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Efficiency of alternative property right allocations when farmers produce multiple environmental goods under the condition of economies of scope*

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The efficiency implications of different property right allocations when two environmental goods can be produced under the condition of economies of scope are analysed. It is assumed that an environmental agency – acting on behalf of the community – employs an auction-based mechanism to buy biodiversity services from farmers. However, farmers' production of biodiversity produces a second good as a by-product (e.g., mitigation of a river pollutant) that is valued by point-source emitters who are engaged in a pollution trading market. The efficiency implications of allocating the property right of the good, mitigation, to either the agency or farmers are analysed. If the agency owns the mitigation then the agency can sell mitigation to point-source emitters, offsetting the cost of biodiversity. If farmers own mitigation, then they sell it directly to point-source emitters. Assuming similar transaction costs associated with each property-right allocation, allocating the property right to farmers improves efficiency, as farmers take account of their private information to make profit-maximising decisions about the supply of biodiversity and mitigation; the agency would have trouble accessing this private information.

1. Introduction

Acting in their own interests, private managers make choices that meet private goals but may fall short of society's expectations about the environment. This problem is not new and policy makers have employed a range of mechanisms including education and awareness programs, legislation and planning, input subsidies and tax incentives to address this issue. More recently, there has been interest in applying market-based mechanisms to environmental problems. Sometimes this is termed the 'creation of

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environmental markets' (e.g., see, Aretino *et al.* 2001). From an economist's perspective, these market-based mechanisms include tradable emission permits (see Tietenberg 1985) and auctions of conservation contracts (see Latacz-Lohmann and Van der Hamsvoort 1997). The heightened interest in market-based mechanisms has occurred for (at least) three reasons. The first is that economists have developed mechanisms to deal with asymmetric information problems where they exist (see Myerson 1999). The second is that there is a much higher probability that environmental scientists and engineers can provide the information needed to make market-based approaches viable. The third is that governments have tended to step back from direct involvement in the microeconomy in recent years.

However, policy makers cannot use a 'one size fits all' approach when considering the use of market-based mechanisms to solve environmental problems. Rather, they need to consider the particular characteristics of the environmental goods in question. One such characteristic is that many environmental goods are linked via biophysical relationships. Hence, the action of one player may affect many other (different types of) players. For example, Heaney *et al.* (2000) have estimated the impact of one land management action – planting trees – on the rate of land degradation caused by salinisation, the volume of run-off water into water catchments used for irrigation and the impact on in-stream salinity.[1] The introduction of trees could also influence carbon sequestration and nutrient movement, and in some cases improve the supply of habitat. Hampicke and Roth (2000) state that farmers are 'joint producers of private commodity goods ... and of public goods associated with the countryside and conservation'.

The fact that several environmental goods may be produced via one action – as with the planting trees example above – means that the goods have certain economic properties. Specifically, environmental goods may be produced under the condition of economies of scope. There are economies of scope in production when one firm can produce two outputs, at specified quantities, at less total cost than two specialised firms (Baumol *et al.* 1988).[2] Baumol, Panzar and Willig (BPW) examine the nature of equilibrium when there are economies of scope, assuming that the relevant goods are sold into competitive private markets. In the BPW framework, the relevant private goods have well-defined property rights; the property right to each good is owned by the producing firm.

Policy makers that are creating environmental markets (such as auctions or tradable permits) need to consider property-right allocations, as property

[1] Trees increase evapo-transpiration and reduce accessions to groundwater.

[2] A more formal definition is given in the Appendix.

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rights are not always well defined in these circumstances. In fact, the role of policy makers is, in part, to allocate property rights in a way that facilitates better outcomes, at least from the policy maker's point of view. Economists would argue that a key consideration for a policy maker who is allocating property rights should be efficiency.

The Coase theorem – which is an interpretation of the article by Coase (1960), 'The problem of social cost' – is commonly viewed as a statement about the efficiency of bargaining in the absence of transaction costs. Specifically, the Coase theorem is said to imply that if property rights are well defined, and transaction costs are zero, then private agents will bargain to reach an efficient solution. Further, given zero transaction costs, the manner in which property rights are allocated affects the distribution of an outcome, but not the efficiency of the outcome.

However, several authors have challenged this conclusion using the argument that the presence of asymmetric information affects efficiency outcomes (Neeman 1999; McKelvey and Page 2000). Further, the Coase Theorem implies that if there are positive transaction costs, then the structure of property rights will affect efficiency. Hence, there would seem to be a compelling reason for policy makers creating environmental markets to carefully consider the structure of property rights.

In the present paper we examine how property-right structures affect efficiency, given that one action by a farmer produces two environmental goods: biodiversity and mitigation. Biodiversity is valued by an environmental agency. Mitigation is valued by point-source emitters (PSE) engaged in a tradable pollution market. A farmer can produce both of these environmental goods on one parcel of land; in other words, these two environmental goods are produced under the condition of economies of scope. We consider the allocation of property rights in a model that combines two mechanisms: tradable permits and auctions for biodiversity.[3] These two mechanisms are 'linked' by the fact that auctions for biodiversity produce mitigation as a by-product, which could be valuable to PSE engaged in a pollution permit trading system.

The property right for mitigation could be allocated to either (i) farmers, who produce mitigation when they provide biodiversity, or (ii) the agency that pays for biodiversity and prompts farmers to produce mitigation as a by-product. Our hypothesis is that there will be an efficiency gain if the property right for mitigation is given to farmers rather than the agency. The

[3] In part, the choice of these mechanisms could be motivated by the presence of asymmetric information and transaction costs. For example, an auction for biodiversity (as per Latacz-Lohmann and Van der Hamsvoort 1997) could be viewed as a way that an agency can get farmers to reveal some private information about opportunity costs, and to minimise the transaction costs of engaging a large number of farmers.

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reason that allocating the property right to farmers could be more efficient is that each farmer has private information about his optimal production level of mitigation.

In Section 2 we provide some background and context for the paper. In Section 3 we present our model. In Section 4 we give the results followed by a brief discussion. In Section 5 we provide a summary, and point to some areas for further research.

2. Market for environmental goods and services

There are three types of players in our model: farmers, PSE and an environmental agency.

Farmers use land to produce three goods: agricultural output, biodiversity and mitigation of pollution. We call the latter two 'environmental goods'. Agricultural output is competitive for land with the two environmental goods. That is, a farmer who increases his (land allocated to) agricultural production would need to reduce his production of at least one environmental good. The two environmental goods can, however, come from the same parcel of land. Specifically, the production of biodiversity leads to mitigation. For example, if a farmer takes a unit of land out of agricultural production and puts it towards biodiversity management, this reduces his total volume of agricultural production and hence his use of fertiliser and herbicide. This, in turn, reduces the run-off of these substances into a stream; it produces the good that we call 'mitigation'.

Although the provision of biodiversity produces mitigation, the reverse is not true: mitigation does not necessarily produce biodiversity. Biodiversity requires specific areas of land. This assumption could be viewed as follows: biodiversity requires active management, whereas mitigation just requires the absence of agriculture. For many years in the USA Conservation Reserve Program (CRP), farmers 'set aside' land, that is, ceased to use the land for agricultural production (Latacz-Lohmann & Van der Hamsvoort 1997; Feather *et al.* 1999). This did not produce any biodiversity benefits. Recently however, the USDA has required that farmers entering the CRP actively manage their land, for example, by providing habitat services. This active management has helped to provide habitat for some native fauna, in contrast to the previous 'set aside' policy.

Point-source emitters operate within a tradable pollution market. An environmental agency legislates a cap on aggregate pollution. The agency makes an initial allocation of permits to polluting firms. The initial allocation is equal to the cap. Each firm holds a certain number of pollution permits and each permit allows the firm to pollute one unit. Hence, the number of permits each firm holds gives it the right to pollute some share

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of the total cap (see Tietenberg 1985). Firms cannot pollute beyond their permit holding. Firms can trade permits as they see fit. In this sense, a pollution permit could be seen as a private good: it is excludable and rival. Each firm reveals its demand/supply for permits by trading in the pollution market. Hence, the demand for pollution permits is decentralised.

This trading scheme could be (e.g.) for river pollution into a bay. If the cap is set on the quantity of pollution that enters the bay, then each PSE must hold a permit for every unit of pollution that it puts into the bay. As explained, farmers can reduce (mitigate) their pollution into the bay by reducing agricultural production. If there is some system to quantify farmers' mitigation – such as a biophysical model – then this quantity could be transferred to PSE. Point-source emitters would be interested in buying mitigation from farmers if it were offered at competitive prices. In other words, farmers' mitigation produces additional pollution permits. Farmers' production of these permits would allow PSE to expand production beyond the constraint imposed by a legislated cap, but without any increase in the amount of pollution entering, for instance, a watershed. If farmers' supply of mitigation reduces the cost of pollution permits, then PSE reap a 'consumer surplus', or 'gains from trade'.

An environmental agency targets biodiversity using an auction mechanism, as advocated by Latacz-Lohmann and Van der Hamsvoort (1997). The agency uses an auction because there is asymmetrical information regarding a biodiversity exchange: farmers have private information about their cost of undertaking biodiversity management and the agency has private information about its biodiversity preferences. The auction allows the agency to obtain information from farmers about their private costs (albeit imperfectly).

The agency is willing to pay farmers for biodiversity management if they divert land away from agriculture. Demand for biodiversity is centralised, in that only the agency buys biodiversity: there is no secondary market for biodiversity. In the pollution trading market, the demand (for pollution permits) is completely decentralised; PSE express their demand via trading. Hence the good, 'biodiversity', differs from the good, 'mitigation'. The demand revelation problem for biodiversity is not completely resolved, even if an agency chooses a biodiversity target, such as a safe minimum standard (see Bishop 1978).

We assume that the agency chooses a certain parcel of land on each farm that could be used to provide biodiversity services. Each farmer then decides the price (bid in the auction) at which he is willing to supply biodiversity. He will base his bid on his opportunity cost of supply, that is, on the opportunity cost of offering land towards biodiversity and away from other profitable activity (agriculture). For example, land might be allocated

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to the conservation of native vegetation (flora), and the provision of habitat for native fauna. This is similar to the BushTender scheme that was trialed by the then Victorian Department of Natural Resources and Environment in Victoria (NRE), which is explained in Stoneham *et al.* (2002).[4] However, there is a key difference: in BushTender, NRE focused on the management of existing remnants so that farmers did not have to divert land away from agricultural production. As a result, we would not expect that a scheme such as BushTender would reduce agricultural production to any significant extent, although there could be some effects on agricultural production if BushTender diverted farmers' scarce labour input.

We use a model of this environmental market to consider two approaches to the allocation of property rights. First, the agency takes possession of any mitigation it receives through the purchase of biodiversity: the 'agency property right' case (APR). In APR, the agency buys biodiversity and appropriates the right to the mitigation that is produced as a by-product. Farmers effectively sell one environmental good in this scheme: biodiversity. That is, farmers never 'own' the mitigation (pollution permits) that they produce as a by-product of the auction. Instead, the agency calculates the quantity of mitigation that comes from farms providing biodiversity services, and it sells this quantity into the tradable pollution market. The agency uses this revenue to offset its budgetary cost of obtaining biodiversity. Farmers analyse the agency's request for land to be put towards biodiversity, and then bid based on their forgone agricultural profit.

Second, the agency allows farmers to sell mitigation directly to PSE: the 'farmer property right' case (FPR). In FPR, as farmers own mitigation, this will affect their agricultural production, irrespective of the biodiversity auction. A farmer will start from a position where he maximises his agriculture-plus-mitigation profit. Hence, FPR could be viewed as a two-stage process. First, a farmer looks at the relative returns from agriculture and mitigation, decides on the amount of land to allocate to both and hence decides on the output of both goods. Then the farmer decides on what bid to put into the biodiversity auction. In his bid, he considers the effect that producing biodiversity may have on his production of mitigation and agricultural output.

It is implied in FPR that each farmer has information about the quantity of mitigation he produces by diverting land away from agricultural production. In other words, in FPR we assume that an agency undertakes some sophisticated central process (like hydrological modelling) to determine the mitigation quantity that would be produced on each farm,

[4] The Victorian Department of Natural Resources and Environment was split in December 2002. The agency now in charge of the BushTender trial is called the Department of Sustainability and Environment.

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given each farmer's nominated land-use pattern. Then, the agency informs each farmer about the quantity of mitigation he produces. Alternatively, the case where farmers do not have this information, or are unable to apply it in a market context, could be seen as analogous to the situation in APR.

We use simulation to analyse the effect – on economic surplus (efficiency) – of the different property rights structures: APR and FPR. We consider the economic surplus outcomes in the light of agency incentives. In APR, the agency can generate revenue from selling mitigation into the pollution market. Although the agency may initially have the aim of selling the mitigation that it receives as a by-product of biodiversity procurement, it may gradually alter its aim to maximising mitigation revenue thus potentially reducing economic surplus. Hence, policy makers' choice regarding property rights will affect institutional incentives, and efficiency outcomes.

3. Model

We explain our model in three parts. In Section 3.1 we explain the base case (where there are no environmental schemes operating) from the perspective of all three types of players. We also introduce the basic formula for each farmer's bidding strategy in a biodiversity auction. In Section 3.2 we explain APR, and in Section 3.3 we explain FPR. We provide information about our measures of economic surplus throughout, which we then use in Section 4 to examine results.

3.1 Base Case

Initially, we assume that farmers produce agricultural output, q_a, to maximise profit. Each farmer's skill level is denoted by A and he allocates, V_a, land to agricultural production. We assume A varies across farmers. Hence, each farmer has a fixed level of human capital captured in A which affects his ability to manage an area of land (the area of land is increasing in A). Land is the only variable input in the model. There are N farmers. The price of agricultural output, P_a, and the rental price on each unit of land, w are exogenously determined. The production function is assumed to be concave of the form:

$$q_a = AV_a^t \tag{1}$$

where $t \in (0,1)$ is a parameter defining the agriculture-wide state of technology. The profit derived from using the profit-maximising amount of land, V_a^*, is given by π_0:

$$\pi_0 = P_a A(V_a^*)^t - wV_a^* \tag{2}$$

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This is a farmer's profit in the absence of any environmental schemes, and it will serve as our reference point – in terms of farmer surplus – when we introduce environmental policies. Neither the agency nor PSE derive any surplus beyond the competitive market equilibrium prior to the introduction of the environmental scheme. Hence, both the agency's and PSE gains are measured from a base of zero.

3.1.1 Farmers' bidding strategies in an auction

The agency uses an auction to procure biodiversity in either scheme: APR or FPR. A farmer always bids into the biodiversity auction according to his forgone profit (π_f). The farmers' forgone profit calculation is different in APR and FPR.

In APR, a farmer bids according to forgone agricultural profit. A farmer must allocate land away from agriculture to produce biodiversity. Hence, biodiversity and agricultural output are competitive in APR.

In FPR the farmer has the property right to mitigation. Hence, the farmer will start from a point where he already produces agriculture plus mitigation. When bidding into a biodiversity auction, a farmer will consider the profit forgone from possibly reducing agriculture or mitigation. However, to produce biodiversity in FPR, a farmer will not necessarily need to reduce agriculture or mitigation. The reason is that biodiversity may be provided on the mitigation land. Hence, mitigation land can be used for biodiversity at zero cost to the farmer. In this model, land is similar to what BPW call a 'public input'. That is, an input that is being used in one activity (mitigation), but with spare capacity to use it for other activities. It is analogous to the use of one piece of capital for the production of several goods. This public input is the source of economies of scope in our model. However, a farmer cannot costlessly transfer land from mitigation to biodiversity over all ranges of output. This costless transfer can occur as long as the agency has asked for biodiversity on land that is a subset of the mitigation land. Alternatively, if the agency has asked a farmer for an amount of biodiversity land that is greater than his mitigation land area, then the farmer must reduce agricultural output, and consider the subsequent profit loss. The circumstances of a particular farmer will affect his bidding strategy.[5]

Latacz-Lohmann and Van der Hamsvoort (1997) derive optimal bidding strategies for (e.g.) a farmer in two cases (i) where he is risk neutral and (ii) where he is risk averse. In the present paper, we assume that each farmer is risk neutral.[6] They derived a farmer's optimal bid price p^*, as:

[5] We explain this further in Section 3.3.2.

[6] Even though some authors – such as Bond and Wonder (1980) and Quiggin (1981) – have argued that farmers are risk averse, Latacz-Lohmann and Van der Hamsvoort found that this assumption did not affect their modelling results.

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$$p^* = \max\left(\frac{\pi_f + \bar{p}}{2}, \underline{p}\right) \qquad (3)$$
$$s.t \quad p^* \geq \pi_f$$

where farmers have an expectation about a minimum acceptable bid price, $\underline{p}$ and a maximum acceptable bid price, $\bar{p}$. Bids are uniformly distributed between $\underline{p}$ and $\bar{p}$. Equation (3) has two parts, a bid price and a constraint.

The bid price is a linearly increasing function of a farmer's profit forgone, and the expected bid cap. A farmer with a profit forgone, π_f, in between $\underline{p}$ and $\bar{p}$ will bid at some price slightly higher than profit forgone in an attempt to extract some rent. A farmer with profit forgone below $\underline{p}$ will bid at $\underline{p}$, again in an attempt to take some rent. A farmer with profit forgone greater than $\bar{p}$ will not bid. In other words, a farmer will only participate in an auction if it improves his pre-auction profits.

In our model, we assume that all farmers have the same expectations about average profit forgone (see Section 4). We assume that the agency uses a price discriminating auction, and writes an individual contract with each farmer. Assuming he is successful in the auction, a farmer undertakes the actions he has volunteered, at the bid price he has submitted.

3.2 Agency property right model

In this section we consider the case where the agency has the property right to mitigation provided by farmers. Modelling the level of mitigation associated with different land-use changes is assumed to occur centrally (by the agency) due to high costs and specialised technical requirements.

There are several reasons why the agency may retain the right to sell mitigation. First, the community may perceive farmers as part of the polluting group and giving them the right to mitigation could be seen as unfair: why should those who have contributed to the problem, then be allowed to profit from its alleviation?

Second, since the production of biodiversity leads to the production of mitigation (at zero additional cost to the farmer), the agency may perceive that it is paying for both goods.

3.2.1 Biodiversity and mitigation in APR

Biodiversity We assume that in the auction, the agency targets land for allocation to biodiversity. We assume that the value of biodiversity is difficult to measure and hence the government takes a safe minimum standard approach.[7] It sets the physical target for biodiversity (B), and minimises the cost of achieving this target.

[7] For a discussion on the use of safe minimum standards see Bishop (1978).

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The agency calls for bids from farmers to provide biodiversity services and visits each farmer that submits an expression of interest to determine the units of land that would be useful from the agency's biodiversity perspective. The area of land targeted by the agency, on a farmer's property, is denoted by V_b. The agency writes a contract against V_b and any related management commitments for successful farmers (bids).

The biodiversity value of different land units will vary by location, species etc. The agency gives land allocated to biodiversity a score, which we denote as $b \in [1,100]$. This value denotes the pay off received by the agency – in biodiversity change units – if the farmer were successful in his bid. A farmer considers his new profit if he were to allocate the land to biodiversity:

$$\begin{aligned} \pi_0^{new} &= P_a A(V_a^{new})^t - wV_T \\ s.t. \quad & V_a^{new} = V_T - V_b \end{aligned} \tag{4}$$

where V_T is total land, and V_a^{new} is the land left for agriculture after the farmer has allocated V_b to biodiversity.[8]

Each farmer will bid according to (3):

$$\begin{aligned} p^* &= \max\left(\frac{[\pi_0 - \pi_0^{new}] + \bar{p}}{2}, \underline{p}\right) \\ s.t. \quad & p^* \geq \pi_0 - \pi_0^{new} = \pi_f \end{aligned} \tag{5}$$

The agency arranges farmers' bids from highest to lowest according to a biodiversity benefits index (BBI), $BBI = \frac{b}{p^*}$. The agency chooses bids such that – when ranked from highest to lowest – they provide, $\sum_i b_i = B$ where i refers to a particular farmer's bid. If successful, a farmer's post-auction profit would be:

$$\pi_1 = \pi_0^{new} + p_s^* \tag{6}$$

where p_s^* is a successful bid price. The equation demonstrates that a successful farmer would receive his agricultural profit, plus his (accepted) bid price.

Pollution mitigation The above model is effectively that given by Latacz Lohmann and Van der Hamsvoort (1997). However, in our model the allocation of land to biodiversity also provides mitigation. As a farmer takes land

[8] We assume that land is fixed for the farmer given his A parameter. Hence, in this case V_T here is equal to V_a^* from (2). However, this will not be the case after we introduce mitigation in the next section.

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out of agriculture and puts it into biodiversity, this affects the amount of agricultural production, and hence reduces damage. We assume that the damage, D, caused by agriculture has an increasing marginal effect for each farmer:[9]

$$D(V_a) = RV_a^{\gamma} \quad (\gamma > 1) \tag{7}$$

where R and γ are parameters.

R captures the specific circumstances of the farmer, for example, whether he is near a river, or close to an important conservation resource, etc. γ is a sector-wide parameter. Assuming that $\gamma > 1$ gives the damage function its increasing marginal effect.

We refer to a reduction in pollution damage as mitigation, denoted by,

$$q_m = D(V_T) - D(V_a^{new}) \tag{8}$$

Note that farmers produce only agricultural product in the base case hence $D(V_T) = D(V_a)$. The maximum reduction in output (and damage) for any farmer is bounded by his pre-policy output (and damage) level: $\max(q_m) = D(V_T)$.

An agency conducting an auction for biodiversity will receive mitigation as a by-product. If there is an effective tradable pollution market in progress, then the agency can sell mitigation units (which amount to pollution credits) into the market, and recoup some of its biodiversity cost.

The agency's aggregate supply of mitigation will equal the sum of all mitigation it picks up from the biodiversity auction. We can write this as:

$$Q_m^s = \sum_i q_{m,i} \tag{9}$$

We assume that PSE demand for mitigation is of the form:

$$Q_m^d = \delta + \lambda P_m \tag{10}$$

where Q_m^d is aggregate demand for mitigation, P_m is the price of mitigation and δ, γ are parameters. In this situation the price is set passively by the intersection of the (perfectly inelastic) supply curve, and the demand curve formed by PSE willingness to pay for mitigation. The equilibrium values for quantity and price are denoted as Q_m^* and P_m^*, respectively.

3.2.2 Farmers in APR

After the auction, a successful farmer's net surplus position – relative to the pre-policy situation – is given by:

[9] The damage function is increasing as land used for mitigation increases.

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$$s_i = \pi_1 - \pi_0 \quad \text{(for the } i\text{th farmer)} \tag{11}$$

Unsuccessful farmers default back to agricultural production on their whole farm, therefore, for these farmers $V_T = V_a^*$, and profit is given by π_0. Hence for unsuccessful farmers $s_i = 0$. Aggregate farmer surplus is the sum of every individual farmer's surplus. For these farmers, aggregate change in surplus is given by:

$$S_F = \sum_i s_i \tag{12}$$

Throughout Section 3.2 we have assumed that farmers' bids would be a linearly increasing function of their forgone agricultural profit. There is some chance that farmers' bidding behaviour would be altered by the fact that the agency were receiving mitigation in addition to biodiversity. Farmers might, for instance, be unhappy that they were not receiving the benefits of their mitigation production and hence bid to try and extract further rent, or less farmers may participate in such an auction, reducing the auction's competitiveness. However, it is difficult to predict – and hence model – exactly how farmers would bid in this situation.[10]

3.2.3 Agency in APR

The agency's surplus, S_A, is determined by $C(B)$, the cost of achieving the biodiversity cap, B, and the revenue that the agency receives from selling any mitigation. The total cost to the agency of achieving the biodiversity target is equal to $C(B) = \sum_i p_{si}^*$, where p_{si}^* denotes a successful bid price for the ith farmer. The agency's surplus is:

$$S_A = Q_m^* P_m^* - C(B) \tag{13}$$

the revenue from the sale of mitigation less the cost of the biodiversity bids. Below, when we compare the two property right structures – APR and FPR – we hold the biodiversity target constant at B.

3.2.4 PSE in APR

For PSE the benefit of APR is determined by the difference in their willingness to pay for mitigation, versus the equilibrium mitigation price. In other words it is the area below their demand curve, but above the mitigation price. For the linear case we have described this is given by:

[10] If farmers were to bid in a more speculative fashion in an effort to extract more rent, then this would diminish the relative benefits of the agency property-right scheme, hence taking account of this speculative behaviour would not alter our basic conclusions (see Section 4).

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$$S_{PSE} = [(-\delta/\lambda) - P_m^*] \times Q_m^* \times 0.5. \tag{14}$$

3.2.5 Total surplus in APR

We can now state how the efficiency of different property right allocations may be calculated. Total surplus, S, is calculated as:

$$S = S_A + S_F + S_{PSE}. \tag{15}$$

Equation (15) is the general form of our surplus calculations in both APR and FPR. However, in the two schemes, the cost of biodiversity, $C(B)$, and the price and quantity of mitigation – P_m^* and Q_m^* respectively – will vary due to the incentives faced by farmers. We now turn to FPR to examine how farmers incentives are altered.

3.3 Farmer property right model

In the above model, the agency buys biodiversity, takes any mitigation that is provided in the process and sells it to PSE who value mitigation offsets. In other words, the agency owns the property right to mitigation. However, an alternative model is one where farmers own the mitigation produced, and can therefore sell it directly to PSE.

Prior to considering a scheme where farmers participate in both a mitigation and biodiversity market, we consider the case where a mitigation market operates independently of a biodiversity market.

3.3.1 Mitigation case

In FPR without the biodiversity auction, each farmer will compare the relative return from land allocated to agriculture, to the return that he can get from reducing agricultural production and recouping a price for each mitigation unit. Therefore, each farmer will maximise:

$$\pi_2 = P_a q_a + P_m q_m - w V_T. \tag{16}$$

The price of mitigation is endogenous to the model. However, we assume a competitive market for mitigation, hence no one farmer can affect the market price. The market clears at an equilibrium price where aggregate supply equals aggregate demand.[11]

Each farmer will compare the marginal benefit from increasing mitigation to the marginal cost of increasing mitigation, according to the following equation:

[11] In Section 3.3.2 we give a fuller explanation of the equilibrating mechanism.

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$$\frac{\partial D}{\partial V_{am}} P_m = \frac{\partial q_a}{\partial V_{am}} P_a \tag{17}$$

where V_{am} is the land dedicated to agriculture in the mitigation scenario. The solution of (17) is given by:

$$V^*_{am} = \left(\frac{P_a t A}{P_m \lambda B} \right)^{\frac{1}{\lambda - t}} \tag{18}$$

which is a direct comparison (ratio) of the relevant benefits from agriculture, to those from mitigation. Note that the price of land, w, is excluded from (18) as the farmer takes his amount of land as fixed when deciding to allocate between agriculture and mitigation.

The land allocated to mitigation is the land left over after calculating the optimal agricultural allocation: $V^*_m = V_T - V^*_{am}$.

We can substitute (18) into (16) and find a farmer's mitigation-plus-agriculture profit level as:

$$\pi_2 = P_a q_a (V^*_{am}) + P_m q_m (V_T - V^*_{am}) - w V_T. \tag{19}$$

The farmer makes a surplus in excess of the agriculture-only case, which is given by

$$M_s = \pi_2 - \pi_0 \tag{20}$$

3.3.2 Joint mitigation plus auction scheme

We noted in APR that when engaging in a biodiversity auction, a farmer will base his bid on forgone agricultural profit. In FPR, a farmer's basis for bidding will be the profit he could have made from agriculture plus mitigation, from (19). Again, we assume that the farmer uses a risk-neutral bidding strategy.

In FPR we assume that there is a two-part process. First, each farmer decides on the amount of land that he would allocate to mitigation, using equation (17). Second, the farmer receives a visit from the agency that points out specific land units which could be allocated to biodiversity.

We assume that each farmer – after seeing the biodiversity land that is valuable to the agency – would put this same land towards mitigation (take it out of production). We make this assumption for simplicity, but relaxing it would not alter our results in Section 4. The reason that a farmer may decide to put biodiversity and mitigation on the same piece of land is because it is profitable for the farmer to be successful in the auction, and producing mitigation and biodiversity on the same land increases his

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probability of success. To see this, consider the opposite case, that is, consider an example where farmer Z knows that a particular parcel of land (parcel *bio*) is valued by the agency for biodiversity purposes, however, he decides to mitigate on a completely separate parcel of land (parcel *mit*). Farmer Z will bid into the biodiversity auction for parcel *bio*, and receive mitigation revenue from parcel *mit.* However, in an auction that is competitive (in that there are a large number of bidders and there is no collusive behaviour), then farmer Z will probably be competing with others who have mitigation land. They will be able to transfer mitigation land to biodiversity at no cost, but farmer Z will base his bid around some forgone agricultural profit. Hence, unless his biodiversity is extremely valuable, he is probably going to be unsuccessful. He can increase his chance of being successful by producing biodiversity on the mitigation land, and submitting a lower (but positive) bid.[12]

In a joint mitigation-plus-biodiversity situation, the agency may request either:

- An amount of land for biodiversity that is smaller than a farmer would have allocated to mitigation, that is, the agency requests $V_{b1} < V_m^*$
- An amount of land for biodiversity that is larger than a farmer would have allocated to mitigation, that is, where the agency requests $V_{b2} > V_m^*$

If the agency requests an amount of land V_{b1}, that is less than V_m^*, a farmer can 'costlessly' use mitigation land for biodiversity. This is the 'public input' nature of the land allocated to mitigation; the farmer has capacity to use the land twice.

However, when the farmer is asked to provide more land to biodiversity than he already provides to mitigation, such as V_{b2}, he must divert land from agriculture.

The general expression for each farmer's new profit level, contingent on V_b relative to V_m^*, is:

$$\pi_{amb} = \begin{cases} P_a q_a(V^*_{am}) + P_m q_m(V_T - V^*_{am}) - wV_T & V_b < V^*_m \\ P_a q_a(V_T - V_b) + P_m q_m(V_b) - wV_T & V_b > V^*_m \end{cases} \tag{21}$$

and so the expression for forgone profit is:

$$\pi_f = \pi_2 - \pi_{amb} \tag{22}$$

[12] A more sophisticated model would assume that the farmer looks at expected return from either using the same parcel of land, or separate parcels, by analysing the probability of success and reward from each option. However, this would only add to the complexity of the model, and it would not alter our conclusions because it would increase the relative surplus associated with FPR (see Section 4).

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which can be substituted into (3) to give each farmer's risk neutral bid price in the biodiversity auction.

Note that the top part of equation (21) – for the case where $V_b < V_m^*$ – gives the same expression for profit as equation (19). Hence, for the case where $V_b < V_m^*$ we have:

$$\pi_f = \pi_2 - \pi_2 = 0. \tag{23}$$

That is, a farmer faces a costless transfer of land from mitigation to biodiversity. The farmer will still bid a positive value into the auction (see equation 3). However, this is purely rent seeking on the farmers behalf. The fact that a farmer's land can be transferred from mitigation to biodiversity at zero cost in this situation reflects economies of scope in our model: it reflects the public input nature of the good, land (see the Appendix).

In our simulations, we solved our model for the price of mitigation endogenously, both in APR and FPR. In APR this was simple: the agency asks for bids on a certain amount of biodiversity; farmers bid into the auction; farmers that are successful supply mitigation and the agency picks up any mitigation that comes as a by-product. This quantity of mitigation is then supplied into the tradable pollution market (to PSE). The intersection of this (inelastic) supply quantity and the demand curve for mitigation forms the mitigation price.

In the farmer property right structure solving the model is more complex: the land being offered towards biodiversity affects mitigation supply and hence mitigation price (although the mitigation demand parameter values – δ and λ – are assumed to stay constant). Therefore, there is feedback between the biodiversity auction outcomes, and the mitigation market.

Our equilibrating process involves the following process. Farmers' solve for their mitigation-plus-agriculture profits, given by equation (19). This provides an initial supply of mitigation, and hence forms a starting price for mitigation. Then – given the agency's suggestion of V_b – farmers calculate their profit forgone (equation 22), and hence their bid price (from equation 3). These bids are assessed by the agency, and it informs farmers about the biodiversity results, and the corresponding mitigation market results. Importantly, farmers are told about the new price of mitigation. Given this new price of mitigation, farmers recalculate their mitigation-plus-agriculture profits (equation 19), and hence their new profit forgone (equation 22). Then they rebid into the auction (equation 3). This process continues until the supply of mitigation does not change from one bidding round to the next.

Note that the above equilibrating process amounts to naïve expectations on behalf of farmers, that is, farmers base their actions on only the current

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price of mitigation, without using any foresight. This makes the model tractable, but it also introduces a cobweb-type restriction: the absolute slope of the mitigation demand curve must be less than the absolute slope of the mitigation supply curve for the model to be stable.

3.3.3 Farmers in FPR

In FPR a farmer that is successful in the auction will receive his bid price, p_s^*, and hence his profits will be:

$$\pi_3 = P_a q_a + P_m q_m + p_s^* - wV_T \tag{24}$$

Farmers unsuccessful in the auction will choose V_{am}^* as per (19).

A successful farmer's change in surplus is given by:

$$s_{FPR,S} = \pi_3 - \pi_0. \tag{25}$$

An unsuccessful farmer's change in surplus is:

$$s_{FPR,U} = \pi_2 - \pi_0 \tag{26}$$

which is the same as in the mitigation case. The aggregate farmer surplus in FPR is the summation of s_{FPR} across all farmers (both successful and unsuccessful).

3.3.4 Agency and PSE surplus in FPR

The basic form of the agency and PSE surplus is the same as in the APR situation (given by (13) and (14) respectively). However, in FPR each farmer chooses the amount of mitigation he sells, and this affects his bid price in the biodiversity auction. Hence, farmers react differently in FPR. Farmers' different strategies feed directly into the surplus of the agency by affecting the price the agency pays for biodiversity. The agency is also affected by the fact that it no longer sells mitigation (it does not receive mitigation revenue). Farmers' different strategies in FPR also affect PSE by altering the quantity and price of mitigation.

In the next section, we examine exactly how these factors play out to alter aggregate surplus from the two schemes. Table 1 gives a written description of the surplus calculations – for each player type – in each of the scenarios. Aggregate surplus is simply the sum of the surpluses from the different player types in each scenario. We assume throughout Section 4 that the transaction costs of running each scheme (e.g., monitoring and enforcement) are the same.

Following Latacz-Lohmann and Van der Hamsvoort (1997), we use simulation modelling to analyse the implications – on efficiency – from the two

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Table 1 Surplus of the different player types in the base case, APR, and FPR

	Base case	APR	FPR
Farmers	Profits from agriculture	Profits from agriculture plus biodiversity bid, less base case	Profit from agriculture plus mitigation, plus biodiversity bid, less base case
PSE	Zero	Gains from trade given mitigation supplied via the agency, less base case	Gains from trade given mitigation supplied via farmers, less base case
Agency	Zero	Mitigation revenue less cost of biodiversity (bid payments), less base case	Mitigation revenue (= zero) less cost of biodiversity (bid payments), less base case

APR, agency property right; FPR, farmer property right; PSE, point-source emitters.

different property right structures. Simulation provides a simple way in which to analyse the model. Using analytical methods to solve the model would be a more complicated approach, but it would probably provide additional insights.

4. Results

In this section we present the results of our model using simulation in an *Excel* spreadsheet. We will present the effect on economic surplus of the two property right structures that we have discussed throughout the paper: APR and FPR.

We ran our model using a range of parameter values. However, for brevity we present results assuming: the price of agricultural output (P_a) is equal to two; land rental (w) is equal to unity; the agriculture wide state of technology (t) is equal to 0.6.

There are N = 300 farmers in our model. We model PSE exclusively through the use of demand parameters. Hence, there are no individual specifications for PSE. Rather, we set PSE aggregate demand parameters, δ and λ, equal to 2 and −1 respectively. As mentioned in Section 3.3.2 the slope of the mitigation demand curve must be less, in absolute terms, than the slope of the mitigation supply curve.[13]

[13] A pivotal, or parallel, shift outwards of the demand curve – due to (e.g.) an increase in the profitability of the PSE industry – would increase the benefits of supplying more mitigation. As will be shown below, this would advantage the farmer property-right structure. A very flat demand curve close to the horizontal axis would lessen the relative advantage of the farmer property-right structure. However, in this case the absolute gains from allowing farmers to interact with PSE is also diminished (there is less economic surplus in the mitigation market).

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For simplicity, we assume that R is the same for all farmers and equal to unity. This means that each farmer has the same damage function. However, a farmer with a value of (e.g.) $A = A_0$, will pollute a different amount to a farmer with $A = A_1$: he will have a different opportunity cost of devoting land to mitigation *vis-à-vis* agriculture.[14]

Each farmer calculates $\bar{p}$ as the average forgone profit plus 40 per cent and $\underline{p}$ as the average forgone profit minus 40 per cent. This is consistent with Latacz-Lohmann and Van der Hamsvoort (1997).[15] We discuss the results assuming different values for the 'damage parameter', γ: low (1.1), medium (1.3) and high (1.5).

Farmers' reactions in FPR depend on whether the agency asks for a relatively large, or small, portion of their land to be dedicated to biodiversity (see equation 21). In our results, we take account of this by running simulations that vary the proportion of farms for which $V_b > V_m^*$. If we denote the ith farm's value of V_b as V_{bi}, and its value of V_T as V_{Ti}, then we can define the percentage of a farm that the agency asks be put towards biodiversity, x_{0i}, as: $x_{0i} = \dfrac{100V_{bi}}{V_{Ti}}$. x_{0i} increases with V_{bi}. We can consider the arithmetic mean of x_{0i} across all farms, x. By varying V_{bi}, for all $i = 1,2, \ldots$ N, we constructed $x = 0,1, \ldots 99$, which is a normally distributed variable, with a standard deviation of two. This allows us to compare FPR and APR for every value of x, that is, it allows us to compare the two property right regimes, for a varying number of farms that satisfy the condition, $V_b > V_m^*$.[16]

If we denote some variable of interest (e.g., surplus or the price of mitigation) as e, then we can examine it over all 100 values of x, in both FPR and APR. We do this via two summary statistics: FPR Advantage and FPR Advantage ratio. These are as follows:

$$\text{FPR Advantage} = \frac{\sum_{x=0}^{99}(e_{FPR,x} - e_{APR,x})}{100} \tag{27}$$

[14] Altering R does not change our basic conclusions.

[15] In the Latacz-Lohmann and Van der Hamsvoort (1997) case, plus or minus 40 per cent is shown to be a case where auctions are superior to fixed-price offers. Since we are assuming that agency uses an auction mechanism, it is worth using a parameter value where it is a superior mechanism.

[16] The relationship between x and the proportion of farms for which $V_b > V_m^*$ is nonlinear. As our model is based around the agency's choices of the V_{bi}s, it is much more convenient to report x (which we can alter directly) rather than the proportion of farms for which $V_b > V_m^*$ (which we derive residually).

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$$\text{FPR Advantage Ratio} = \frac{\sum_{x=0}^{99}\{(e_{FPR,x} - e_{APR,x})/e_{APR,x}\}}{100}. \tag{28}$$

Hence, FPR Advantage is positive when the variable in question is generally larger under FPR. The statistic is negative when the variable in question is generally larger under APR. 'Generally' here refers to a comparison of FPR and APR over all values of x.

4.1 Total economic surplus

Given the preceding parameter values, total economic surplus is always greater in FPR. Assuming medium damage, the FPR advantage ratio for total economic surplus is 13.3.

Table 2 gives some values of FPR advantage (from equation 27). Over the full range of values for x, total surplus in the farmer property right structure is on average $201 685 greater than in the agency property right structure when the damage parameter is low. This rises to $5 706 535 for a high value of the damage parameter. The farmer property right structure consistently delivers more mitigation units: 227 295 more than the agency property right structure (averaged over x) when the damage parameter is low, and 4 001 915 more when damage is high. Farmers and PSE prefer the farmer property-right structure, and they prefer it better when the damage parameter is high. The agency, on the other hand, loses less when the damage parameter is low (a loss of $4612), compared to when the damage parameter is high (a loss of $342 520).

The reason the total surplus for FPR is generally greater becomes clear if we consider the nature of the two systems. In FPR, farmers are able to choose the profit maximising quantity of land to allocate to mitigation.

Table 2 Summary of results by farmer property right advantage

	Damage parameter		
Variable	Low	Medium	High
Total surplus ($)	201 685	1 302 473	5 706 535
Mitigation (units)	227 295	1 011 239	4 001 915
Mitigation Price ($/credit)	–0.803	–0.934	–0.953
Farmers' surplus ($)	102 169	859 264	3 962 673
Agency's surplus ($)	–4612	–80 339	–342 520
PSE surplus ($)	104 129	523 548	2 086 382

PSE, point-source emitters.

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When the agency holds the property right, the agency decides on the quantity of mitigation produced. Yet the agency does not consider market factors; the agency chooses the amount of mitigation only residually, or as a by-product of its biodiversity demand. In APR, the agency under-supplies mitigation. This result holds for most parameter values except for one special case which is analysed in Section 4.5.

As long as the biodiversity auction is competitive (a large number of bidders with no collusive behaviour), then farmers are limited in their ability to 'double dip' in FPR meaning that they are limited in their ability to charge twice for the use of one piece of land. Under FPR, a farmer will maximise profit via his choice of mitigation and agriculture. Given that $V_b < V_m^*$, a farmer can costlessly use mitigation land for biodiversity. A competitive biodiversity auction will enable the agency to force bids down towards zero (the farmer's opportunity cost). Hence, under FPR the agency will pay less for a given amount of biodiversity.

4.2 Farmer economic surplus

The damage parameter (γ) affects farmer surplus under the two property-right regimes. For all damage parameters considered, farmers are always better off under FPR. When damage is medium, the FPR Advantage Ratio is 53.6.

Farmers prefer FPR when the damage parameter is relatively high because FPR allows them to determine their profit maximising quantity of mitigation. On the other hand if a farmer's agricultural production has only a small impact on pollution (i.e., a low damage parameter), then a farmer is limited in the amount of mitigation he can supply. Hence, the value of being able to choose his mitigation level (i.e., FPR) is diminished; the inefficiency from the agency choosing the quantity of mitigation – as opposed to market factors – is reduced.

4.3 Point-source emitter economic surplus

Point-source emitters always prefer FPR. For the medium damage parameter, the FPR Advantage Ratio is 287. Point-source emitters prefer FPR because farmers, generally, supply more mitigation in FPR. Hence, the price of mitigation is pushed down.

4.4 Agency economic surplus

For all the damage parameters considered, the agency always receives a larger surplus if it holds the property right (APR). The case of a medium damage parameter is shown in Figure 1.

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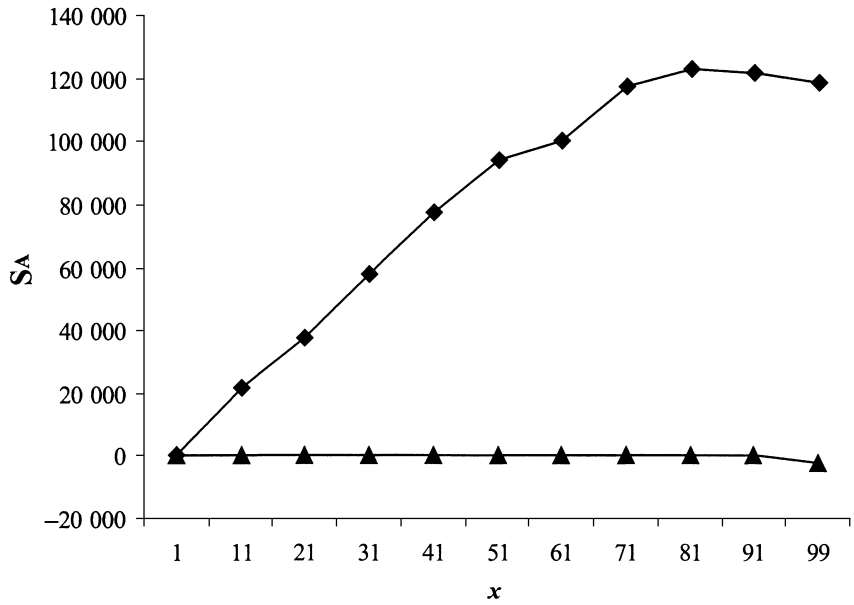

Figure 1 Agency Surplus damage from agriculture *medium* ($\gamma = 1.3$).
—◆— APR Agency's surplus; —▲— FPR Agency's surplus

The intuition behind these results is as follows. The agency gains a larger surplus if it holds the property right, as damage from agriculture increases, because this allows the agency to sell more mitigation credits into the tradable permit market. Under FPR, the agency does not receive any revenue. The agency uses the receipts in APR to offset the cost of purchasing biodiversity. If damage from agriculture is lower, then the agency receives (and sells) less mitigation, hence, it moves to a lower net-budget position.

4.5 A special case

There is only one case in our model, that we know of, where the two property-right structures will provide equal economic-surplus gains (Figure 2). This special case has two requirements. First, V_b must be greater than V_m^* for a large proportion of farms (i.e., x must be relatively high).[17] Second, the agency targets all the biodiversity available. Consider these in turn.

If, for a given farmer, $V_b < V_m^*$, then he will provide more land to mitigation if he holds the property right. In particular, he will supply an area of V_m^* for

[17] We will explain what 'high' means for a particular example later in this section.

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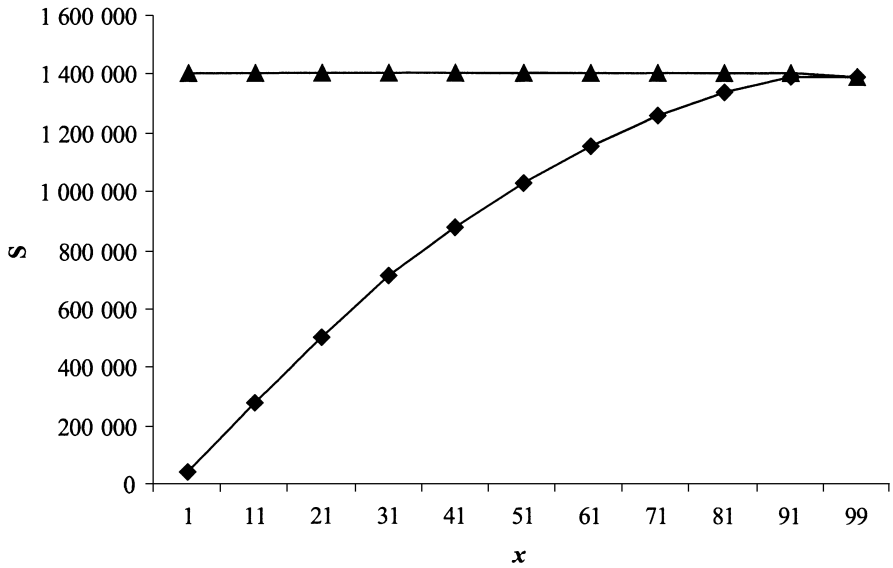

Figure 2 Total Surplus in the Special Case.
—◆— APR total surplus; —▲— FPR total surplus

mitigation in FPR, but only $V_b < V_m^*$ for mitigation in APR. Yet he provides the same amount of biodiversity in both schemes: an area of V_b. However, if $V_b > V_m^*$ then a farmer provides the same amount of mitigation and biodiversity in both property right structures. Therefore, when there is a large proportion of farms with $V_b > V_m^*$, the superiority of the farmer holding the property right – which is due to the fact that it usually provides more mitigation – is eroded.

The second requirement is that the agency must target all biodiversity available. That is, for farms that can provide both mitigation and biodiversity under economies of scope, the agency must buy the sum-total of biodiversity change available. The reason for this is that if the agency targets just less than the total, then there will be at least one farmer who, in FPR, would provide mitigation that would not be picked up when the agency holds the property right.

This second requirement is highly unlikely to hold in practice: the agency cannot hold a credible auction when it intends to accept all bids. An auction relies on competitive behaviour. If farmers realised that the agency was to accept all bids, then they would hardly bid in a competitive fashion. At best, the agency would be able to hold such an auction once. Thereafter, it would be public knowledge that any bid were acceptable, and farmers would bid accordingly.

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4.6 Discussion

As stated in the previous section, as the damage parameter (from agriculture) increases, the agency has a greater incentive to hold the property right to mitigation. Even though there would (generally) be an efficiency loss under APR. The community may reinforce this agency incentive: they may perceive the divestment of pollution rights to farmers as unfair, as farmers would benefit from reducing pollution that they should never have produced in the first place.

Under APR, the agency may also have incentive to alter its scoring index towards mitigation. There are two reasons for this. First it could provide the agency with greater revenue. Second, the agency may perceive that it could correct – via its scoring system – for the efficiency losses in APR.

The agency, however, would face considerable information costs in attempting to mimic FPR. It is more efficient for farmers to hold the property right because farmers hold private information on agricultural technology, and hence their profit maximising allocation of land to mitigation. The agency would need to discover this private information for heterogenous farmers, and then attempt to purchase the optimal quantity of mitigation.

5. Concluding comments

Many environmental problems are due to the economic decisions made by point-source and diffuse emitters of pollution (e.g., farmers). The economics of information, and knowledge development in the physical sciences, has equipped policymakers with an additional suite of environmental policy tools to engage different sources of pollution in environmental management. Two such policy mechanisms are tradable pollution permits and auctions of conservation contracts.

Environmental markets, however, raise important institutional questions with respect to the interaction of players. One important question is the allocation of property rights when (e.g.) a farmer can potentially generate more than one environmental good from a single action, i.e., when there are economies of scope in the provision of environmental goods. Previous research has considered the situation where there are economies of scope in the provision of goods sold into competitive markets (Baumol *et al.* 1988). In the present paper, however, one environmental good is sold to PSE and the other to an agency using an auction system. Some authors advising bodies associated with environmental management (e.g., Alexandra and Associates 2002) have argued that a central environmental agency could act as the sole purchaser of several environmental goods from farmers, and

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then undertake the trading with external investors. The present paper has raised warnings about taking such an approach.

In our model, we assumed a biodiversity-mitigation link that was due to the fact that land allocated towards biodiversity, was allocated away from agriculture. Hence, agricultural output fell, and so did any associated pollution. This is applicable to a setting such as the (native) revegetation of land that is currently used in agriculture. To date, auctions for conservation contracts in Australia – such as NRE BushTender scheme – have been mostly focused on the management of existing remnants, rather than revegetation (Stoneham *et al.*, 2002). This is for two main reasons: BushTender is focused on one good (biodiversity), not multiple environmental goods, and revegetation is relatively expensive. If Australia's environmental agencies start to focus on multiple environmental goods and the cost of revegetation falls through time, then our model becomes relatively more applicable. Our model could be viewed as more closely representing the CRP in the USA, where land is often 'set aside' (diverted from agricultural production). Historically, this was solely for the purpose of reducing agricultural production. More recently, the USDA has been trying to procure additional management from this land, so that environmental goods are provided to the community.

Using a simulation model we have shown that it is generally more efficient for farmers to own the property right to mitigation, even though mitigation may be provided as a by-product from the production of biodiversity. That is, mitigation and biodiversity are produced under the condition of economies of scope. The intuition for this result is that when farmers have the property right to mitigation, they efficiently allocate land to it: they maximise the economic surplus in a tradable pollution (mitigation) market. However, if the agency has the property right to mitigation, it derives an amount of mitigation residually, from its purchase of biodiversity. In most cases the agency will under supply mitigation, hence the economy will forgo gains from trade.

The other key aspect of this result is that the agency will pay less for biodiversity when farmers own the right to their own mitigation. Farmers will take account of the fact that land allocated to mitigation already receives a price in the market. In the model, mitigation land is – in BPW parlance – the 'public input'; sometimes it can be costlessly transferred to biodiversity. A competitive biodiversity auction will exploit this costless transfer from mitigation to biodiversity (albeit imperfectly).

Our results imply that an agency concerned with efficiency should have a very strong bias in favour of allocating property rights of environmental goods that can be sold into tradable pollution markets (or other competitive markets) to the producers of those goods, and not to an agency.

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Appendix

Economies of scope

We follow the approach of Baumol *et al.* (1988) that defines economies of scope in terms of a cost function. However, we use an equivalent – but for our purposes more convenient – representation of economies of scope (EOS) as given by Schroeder (1992):

$$EOS = \frac{c(q_m) + c(b) - c(q_m,b)}{c(q_m,b)} \tag{A.1}$$

Where, $c\ (q_m,b)$ is the cost to a single farm of producing q_m units of mitigation and b units of biodiversity jointly and $c\ (q_m)$, $c(b)$, are the costs to specialised farms of producing q_m and b respectively. There are economies of scope in equation (A.1) when EOS is greater than zero.

BPW explain that $c(b)$ represents the cost of producing biodiversity only. However, BPW acknowledge that in some cases two goods will be technologically interdependent, and hence always produced together. BPW cite the example of meat and hides, but in our case, an analogous example is biodiversity and mitigation. BPW argue that in this case, the specialised cost function could be viewed as the cost of producing both goods and then discarding one of them.[18]

In our case, we can view the function $c(b)$ as the specialised cost of producing biodiversity, that is, the cost of producing biodiversity and ignoring, or 'discarding', the associated mitigation. Given the technological interdependence between biodiversity and mitigation, there will be economies of scope in our model. This can be seen from equation (A.1) above. If the cost of discarding mitigation is zero, then $c(b) = c(q_m,b)$, hence equation (A.1) becomes:

$$EOS = \frac{c(q_m) + c(q_m,b) - c(q_m,b)}{c(q_m,b)} = \frac{c(q_m)}{c(q_m,b)} > 0 \tag{A.2}$$

[18] See Baumol *et al.* (1988), page 73, footnote 3.

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