$

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[1] Although the numerical model would account for sediment interception based on the location of the land unit in the catena, such details are omitted here.

$$A_m - \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} x_{ijk}^{m} = 0, \;\; \forall i, j \; , \tag{6}$$

where $\pi_{ij_ck}^{m}$ is the quasi rent per hectare achieved under current land use and π_{ijk}^{m} is the quasi rent per hectare achievable under different land uses including the current land use.

The offsite pollution abatement cost for a given level of abatement is a fixed cost $C_m\left(S_m^1\right)$. The total sediment load at the downstream interception facility S_m^1 is derived from all agricultural activities *j* across all land units in that sub-catchment.

Therefore
$$\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} s_{ijk}^{m}.x_{ijk}^{m}.\delta_{ijk}^{m} \le S_m^1 \tag{7}$$

The associated optimisation problem for onsite and offsite pollution abatement is given by:

Minimise
$$\left[\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} \pi_{ij_ck}^{m}\, x_{ij_ck}^{m} - \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} \pi_{ijk}^{m}\, x_{ijk}^{m}\right] + C_m\left(S_m^1\right) \tag{8}$$

Subject to

$$S_m^0 - \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} s_{ijk}^{m}.x_{ijk}^{m}.\delta_{ijk}^{m} - S_m^1 \ge \tilde{\mathrm{T}}_m \tag{9}$$

$$A_m - \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} x_{ijk}^{m} = 0, \;\; \forall i, j \tag{10}$$

$$\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I} s_{ijk}^{m}.x_{ijk}^{m}.\delta_{ijk}^{m} \le S_m^1 \tag{7}$$

The distribution of costs between onsite and offsite abatement depends on the marginal costs of pollution abatement. If the marginal cost of abatement through defensive management onsite is higher than the marginal cost of abatement through mitigation downstream the more abatement would occur downstream in the optimal solution.

Data needs

The implementation of this model will require a range of biophysical and land use data at relevant spatial resolutions to be able to map activities relating to water quality and land management at a catchment level. Within a catchment, the project will cover all land uses and work at a landscape scale represented by homogeneous land parcels or land units. This will require detailed GIS datasets on land use, infrastructure networks, socio-demographic and economic data to provide an accurate and comprehensive view of GBR catchment land-use influencing the delivery of pollutants to the Reef. . Data including: soil type, land cover, rainfall, terrain, land use, would be able to be sourced from existing sources whereas data on farm management practices will need to be collected through detailed farm surveys. Data on water quality would be sourced initially from existing monitoring activities. Continuos water quality and sediment monitoring at strategic locations will be needed to support ongoing project implementation.

The socio-economic data will be collected by ABARE using face-to-face farm household surveys. The survey will be aligned to cadastral boundaries at farm/paddock level and will allow spatial referencing of farm financial, biophysical and socio-demographic data with other resource information such as soil and land use maps in a GIS.

Effective implementation of this framework will thus require a facilitated process of co-research, involving regional planners and local technical experts and the local community. It is envisaged that the research team will work closely with the Far North Queensland NRM Board and the Reef Plan implementing agencies, such as the Queensland state natural resource management agencies, the Great Barrier Reef Marine Park Authority, CSIRO and Department of Agriculture, Fisheries and Forestry and the Department of the Environment and Water Resources.

Implementation

The implementation of this model as a case study of the Baron catchment in north Queensland will follow an integrated economic, environmental and GIS modelling framework that incorporates land use and sediment abatement as joint decisions. This approach extends the model development in Mallawaarachchi and Quiggin (2001) by essentially incorporating sediment abatement objectives into the activity mix as foreshadowed in Jacobsen and Mallawaarachchi (2002). The first step is to simulate the current land use system and assess the potential sediment contribution associated with current land use. Then land use allocations that incorporate best management practices consistent with the biophysical characteristics of each site will be simulated and their contribution to sediment abatement estimated. Then the simulations can be extended to include arbitrary levels of pollution abatement targets to understand the nature of production-pollution abatement tradeoffs.

This will provide, at the outset, a basis to explore opportunity costs in undertaking joint onsite and offsite pollution abatement in the Baron catchment. This information will then be used in the design of a collective contract that identifies cost-effective strategies for joint onsite and offsite mitigation of land-based pollution from agricultural activities that pose a risk to water quality in the GBR. By expressing production and pollution abatement costs as a function of land management we create a model that internalises the externality. Splitting the costs of meeting the externality onsite and offsite gives us a transparent tool for determining the potential for sharing costs, between the local community and land users, for addressing environmental risk on the GBR. The regional natural resource management board will provide a useful mechanism to coordinate public participation in the refinement of the proposed strategy.

Pooling mitigation effort through collective contracts

An important question that arises in investigating the feasibility for joint onsite and offsite pollution mitigation is how to ensure increased risk management performance among all catchment land users. We can explore this issue in relation to a collective contract, a mechanism that can be used to coordinate individual action. Some key issues are discussed below.

Design and construction issues aside, benefits of an offsite pollution mitigation facility, such as a constructed wetland, depend on both the intrinsic efficiency of the facility to treat pollution and the degree of participation by land users. The other important determinant of its effectiveness is the level of pre-treatment of material directed to the facility – the level of risk sharing, a function of onsite pollution abatement. The provider of the facility will face several issues: gaining knowledge about the quality of material expected in the facility (adverse selection), ensuring correct choice of on-farm practices once the entry is granted (moral hazard), gaining knowledge about the outcome of offsite treatment with regard to meeting the downstream pollution target (costly state verification), and to ensure that the utility fees are enforceable.

In the modelling framework discussed earlier, if individual land users are to deviate from the optimal land use pattern, the planner does not have accurate information on individual performance. While the actual soil erosion and nutrient removal is not observable to either the land user or the planner, the soil nutrient and sediment runoff potential can be evaluated from information on site characteristics which are known *a priori*. This will substantially address the adverse selection problem.

The policy planner still faces a risk of moral hazard, because individual land users may deviate from optimal risk management and thus increase the risk of failure in the pooled downstream mitigation efforts. The other factor which determines the performance is the stochastic nature of abatement efficiency because efficiency depends partly on random events such as local climatic conditions. As discussed earlier, because the utility fee for the mitigation facility will act as a ceiling for onsite-abatement, the planner could use utility fees as a key instrument to drive polluter performance.

If this mechanism were to act as a useful tool that distributes the risk between different parties and abatement methods, which consequently minimizes the risk and provides incentive for land users to reduce pollution emissions, a planner needs to design a contract mechanism consistent with incentive compatibility and individual rationality constraints. That will ensure the contract produces truthful revelation of the participants' motives and the participants find it profitable to accept the contract. Moreover, a properly designed collective contract at each small sub-catchment scale could offer better regional co-ordination of management efforts, increase the participation rate and provide better internal information. Moreover, the information about the costs of compliance and benefits of abatement for individual land units that can be gained from model simulations can further dissipate moral hazard and adverse selection problems. This in turn could allow future adjustment of environmental targets and better distribution of compliance costs, making abatement actions more affordable. For those who may not benefit from participation, on their own, side payments may be made to encourage participation.

While the modelling framework discussed in this paper is essentially virtual, in this project, in partnership with the Far North Queensland Natural Resource Management Board, the modelling framework discussed above will be used to determine and test out various sediment loss, sediment abatement and mitigation cost assumptions to better understand the role of technological constraints, incentives payments and the role of monitoring mechanisms in the design of practical measures aimed at minimising the risk to GBR water quality from land use activities in the Baron catchment.

Concluding comments

In this paper, we have presented a modelling framework designed to understand factors influencing cost-effective mitigation of non-point source pollution risk in a coastal catchment. The model design focuses on using information technologies and incentive mechanisms to encourage risk averse land users to coordinate to provide a social good (pollution abatement) in the presence of moral hazard, hidden information and risk sharing problems characteristic to non-point source pollution problems. The catchment scale model outlined provides a useful tool to explore cost-effective strategies for joint onsite and offsite pollution abatement under a voluntary collective contract where land users, the broader community and governments could jointly seek cooperative solutions that has the potential to maximise net social welfare. Although the modelling framework has been developed using GBR as an example, it is also applicable for the analysis of pollution management problems in other contexts.

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