The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
http://ageconsearch.umn.edu
aesearch@umn.edu

Papers downloaded from ***AgEcon Search*** *may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

No endorsement of AgEcon Search or its fundraising activities by the author(s) of the following work or their employer(s) is intended or implied.

The Australian Journal of
Agricultural and
Resource Economics
Journal of the Australian Agricultural and Resource Economics Society

The Australian Journal of Agricultural and Resource Economics, 56, pp. 280–301

Optimal environmental policy design for mine rehabilitation and pollution with a risk of non-compliance owing to firm insolvency*

Ben White, Graeme J. Doole, David J. Pannell and Veronique Florec†

The modified Pigovian tax approach to regulating stock and flow pollutants from a non-renewable resource firm (Farzin, 1996) provides incentives for the firm to abate optimally, but does not allow for the possibility that a firm may become insolvent. In contrast, the current environmental bond policy applied in most jurisdictions across Australia and New Zealand provides funds in the case of insolvency, but often does not provide optimal incentives for rehabilitation. This study analyses these alternative policy approaches through a theoretical model and an empirical case study. From the case study for a mineral sands firm, the policy recommendation is that, based on economic efficiency alone, a modified Pigovian tax (termed here a damaged land tax) is optimal for most combinations of parameters. However, both risk-sharing and efficiency objectives can be simultaneously addressed by a mixed policy that includes a damaged land tax and an environmental bond.

1. Introduction

There are currently 341 operating mines in Australia, with a further 219 projects in development (Geosciences Australia, 2011). The five most important mineral commodities extracted using open-cut mining in order of value in 2007–2008 are coal, iron ore, copper, gold and nickel (Australian Bureau of Agricultural and Resource Economics and Science 2010, Table 33). Australian mining had a value added in 2009–2010 of \$121.5 billion accounting for 9.61 per cent of GDP (Australian Bureau of Statistics 2010). Australian mines occupy 0.02 per cent of total land area (National Land and Water Resources Audit 2002). New Zealand mining is mainly for gold and aggregates. In 2010, NZ mining had a value added of \$2.1 billion and accounted for 4.3 per cent of GDP (Statistics New Zealand, 2010). NZ mines occupy 0.015 per cent of the total land area (New Zealand Government, 2010). Despite occupying a small land area, mining can cause high levels of environmental damage, both

---

* The authors acknowledge funding from ARC Discovery Project DP0988368.

† Ben White (email: benedict.white@uwa.edu.au), Graeme J. Doole, David J. Pannell and Veronique Florec are in School of Agricultural and Resource Economics, University of Western Australia, Crawley, WA, Australia. Graeme J. Doole, David J. Pannell and Veronique Florec are in Centre for Environmental Economics and Policy, University of Western Australia, Crawley, WA, Australia. Graeme J. Doole is in Department of Economics, Waikato Management School, University of Waikato, Hamilton, New Zealand.

© 2012 The Authors
AJARE © 2012 Australian Agricultural and Resource Economics Society Inc. and Blackwell Publishing Asia Pty Ltd
doi: 10.1111/j.1467-8489.2012.00591.x

within the mine site (Bell and Donnelly 2006) and throughout a region through the transportation of pollutants by air and water. Moreover, mining has been identified as a major source of greenhouse gases (DCCEE 2011). Mining is also constantly shifting to new sites and leaves behind disused mines that can remain environmentally damaged for many years. The major environmental problems associated with mines are disturbance to agricultural land and native vegetation, mine drainage, tailings pond (especially those containing toxic waste), rock dumps, hard standing areas (for parking), temporary roads, contaminated dust, greenhouse gases and other air pollutants, including arsenic (Mudd, 2007, 2010). The external social costs incurred by these impacts typically depend on the location of the mine in relation to centres of population and the ecological status of the region.

The standard economists policy prescription for point source pollution problems, such as those generated by mining, is to price pollution through a tradable permit or a Pigovian tax on emissions (for instance see Baumol and Oates 1988), thereby giving firms an incentive to 'internalise the externality'. This policy approach has been extended in a theoretical model to non-renewable resources and stock pollutants by Farzin (1996) and to heterogeneous environments by Xabadia *et al.* (2006). Specific Pigovian tax or tradable permit policies have not been widely applied to mining pollution in Australia or New Zealand. Instead, specific environmental policies for mines are based around environmental bonds that payout in the event of either non-compliance or firm bankruptcy. The focus on environmental bonds has developed to address a growing problem of abandoned (or orphaned mines). For instance in Western Australia alone, there are 11 411 so-called Historic Mine Sites of these 4995 (44 per cent) are categorised as a high priority in terms of safety or environmental concerns (Ormsby *et al.* 2003).

Environmental bonds were first identified as a potential environmental policy by Solow (1971). Subsequent research has shown that bonds have several advantages, relative to other policy instruments. First, they provide funds for restoration that can be used if a firm defaults on its environmental commitments. Second, they are often administered by private surety companies (banks or insurance companies), which reduces the transaction costs for regulators (Boyd 2001). Effectively, they are market-based instruments as the surety company does the initial risk assessment, sets bond service charge (largely a risk premium), and also monitors the firm's compliance with the environmental contract through time. Third, bonds transfer some of the environmental risks that accompany bankruptcy from society to the private sector (Gerard 2000). Fourth, bonds can provide incentives for firms to take their negative impacts on the environment into account (Solow 1971). Fifth, bonds can reduce monitoring frequency and cost (Bohm and Russell 1985; Perrings 1989). Last, bonds place the burden of proof for compliance onto the firm; thus, they effectively avoid the moral hazard problems associated with many environmental policies. Bond instruments also have disadvantages. First, a firm may have an incentive to strategically declare bankruptcy to avoid remediation costs. For this reason, most jurisdictions throughout Australia and New Zealand require bonds to be unconditionally guaranteed by a bank (see, for instance, the arrangements that apply in Western Australia (WA) (ICMM, 2005)). Second, a bond instrument may be set too low to provide sufficient motivation for rehabilitation. Third, bonds impose additional transaction costs on the firm and the surety company. Fourth, bonds often impose liquidity constraints on firms by tying up operating capital and reducing lending limits (Shogren *et al.* 1993). Last, there exists a potential moral hazard where the regulator has an incentive to call on funds, even when a firm has complied with the environmental contract, as a mechanism for generating revenue (Shogren *et al.* 1993).

The aim of this study is to reconcile the Pigovian tax and bond approaches to environmental regulation. The modified Pigovian tax policy of Farzin (1996) addresses the incentive effect, but does not account for the possibility of non-compliance owing to insolvency. In turn, bond policies do not necessarily provide optimal incentives for timely mine rehabilitation. This study explores the potential for a mixed policy where a bond addresses the risk-sharing concerns of the regulator, and a modified Pigovian tax provides additional incentives for rehabilitation.

The study is structured as follows. Section 2 presents a theoretical model and analyses the relative efficiency of a bond and a modified Pigovian tax termed the damaged land tax (DLT). Section 3 reviews the current environmental policies for mining in Australia and New Zealand and assesses these policies with reference to the theoretical model. In Section 4, the implications of different policy designs are analysed in a case study for the mineral sands sector in WA. Section 5 discusses policy implications of the results and Section 6 concludes.

2. Theoretical model

The regulator aims to maximise social welfare from mining by accounting for damage owing to stock and flow pollutants subject to the dynamics of the resource stock and stock and flow pollutants. The theoretical model is developed in stages. First, the deterministic social-welfare maximising solution is derived. Second, we show how this can be implemented through modified Pigovian taxes charged in each period on the stock and flow pollutants. Third, the model is extended to include a stochastic variation where the firm may abandon the mine at the end of the planning horizon, and this allows us to introduce a bond policy into the model so that we can compare a Pigovian tax policy with a bond policy.

2.1. Deterministic model

The analysis focuses on a finite time period over the range $t = [0, 1, \ldots, T]$. The distribution of land type by its social value is indicated by a land type

Table 1 Coefficient, variable and function descriptions and values used

Symbol	Description	Unit	Value/functional form
Indices			
k	Index of land type	–	$k = [1, 2, 3]$
t	Time period	–	$t = [0, 1, \ldots, 10]$
T	Terminal time period	–	$T = 10$
Parameters			
r	Discount rate	Per cent	$r = 0.05$(5 per cent)
δ^t	Discount factor at time t	Per cent	$\delta^t = (1/(1 + r))^t$
p	Price of extracted mineral	$\$ t^{-1}$	$P = 34$
d_k	Annual damage cost as a function of land quality	$\$ \text{ ha}^{-1}$	$d_1 = 500$, $d_2 = 4000$, $d_3 = 8000$
c_k	Rehabilitation cost as a function of land quality for the firm	$\$ \text{ ha}^{-1}$	$c_1 = 750$, $c_2 = 6000$, $c_3 = 34000$
c_k^r	Rehabilitation cost as a function of land quality for the regulator	$\$ \text{ ha}^{-1}$	$c_k^r = (1 + 0.3)c_k$
h	Land degradation per tonne of extraction	ha $(\text{tonne})^{-1}$	$h = 0.0005$
ψ	Parameters estimated for mining cost function	Coefficient (P-value)	$\psi_1 = 1,435,953(0.69)$, $\psi_1 = 0.5(\text{fixed})$ $\psi_2 = 0.00000014(0.001)$, $\psi_3 = 5.461(0.04)$
a	Initial resource	t	$a_k = 2\,000{,}000\ \forall k$
b_k	Initial stock of damaged land in each cohort	ha	$b_k = 0 \forall k$
κ	Deadweight loss of taxation		$\kappa = 0.1$
φ	Probability of firm bankruptcy at time T		
α	Bond service charge	Per \$	$\alpha = 0.025$
β	Rehabilitation cost coefficient		$\beta = 1.3$
η	Bond rate applied to damaged land	$\$ \text{ ha}^{-1}$	*various*
τ	Pigovian tax rate applied to damaged land	$\$ \text{ ha}^{-1}$	*various*
ξ	Total incentive rate	$\$ \text{ ha}^{-1}$	$\xi = \alpha\eta + \tau$
γ	Opportunity cost of bond in terms of reduced borrowing	Per cent	$0 \leq \gamma \leq 0.025$
Variables			
$Q_{k,t}$	Ore extraction from the mine in land type k time t	tonne	
$E_{k,t}$	Land rehabilitated of type k at time t	ha	
$Y_{k,t}$	Stock of damaged land of type k at time t	ha	
$X_{k,t}$	Ore stock from land type k at time t	tonnes	
Functions			
$s(Y_{k,T})$	Terminal value function	$\$ \text{ ha}^{-1}$	$s_k(y_{k,10}) = d_k/r$
$s^f(Y_{k,T})$	Terminal cost of rehabilitation to the firm	\$	$s_k(y_{k,10}) = c_k y_{k,10}$

Table 1 (*Continued*)

Symbol	Description	Unit	Value/functional form
$s^r(Y_{k,T})$	Terminal cost of rehabilitation to the regulator	\$	$s_k(y_{k,10}) = c^r_k y_{k,10}$
$w(X_{k,t}, Q_{k,t})$	Mining cost function	\$	*See text.*
$c_k(E_{k,t})$	Rehabilitation cost function	\$	$c_k(E_{k,t})^{\beta}$
$d_k(Y_{k,t})$	Damage cost function	\$	$d_k Y_{k,t}$
$\pi_k(p_t, X_{k,t}, Q_{k,t})$	Profit from cohort k at time t	\$	*See text.*
$\pi^T(\xi), d^T(\xi)$	Present-value of profit function and damage function from $t = 0$ to $t = T$	\$	*See text.*
J^{SWF}, J^f, J^r	Optimal value function from $t = 0$ to T for social welfare (SWF), the firm (f) and the regulator (r) acting as a Stackelberg leader	\$	–

index $k = [1, 2, \ldots, K]$ and increasing in k. A single firm extracts from all mines and is a price taker, and the price of ore is fixed. Notation and definitions for the theoretical and empirical models are given in Table 1.

The firm has two decision variables: $Q_{k,t}$ mineral extraction (measured in tonnes) from land type k at time t; $E_{k,t}$ remediation effort (measured in hectares) from land type k at time t. These decision variables are a function of land type as an optimal mining policy may require different management for each type. Mining activity by the firm affects two resources: $X_{k,t}$ is the mineral stock (measured in tonnes) on land type k at time t; $Y_{k,t}$ is the stock of damaged land (measured in hectares) in type k at time t. The cost of extraction is defined as $w(X_{k,t}, Q_{k,t})$. This cost increases as the stock declines; thus, $w_X < 0$ and $w_{XX} < 0$ (Pesaran 1990), where a subscript indicates a partial derivative. Moreover, mining cost increases with extraction; thus, $w_Q > 0$.

The cost of rehabilitation $c_k(E_{k,t})$ is a convex function. Degradation owing to extraction is defined as $hQ_{k,t}$, where h (measured in hectares damaged per tonne of mineral extracted) denotes the effect of mining on the stock of damaged land.

The social cost of damaged land is assumed to be given by the linear function, $d_k(Y_{k,t}) = d_k Y_{k,t}$. A terminal-value function $s^f_k(Y_{k,T})$ represents the net cost of damaged land of type k at time T. Mines generate both flow and stock pollutants. In addition to the social cost of damaged land, which is represented as a stock pollutant, mining may also generate flow emissions such as sulphur dioxide, greenhouse gases, dust and particulate matter. A flow pollutant, for instance GHG emissions from mining activity, is presented as a function of the rate of extraction and the stock of damaged land, $d^f_k(Q_{k,t}, Y_{k,t}) = d^{fQ}_k Q_{k,t} + d^{fY}_k Y_{k,t}$. This is defined as a linear-separable function to simplify the analysis below.

© 2012 The Authors
AJARE © 2012 Australian Agricultural and Resource Economics Society Inc. and Blackwell Publishing Asia Pty Ltd

The firm's profit function in land type k is given by:

$$\pi_k(p_t, X_{k,t}, Q_{k,t}) = p_t Q_{k,t} - w(X_{k,t}, Q_{k,t})$$

where p_t is the unprocessed ore price.

Optimal management by a regulator maximises social welfare, which considers the profitability of the firm and the societal impacts of land degradation. The problem is:

$$\max_{X_{k,t}, Q_{k,t}, Y_{k,t}, E_{k,t}} J^{SWF} = \sum_{t=0}^{T-1} \delta^t \left[\sum_{k=1}^{K} \pi_k(p_t, X_{k,t}, Q_{k,t}) - c_k(E_{k,t}) - d_k(Y_{k,t}) - d_k^f(Q_{k,t}, Y_{k,t}) \right] - \delta^T \sum_{k=1}^{K} s_k^c(Y_{k,T}), \tag{1}$$

subject to:

$$X_{k,t+1} = X_{k,t} - Q_{k,t} \text{ for } k = [1, 2, ..., K] \text{ and } t = [0, 1, ..., T-1] \tag{2}$$

$$Y_{k,t+1} = Y_{k,t} + hQ_{k,t} - E_{k,t} \text{ for } k = [1, 2, ..., K] \text{ and } t = [0, 1, ..., T-1] \tag{3}$$

$$Q_{k,t} \geq 0 \text{ for } k = [1, 2, ..., K] \text{ and } t = [0, 1, ..., T] \tag{4}$$

$$E_{k,t} \geq 0 \text{ for } k = [1, 2, ..., K] \text{ and } t = [0, 1, ..., T] \tag{5}$$

$$X_{k,0} = a_k \ \forall k, \text{ and } \mathrm{Y_{k,0} = b_k}, \text{and } \forall \mathrm{k} \tag{6}$$

where δ is a discount factor equal to $(1 + r)^{-1}$, r is the discount rate, and where $a_k \forall k$ and $b_k \forall k$ are initial conditions. The terminal value of the mine site is zero, as it is assumed that all economically viable mineral extraction has been completed, while the stock of damaged land of type k at time T incurs a societal cost. Equations 4–5 are inequality constraints stating that the control variables must be non-negative. Equations 1–6 together define a distributed control problem (Doole and White 2011) as all state and control variables are distributed over two dimensions: time and land type. The first-order conditions for an optimal solution to this system are presented in the Mathematical Appendix.

2.2. Social-welfare maximising equilibrium

From the results in the Mathematical Appendix and the assumption that the damage functions are linear in the case of the stock damage and linear and separable in the case of the flow emissions, the optimal policy can be implemented by a policy that sets two taxes: a tax on extraction to account for the flow emissions, such that $\tau_k^{fQ} = d_k^{fQ}$, and a tax on the stock of damaged land

© 2012 The Authors
AJARE © 2012 Australian Agricultural and Resource Economics Society Inc. and Blackwell Publishing Asia Pty Ltd

that accounts for both flow emissions and the social cost of damaged land, $\tau_k^{sY} = d_k^{sY} + d_k^{fY}$.

This gives us the first important result that for an optimal policy, the marginal cost of emissions to the firm should equal the damage cost. This result follows immediately from the first-order conditions in the Mathematical Appendix. In particular, if we take the internal solution for the derivative with respect to $Q_{k,t}$ (equation A4), we have:

$$p_t - w_Q(X_{k,t}, Q_{k,t}) - d_{k,Q}^f - \delta(\lambda_{k,t+1} - \gamma_{k,t+1}h) = 0,$$

where $\lambda_{k,t+1}$ is the shadow price (Lagrange multiplier) of the resource stock and $\gamma_{k,t+1}$ is the shadow cost of damaged land. With a tax, this condition becomes:

$$p_t - w_Q(X_{k,t}, Q_{k,t}) - \tau_k^{fQ} - \delta(\lambda_{k,t+1} - \gamma_{k,t+1}h) = 0. \qquad (7)$$

Further for the stock of damaged land, from equations A3 and A5, we have:

$$1 + r = (d_k^{sY} + d_k^{fY} + c_{k,E}(E_{k,t}))/c_{k,E}(E_{k,t-1}).$$

It is notable from this equation that the rate of rehabilitation is independent of the rate of extraction, and it drives the time path for damaged land so that the return from rehabilitation in the current period equals the reduction in the damage costs, $d_k^{sY} + d_k^{fY}$. With τ_k^{sY} a damaged land tax (DLT), this would become:

$$1 + r = (\tau_k^{sY} + c_{k,E}(E_{k,t}))/c_{k,E}(E_{k,t-1}), \qquad (8)$$

and would result in the firm following a socially optimal time path for the stock of damaged land.

2.3. Stochastic model

To simplify the model, assume bankruptcy occurs only in the terminal period, and if the mine is abandoned, the cost of rehabilitation is incurred by the regulator. White and Doole (2011) give a generalised stochastic control solution to this problem, and Tirole (2010) gives a theoretical analysis of the problem of firms with limited liability. In this case, the terminal condition $s_k^c(Y_{k,T})$ in equation (1) is replaced by:

$$\varphi s_k^c(Y_{k,T}) + (1 - \varphi)(1 + \kappa)s_k^r(Y_{k,T}), \qquad (9)$$

where φ is the probability of solvency at time T, $s_k^c(Y_{k,T})$ is the cost of re-habilitation when the firm is solvent, $s_k^r(Y_{k,T})$ is the cost to the regulator when the firm is insolvent, and κ is the shadow price of public funds. The shadow price of public funds accounts for the fact that the funding for mine rehabilitation comes from general tax revenue and thus incurs a deadweight loss (Campbell and Bond 1997). The term $s_k^r(Y_{k,T})$ allows for the fact that the regulator typically incurs a significant mobilisation cost to complete rehabilitation and thus $s_k^c(Y_{k,T}) < s_k^r(Y_{k,T})$.

2.4. Comparison of policy instruments

Environmental policy has two stated objectives: first to provide funds for rehabilitation in the event of non-compliance (a surety target), and second to ensure timely rehabilitation (an incentive target). In practice, these two objectives are typically pursued with a single instrument, that is, a bond. Following Tinbergen's principle (1952), that the number of instruments must at least equal the number of objectives, a policy based on a bond alone is unlikely to be optimal. To analyse the optimal policy, we incorporate the bond and a DLT into a simplified social-welfare function J^T where the regulator is a Stackelberg leader, in the sense that the regulator is able to anticipate how the firm will respond to the DLT and bond policy, and the firm is a follower (Baron 1985). Here, the land type subscript is dropped for clarity.

We apply the envelope theorem to define the firm's profit through time:

$$J^c(\alpha\eta + \tau^{sY}) = \max_{X_t, Q_t, Y_t, E_t} \begin{bmatrix} \sum\limits_{t=0}^{T-1} (\delta^t \pi(p_t, X_t, Q_t) - c_k(E_t) - (\alpha\eta + \tau^{sY}) Y_t) \\ -\delta^T (1-\varphi) s^c(Y_T); \\ \text{subject to equations(2) to (6)} \end{bmatrix}. \quad (10)$$

That is, $J^c(\alpha\eta + \tau^{sY})$ gives the present-value of profit for the firm from $t = 0$ to T as an optimal response to the DLT and bond rate. Define the term $\xi = \alpha\eta + \tau^{sY}$. This gives the firm's marginal cost of the stock of damaged land. It has two terms. The first term is made up of the bond rate η set by the regulator and the service charge set by the bond company α. The second term τ^{sY} is the DLT. The effect of the bond on rehabilitation effort and damage depends on the service charge set for the bond by the surety company. In the empirical model analysed in Section 4, it also depends on the opportunity costs of borrowing restrictions γ. Here, this term is set to zero. Note that the firm through $(1-\varphi)s^c(Y_T)$ in equation (10) accounts for its own risk of insolvency. If this term is relatively small, the firm will tend to reduce the rehabilitation effort.

The social-welfare function is:

$$\begin{aligned} J^T(\xi) = \pi^T(\xi) - d^T(\xi) - \delta^T\{\varphi s^c(\xi) + (1-\varphi)(1+\kappa)s^r(\xi)\} \\ -\alpha\eta \sum_{t=1}^{T} Y_t(\xi)\delta^t + \delta^T(1-\varphi)\kappa\eta Y_T + \kappa(\tau^{sY} \sum_{t=1}^{T} Y_t \delta^t) \end{aligned}, \quad (11)$$

© 2012 The Authors
AJARE © 2012 Australian Agricultural and Resource Economics Society Inc. and Blackwell Publishing Asia Pty Ltd

where $d^T(\xi)$ gives the present-value of external social costs. The first two terms on the right-hand side give the social-welfare function up to period $T-1$. The third term in curly brackets gives the expected cost of restoring the mine after mining ceases. The fourth term gives the bond cost to the firm. The fifth term is the expected payout of the bond with probability $1-\varphi$ defined as a reduction in the deadweight loss of taxation, and the final term gives the net benefit of the sum of environmental taxes.

To analyse the alternative policies, we make the following simplifying assumptions. First, the policy is set so that the incentive to rehabilitate is constant and set at the marginal damage. Define $\alpha\hat{\eta} = d^{sY}$ for bond-only and $\hat{\tau}^{sY} = d^{sY}$ for DLT-only policy. Thus, if we take the difference between the bond-only social welfare $J^T(\alpha\hat{\eta})$ and DLT-only social-welfare $J^T(\hat{\tau})$, the first three terms on the right-hand side of equation (11) cancel out, as the incentive effect is identical across the two policies by assumption. Accordingly,

$$\begin{aligned} J^T(\alpha\hat{\eta}) - J^T(\hat{\tau}^{sY}) = {} & \left(\left[\delta^T(1-\varphi)\kappa\hat{\eta}Y_T(\alpha\hat{\eta})\right] - \alpha\hat{\eta}\sum_{t=1}^{T-1} Y_t(\alpha\hat{\eta})\delta^t \right) \\ & - \kappa\hat{\tau}^{sY}\sum_{t=1}^{T-1} Y_t(\hat{\tau}^{sY})\delta^t. \end{aligned} \tag{12}$$

If equation (12) is positive (negative), then a bond (environmental tax) instrument is preferred. By definition, $\hat{Y}_t = Y_t(\alpha\hat{\eta}) = Y_t(\hat{\tau})$ and $\alpha\hat{\eta} = \hat{\tau}^{sY}$. Thus, equation (12) can be rewritten to give a condition for the bond to be strictly preferred by the regulator:

$$J^T(\alpha\hat{\eta}) - J^T(\hat{\tau}^{sY}) > 0 \Rightarrow \left[\delta^T(1-\varphi)\kappa\hat{\eta}\hat{Y}_T\right] > \hat{\tau}^{sY}(\kappa+1)\sum_{t=1}^{T-1}\hat{Y}_t\delta^t. \tag{13}$$

It shows that a bond is preferred if expected revenue from the bond exceeds the bond cost to the firm plus the tax revenue generated by the DLT.

The other aspect of this policy is downside risk, and the expected 'loss' to the regulator is measured as the expected difference between the funds available from a bond and/or an environmental tax and the costs of rehabilitation. The bond can be set so that $\eta = s^r(\xi)$, and the risk to the regulator of a shortfall of funds in the event of insolvency is zero. This policy does not guarantee an optimal incentive. However, a DLT policy could represent a significant risk to the regulator when the expected life of the mine is relatively short and the probability of bankruptcy high. Thus there are advantages of using a mixed policy where the bond optimally reduces risk and the DLT provides an optimal incentive for rehabilitation.

3. Current environmental policies in Australia and New Zealand

With reference to the theoretical model, this section briefly reviews current specific environmental policies for mining. In Australia, New Zealand and internationally (Cobby 2006; Peck and Sinding 2009; World Bank, 2009), environmental bonds are the main policy instrument. Bonds are typically arranged as follows. The firm puts forward a mining proposal to the regulator for approval. Prior to approval, the firm must agree with an environmental contract that states the expected nature and extent of environmental damage and the remedial actions to be taken. In addition, the firm must arrange financial assurance (a bond), usually through a financial institution (usually a bank or insurer), to cover some proportion of rehabilitation costs. The regulator can 'call in' the bond (i.e. acquire the funds from the financial institution) unconditionally if the firm does not comply with the environmental contract.

Normally, the bond is only 'called-in' when the mining firm is declared bankrupt. In Western Australia, less than 2 per cent of outstanding bonds are called-in (Department of Mines and Petroleum (DMP) 2010a,b), and these are often for relatively small-scale operations. More commonly for mines with profitable ore reserves, the mine is sold to another firm as a going concern and the liability for the environmental contract transfers to the new holder of the mining lease. The financial institution (usually one of the major banks) receives an annual service charge for the bond, typically between 0.5 and 3 per cent of the bond amount. The service charge is set based on the firm's insolvency risk rating. Table 1 indicates the significance of bonds and their coverage of rehabilitation costs in Australia.

The requirement for environmental bonds arises because of the anticipated shortfall of funds to meet the environmental liabilities as a result of bankruptcy. For instance, insolvency law in Australia makes no explicit provision to cover environmental liabilities before other liabilities are met (Briggs 2006; Omar 2010). In fact other liabilities, such as workers redundancy payments and unpaid tax, often take a higher precedence.

Table 2 Estimates of outstanding bonds and per cent of rehabilitation costs in Australian states and territories

State or Territory	Total value of bonds (A$ million)	Estimated % of total rehabilitation costs
New South Wales	460	40–50%
Northern Territory	115	Not estimated
Queensland	785	45–50%
South Australia	88	40–50%
Tasmania	27	Not estimated
Victoria	110	40–50%
Western Australia	480	25%
Total value (A$ million)	2035	

Source: Cobby (2006).

© 2012 The Authors
AJARE © 2012 Australian Agricultural and Resource Economics Society Inc. and Blackwell Publishing Asia Pty Ltd

The number and frequency of reviews of environmental policy for mining (Cobby 2006; Department of Environment and Resource Management, 2007; Department of Mines and Energy, 2007; DMP, 2009; Department of Primary Industries NSW, 2006; Department of Primary Industries Victoria, 2009; Department of Resources, 2006, 2007; Department of Environment and Resource Management, 2007; Mineral Resources Tasmania, 2008; Ministry of Economic Development, 2011) reflects a shift towards a polluter-pays approach to environmental policy as applied to mining as the regulations are tightened and the funds firms are expected to provide as financial assurance increases. Regulators are keen to avoid the high-profile mistakes of the past. For instance, the Woods Reef asbestos mine in New South Wales (NSW) was abandoned when Chrysotile Mining Corporation ceased trading in 1983 and has not been rehabilitated 27 years later (NSW Ombudsman, 2010). The expected cost of removing the asbestos processing plant was estimated at $5.5 million in 2010 (NSW Ombudsman, 2010). The cost of rehabilitating the 400-ha site itself is expected to be many times higher.

Current environmental policies used throughout Australia and New Zealand are summarised in Table 3. Environmental policy for mines, in most cases, is incorporated into state mining acts as later amendments. Significant departures from this are Queensland, which separated its Environmental Protection Act 1994 from its Mineral Resources Act 1989, and Western Australia, which has a Mining Act 1978 and separate State Mining Agreements (various dates) for larger projects. All jurisdictions require bonds (Table 2). The preferred financial instrument is an unconditional bank guarantee, although four jurisdictions accept cash and two (NSW and Queensland) accept insurance bonds.

The current application of bond policy is generally not entirely consistent with the theoretical model in Section 2. This can be explained by the fact that the bond policy is driven by risk management and cost recovery concerns and not by efficiency concerns. However, measures have been taken in a number of jurisdictions to improve the efficiency of the bond policy.

1. The bond rate per hectare is calculated, in all Australian and New Zealand jurisdictions, using the estimated costs of rehabilitation for the firm, and not the marginal social cost of environmental damage as proposed by the theoretical model. This means that there is no attempt made to differentiate between mines with different environmental damage costs through bond rates.
2. The theoretical model advocates immediate bond reduction as rehabilitation progresses to provide an incentive effect (Jones 2006; Mackenzie *etal.* 2007). Most jurisdictions allow bond adjustments as part of a periodic review process. WA has specified fixed reduction rates for particular stages of rehabilitation, including carrying out primary remedial earthworks, replacement of topsoil and revegetation.

3. Bond rates, according to the theoretical model, should reflect the risk of firm non-compliance. Queensland recognises this and provides bond discounts to companies that have good performance records and have adopted ISO 14 000 standards. However, none of the jurisdictions assess the probability of insolvency directly.
4. In a recent development (DMP, 2011), WA is undertaking a further review of bonds and is currently proposing a combined bond and ‘Fidelity Fund’ scheme where firms are required to provide surety and pay into a fund to provide for the costs of non-compliance across the sector. This is a move towards adding a form of damaged land tax (DLT) to a bond policy

4. Empirical case study

The case study in this Section analyses the efficiency gains associated with optimal policy using either a bond policy, a DLT or a mixed policy for different land types in terms of environmental damage. The analysis also shows the loss in efficiency associated with policy that does not discriminate between high-value and low-value environmental assets, and does not provide optimal incentives for rehabilitation.

4.1 Model parameterisation

The case study is based on firm data for the WA mineral sands sector. Full details of the case study are given in White and Doole (2011) and Doole and White (2011), including methods of determining the probability of insolvency. The model is defined in equations (1) to (6) with $K = 3$ and $T = 10$. Table 1 gives parameter values and definitions. A single firm extracts from all land types. The resource stock is divided equally among the three land types to simplify the comparison.

Damage and rehabilitation costs are increasing with k. Three different types of mines are defined, each with different levels of social cost incurred for a given level of mine site damage. Damage costs for the first land type ($k = 1$) are the annual opportunity cost of lost agricultural production, those in the second land type ($k = 2$) are the annual lost value of agricultural production and non-market values given the site’s proximity to an urban centre, and those in the third type ($k = 3$) represent non-market values of disturbed high biodiversity state forest. The one-off rehabilitation cost for the third land type is much higher than for the other land types (Table 3). This reflects the high cost of restoring a natural ecosystem and is based on information from a variety of mining firms (Koch and Hobbs 2007).

The mining cost function is that used by Pesaran (1990):

$$w(X_{k,t}, Q_{k,t}) = \psi_1 + \psi_2 Q_{k,t}^2(\psi_3 + \psi_4 X_{k,t}^{-1}), \tag{14}$$

Table 3 Summary of environmental bond policies in Australia and New Zealand

Region	Bond instrument	Basis of bond costs	Progressive bond release	Risk adjustment	Target per cent of costs
Australia					
Northern Territory	Cash, bank guarantee	Standard cost estimator	Yes, review	No	100
New South Wales	Cash, bank guarantee, insurance bond	Standard cost estimator	Yes, review	No	100 plus 25% for mobilisation costs
Queensland	Cash, bank guarantee, insurance bond	Standard cost estimator	Yes, review	Yes, based on performance and adoption of ISO14000	100
South Australia	Bank guarantee	Standard cost estimator	Yes, discretionary	No	100 or above
Tasmania	Cash, bank guarantee	Standard cost estimator, fixed rates for smaller projects	Yes, funds released to fund rehabilitation work	No	100
Victoria	Bank guarantee	Standard cost estimator, fixed rates for simple projects	Yes, review	No	100
Western Australia	Bank guarantee	Fixed rates	Yes, at fixed rates	No	50
New Zealand	Cash, bank guarantee	Fixed	No	No	100

Sources: Cobby (2006); Department of Environment and Resource Management (2007); Department of Mines and Energy (2007); Department of Mines and Petroleum (2009); Department of Primary Industries NSW (2006); Department of Primary Industries Victoria (2009); Department of Resources (2006); Department of Environment and Resource Management (2007); Mineral Resources Tasmania (2008); Ministry of Economic Development (2011).

© 2012 The Authors
AJARE © 2012 Australian Agricultural and Resource Economics Society Inc. and Blackwell Publishing Asia Pty Ltd

where ψs are estimated parameters. This function is estimated through the regression of cost data using a random-effects model for a panel data set containing information from individual mine sites (White and Doole 2011).

The results also include an analysis of a carbon 'tax' policy. The carbon tax in New Zealand is fixed at \$NZ12.50 per tonne of CO_2 (approximately \$A15.67) and in Australia at \$23 per tonne. Mudd (2007) estimates a figure of 21.7 kg of CO_2 per tonne of ore for Australian mining, although this depends on haul distances and other factors.

4.2. Deterministic social-welfare maximising solution

The social-welfare maximising solution provides a benchmark against which second-best policy solutions can be compared. Figure 1 illustrates the state variables of ore and damaged land and the decision variables of extraction and rehabilitation, both through time and across land types, for the cases of social-welfare maximisation and no-regulation. Taking the no-regulation case, each land type is mined in an identical fashion by the firm, there is no rehabilitation during mining, and the area of damaged land is the whole area available for mining. Where social welfare is maximised, extraction in each land type follows a different time path. Where there is a low social cost of damaged land ($k = 1$), mining patterns are similar to the no-regulation case. For the land type with a high social cost and high cost of rehabilitation ($k = 3$), extraction is minimal and rehabilitation is rapid. For this land type, environmental policy induces high grading where only the lowest-cost resources are extracted.

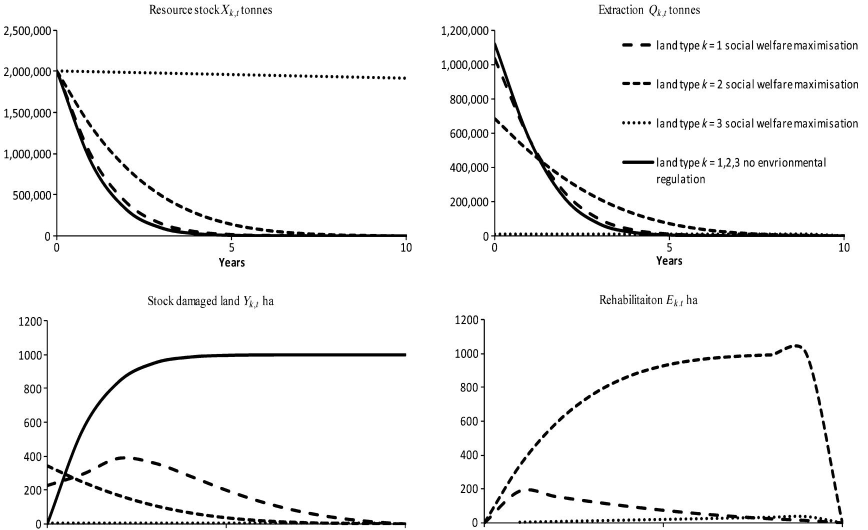

Figure 1 Comparative dynamics by cohort for a social-welfare maximising and unregulated profit-maximising firm.

4.3. Policy with a probability of bankruptcy

The regulator can apply a DLT and bond rate differentiated by land type either separately or in a mixed policy. In designing policy, the regulator also accounts for the shadow price of tax funds κ, the probability of bankruptcy φ, the mobilisation cost for the regulator to rehabilitate measured as a proportion of the cost to the firm S^r/S^c and the opportunity cost of the bond amount in terms of reduced borrowing and capital investment γ. It is reasonable to assume that the regulator operates under some further policy constraints. First, the bond amount cannot exceed the regulator's costs of rehabilitation to the regulator: $s^r(Y_T) \leq \eta Y_T$. Notably in the analysis below, it is necessary in some instances to set $s^r(Y_T) < \eta Y_T$ to ensure an optimal incentive effect. Second, in a mixed policy, the total bond service charge plus the tax on damaged land must be less than or equal to the marginal damage cost: $d_k^{sY} \geq \tau_k^{sY} + \alpha\eta_k$.

Table 4 presents the baseline results. A number of important points are evident. The social-welfare maximisation problem gives the first-best solution where the regulator determines all variables directly. An unregulated firm imposes a significant cost on society and reduces social welfare, but the firm's profit increases significantly. If the firm is regulated by a tax or bond set at their maximum level, then it approximately maximises total social welfare. If the tax and bond are set to give the same marginal incentive, differences in social welfare are owing to differences in the present-value of tax revenue. If the current WA bond policy is applied, then social welfare is significantly reduced compared to the first-best solution.

The effects of the carbon tax on model output are relatively small. In the unregulated case, it only reduces profits by 2 per cent. With an optimal DLT, the carbon tax reduces profit by 3 per cent compared to profit with the DLT but without the carbon tax. Interestingly, the carbon tax increases social welfare through a double-dividend effect, even when, as here, the external damage cost of carbon dioxide is not included.

Table 4 Base model output for expected parameter values

	Social welfare ($ millions)	Profit ($ millions)
1. Maximise social welfare	92.95	92.95
2. Unregulated profit	45.35	149.81
3. Damaged land tax (DLT) only	88.35	95.05
4. Bond only	88.67	95.05
5. WA bond policy	64.80	101.29
6. Profit with carbon tax	46.26	146.91
7. DLT only with carbon tax	88.50	92.51

Note: base parameters are $\gamma = 0$ (no credit limit); $\kappa = 0.1$ deadweight loss of taxation; $\phi = 0.1$ probability of bankruptcy resulting in non-compliance; $S^r/S^c = 2$ is the ratio of the cost of rehabilitation to the regulator to the cost of rehabilitation to the firm and measures the regulator's mobilisation cost.

© 2012 The Authors
AJARE © 2012 Australian Agricultural and Resource Economics Society Inc. and Blackwell Publishing Asia Pty Ltd

For a range of plausible parameter values applied in a sensitivity analysis, a tax policy is optimal (Table 5). However, when the probability of bankruptcy φ is relatively high (40 per cent), the opportunity cost of the bond γ is relatively low, the shadow price of public funds κ is high, and then, the bond is optimal. Across all parameters, the current WA bond policy reduces social welfare compared to the optimal policy which is either a bond or an environmental tax set between 15 and 33 per cent of costs, with an average for the parameter sets of 24 per cent.

Environmental bonds are favoured by regulators as they are risk reducing. To ensure the optimal incentive per ha, the bond rate would have to be very high because of the low level of the service charge rate. In this case, under optimal management, for land type 1 the bond is \$20 000 per ha, for land type 2 the bond is \$170 000 per ha, and for land type 3 the bond is \$330 000 per ha (Table 6). These amounts far exceed the cost of rehabilitation and would likely be untenable. They serve to illustrate an evident problem with a bond policy that to achieve an adequate incentive level, at current service charge rates set by the surety company, it is necessary to set unrealistically high bond rates, often many times the rehabilitation costs. The DLT policy generates funds over the life of the mine, but these funds may not be sufficient to cover the cost to the regulator of rehabilitation. Risk levels are analysed in Table 6 as the percentage of the final rehabilitation cost covered. The tax policy gives an adequate coverage for the mine on land with the low environmental value, but partial cover for mines with medium and high environmental values. There is a similar pattern of cost coverage for the WA bond.

Table 5 Sensitivity analysis and comparison with current WA policy

Parameters				Tax only		Bond only		WA policy	
γ	κ	φ	S^r/S^f	SW	Profit	SW	Profit	SW	Profit
0	0	0	0	92.95	92.95	89.37	92.95	75.25	103.10
0	0	0	1	92.94	92.94	89.15	92.94	68.35	101.29
0	0	0.4	0	92.94	101.34	89.15	101.34	65.29	95.85
0	0	0.4	1	84.54	101.34	80.75	101.34	72.02	103.10
0	0.2	0	0	93.39	92.95	89.37	92.95	75.60	103.10
0	0.2	0	1	93.40	92.94	89.15	92.94	66.10	101.29
0	0.2	0.4	0	91.72	101.34	103.75	101.34	71.98	99.47
0	0.2	0.4	1	81.64	101.34	93.67	101.34	73.61	101.29
0.04	0	0	0	92.95	92.95	83.63	87.22	71.62	99.47
0.04	0	0	1	92.94	92.94	83.10	86.88	64.72	97.66
0.04	0	0.4	0	92.94	101.34	83.10	95.28	68.39	99.47
0.04	0	0.4	1	84.54	101.34	74.69	95.28	68.39	99.47
0.04	0.2	0	0	93.39	92.95	83.63	87.22	71.98	99.47
0.04	0.2	0	1	93.40	92.94	83.10	86.88	62.47	97.66
0.04	0.2	0.4	0	91.72	101.34	97.69	95.28	68.35	95.85
0.04	0.2	0.4	1	81.64	101.34	87.61	95.28	69.99	97.66

Table 6 Estimates of cost coverage (the proportion of total rehabilitation costs covered through the use of a given policy instrument) by mine for the damaged land tax (DLT), bond and WA bond policy

Policy	Land type (k)			
	1	2	3	Total
Parameters				
Y_{kT} (ha)	624.00	2.55	988.76	1615.31
Rehabilitation cost ($ per ha)	750.00	2000.00	33000.00	
Total rehabilitation cost (millions)	0.47	5100.00	33.62	34.09
Bond policy				
Bond ($ per ha)	20000.00	170000.00	330000.00	
Total bond revenue ($ million)	12.48	0.43	326.29	339.20
Cost coverage bond	26.55	85.00	9.71	9.95
DLT policy				
DLT ($ per ha)	500.00	4000.00	8000.00	
Tax revenue ($ millions)	2.16	0.00	1.43	3.59
Cost coverage tax	4.61	0.00	0.04	0.11
WA bond policy				
WA bond revenue ($ per ha)	7500.00	7500.00	7500.00	
Total WA bond ($ million)	4.68	0.02	7.42	12.11
Bond cost coverage WA bond	10.00	3.75	0.22	0.36

Cost coverage is given by the present-value of revenue from a called-in bond or damaged land tax (DLT) revenue divided by the total cost of rehabilitation to the regulator. For example, the cost coverage of the bond for land type 1 is 12.48/0.47 = 26.55.

5. Policy implications

The policy implications of the theoretical analysis and case studies are as follows:

1. Optimal policy in social-welfare terms entails setting policy so that the charge for damaged land equals the marginal damage cost, and thus, this requires the regulator to assess how much the damaged land costs society per year. This may be straightforward for agricultural land, but more difficult to estimate for natural ecosystems (Burton *et al.*, 2012).
2. Mixed policies may be advantageous where a DLT supplements a bond. The new Fidelity Fund proposal in Western Australia (Department of Mines and Petroleum, 2011) is already considering this type of option. From the theoretical analysis, a bond is preferred to a DLT where the probability of bankruptcy is high and progressive rehabilitation is difficult. If the extra resource cost to society of the surety company providing the bond and the opportunity cost of credit is taken into account, then the evidence favours a DLT in preference to a bond. In general, it is assumed that the regulator favours an instrument mix that generates more tax than less. This is because the policy brings a double-dividend effect in terms of reducing the call on general tax revenue.
3. As a second-best policy, setting the bond rate at the cost to the regulator of rehabilitation may be an improvement, especially in WA where

© 2012 The Authors
AJARE © 2012 Australian Agricultural and Resource Economics Society Inc. and Blackwell Publishing Asia Pty Ltd

currently the bond rates are only 50 per cent of the rehabilitation cost to the firm. This increase in rates reduces risk to the regulator and increases the incentive effect.

4. The carbon tax will lead to a reduction in output and may also reduce other stock and flow externalities from mining, but has a relatively minor effect in this case study.

6. Conclusions

Environmental policy in the Australian and New Zealand mining sectors primarily focuses on providing funds to rehabilitate abandoned mine sites. This analysis has indicated that this focus may be partially misguided in that, at typical bond rates set by the regulator and bond service charges set by the surety company, a bond policy alone provides little incentive for progressive rehabilitation.

The case study for the mineral sands sector in Western Australia indicates that a DLT may be a better policy and, if necessary, can be combined with a bond to reduce the risk to the regulator of firm insolvency. The other advantage of a DLT policy is that it also generates funds that could be used to cover the cost of administering the environmental scheme and funding substitute conservation measures elsewhere as an environmental offset.

A significant drawback of a bond policy is that while the firm is paying for the costs of servicing the bond, it does not generate funds that can be used by the regulator. In this respect, a DLT that generates some of the costs of rehabilitation may be preferable, as it increases the funds available for environmental conservation.

References

Australian Bureau of Agricultural and Resource Economics and Science (2010). *Australian Commodity Statistics 2010*. ABARES, Canberra.

Australian Bureau of Statistics (ABS) (2010). *Australian System of National Accounts*. Australian Bureau of Statistics, Canberra. http://www.ausstats.abs.gov.au/ausstats/subscriber.nsf/0/556894E44C26469ECA2577CA00139858/$File/52040_2009-10.pdf, accessed 20 April 2011.

Baron, D.P. (1985). Noncooperative regulation of a nonlocalised externality, *Rand Journal of Economics* 16, 553–568.

Baumol, W.J. and Oates, W.E. (1988). *The Theory of Environmental Policy*, 2nd edn. Cambridge University Press, Cambridge UK.

Bell, F.G. and Donnelly, L.J. (2006). *Mining and its Impact on the Environment*. Taylor and Francis, London.

Bohm, P. and Russell, C. (1985). Comparative analysis of alternative policy instruments, in Kneese, A.V. and Sweeney, J.L. (eds), *Handbook of Natural Resource and Energy Economics, vol. 1*. Elsevier, New York, pp. 395–460.

Boyd, J. (2001). *Financial Responsibility for Environmental Obligations: Are Bonding and Assurance Rules Fulfilling their Promise?* Resources for the Future Discussion Paper 01-42, Resources for the Future, Washington, DC.

© 2012 The Authors
AJARE © 2012 Australian Agricultural and Resource Economics Society Inc. and Blackwell Publishing Asia Pty Ltd

Briggs, J. (2006). Managing for mine closure. Australian Mining and Petroleum Law Association Yearbook 2006: 464–487.

Burton, M.P., Zahedi, S.J. and White, B. (2012). Public preferences for timeliness and quality of mine site rehabilitation. The case of bauxite mining in Western Australia, Resources Policy. Available from URL: http://dx.doi.org/10.1016/j.resourpol.2012.01.004 [accessed 8 March 2012].

Campbell, H.F. and Bond, K.A. (1997). The cost of public funds in Australia, *Economic Record* 73, 22–34.

Cobby, G. (2006). Review of environmental performance bonds in Western Australia, in Fourie, A. and Tibbett, M. (eds), *Mine Closure 2006: Proceedings of the First International Seminar on Mine Closure*. Australian Centre for Geomechanics, Perth, Western Australia. pp. 75–80.

DCCEE (2011). *National Inventory Report by Economic Sector 2009*. DCCEE, Canberra, Australian Capital Territory.

Department of Environment and Resource Management (2007). *Environmental Management – Mining*, Department of Environment and Resource Management, Brisbane, Queensland, http://www.derm.qld.gov.au/environmental_management/land/mining/index.html, accessed 20 Jan 2010.

Department of Mines and Energy (2007). *Environmental Management and Regulation of Mining in Queensland*, Department of Employment, Economic Development and Innovation – Queensland Mines and Energy, Brisbane, Queensland. http://www.dme.qld.gov.au/mines/environment.cfm, accessed 20 Jan 2010.

Department of Mines and Petroleum (2009). *Bond Policy Effective 1 July 2008: Mineral Guidelines*, Department of Mines and Petroleum, Perth, Western Australia, http://www.dmp.wa.gov.au/836.aspx, accessed 20 April 2011.

Department of Mines and Petroleum (2011). *Policy Options for Mining Securities in Western Australia*. Department of Mines and Petroleum, Perth, Western Australia.

Department of Primary Industries NSW (2006). *Rehabilitation Security Deposit Requirements for Mining and Petroleum Titles, ESB20, June, Mineral Resources Division*, Department of Primary Industries NSW, Sydney, NSW. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0020/96131/esb20-Rehabilitation-Security-Deposit-Requirements-for-Mining-and-Petroleum-Titles.pdf, accessed 20 April 2011.

Department of Primary Industries Victoria (2009). *Review of the Mineral Resources (Sustainable Development) Act 1990 – Release of targeted discussion papers*, Department of Primary Industries, Melbourne, FL. http://www.dpi.vic.gov.au/DPI/nrenmp.nsf/childdocs/-369C0-5B2054996AA4A256A1E001F3045-D9E77F4A47EA6484CA25759E001DB6FD-316009-7D20197143CA2574D50002AAA7?open, accessed 20 April 2011.

Department of Resources (2006). *Security Policy*, Northern Territory Department of Resources – Minerals and Energy, Darwin, Northern Territory. http://www.nt.gov.au/d/Minerals_Energy/Content/File/Forms_Guidelines/AA7-003_200605_SECURITY_POLICY_FINAL_CAB_ENDORSED.pdf, accessed 20 April 2011.

Department of Resources (2007). *Security Calculation Procedure*, Northern Territory Department of Resources – Minerals and Energy, Darwin, Northern Territory, http://www.nt.gov.au/d/Minerals_Energy/Content/File/Forms_Guidelines/AA7-013_Security_Calculation_Procedure_Guide.pdf, accessed 25 Jan 2010.

DMP (2010a). *Department of Mines and Petroleum bond policy*. DMP, Perth, Western Australia.

DMP (Department of Mines and Petroleum) (2010b). *Policy Options for Mining Securities in Western Australia*. Department of Mines and Petroleum, Perth, Western Australia.

DMP (Department of Mines and Petroleum) (2011). *Western Australia's Mining Security System: Preferred Option Paper*, Department of Mines and Petroleum, Perth, Western Australia.

Doole, G. and White, B. (2011). *Optimal Dynamic Regulation of the Environmental Impact of Mining Across Diverse Land Types*. University of Waikato Discussion Paper, Hamilton.

Farzin, Y.H. (1996). Optimal pricing of environmental and natural resource use with stock externalities. *Journal of Public Economics* 62, 31–57.

Geosciences Australia (2011). *Australian Mine Atlas Data Sheets*, Geosciences Australia, Canberra, http://www.australianminesatlas.gov.au/mapping/downloads.jsp#ozmin, accessed 20 April 2011.

Gerard, D. (2000). The law and economics of reclamation bonds, *Resources Policy* 26, 189–197.

ICMM (2005). *Financial Assurance for Mine Closure and Reclamation*. International Council on Mining and Metals, London, UK.

Jones, H. (2006). The surety conundrum, in Fourie, A. and Tibbett, M. (eds), *Mine Closure 2006: Proceedings of the First International Seminar on Mine Closure*, Australian Centre for Geomechanics, Perth, Western Australia. pp. 475–485.

Koch, J.M. and Hobbs, R.J. (2007). Synthesis: is Alcoa successfully restoring a jarrah forest ecosystem after bauxite mining in Western Australia, *Restoration Ecology Supplement* 15, 137–144.

Mackenzie, S., Jasper, D., Lacy, H.W.B. and Bow, B. (2007). Progressive reduction of liabilities and recovery of financial sureties in recognition of successful rehabilitation in Western Australia. in Fourie, A., Tibbett, M. and Wiertz, J. (eds), *Mine Closure 2007: Proceedings of the Second International Seminar on Mine Closure*, Australian Centre for Geomechanics, Perth, Western Australia. pp. 365–374.

Mineral Resources Tasmania (2008). *The Tasmanian Security Deposit System for Mining and Exploration Tenements*, Tasmanian Department of Infrastructure, Energy and Resources, http://www.mrt.tas.gov.au/pls/portal/docs/PAGE/MRT_INTERNET_PAGE_GROUP/MRT_EXPLORATION_AND_MINING/MRT_EXPLORATION_LICENCES/GENERAL%20_CONDITIONS/UR2008_02.PDF, accessed 20 April 2011.

Ministry of Economic Development, New Zealand (2011). Bonds and cash deposits. Worksite Document No. 621551.

Mudd, G.M. (2007). Global trends in gold mining: towards quantifying environmental and resource sustainability, *Resources Policy* 32, 42–56.

Mudd, G.M. (2010). The environmental sustainability of mining in Australia: key mega-trends and looming constraints, *Resources Policy* 35, 98–115.

National Land and Water Resources Audit (2002). *Australian Natural Resources Atlas*, Australian Government, Canberra, Australian Capital Territory. http://www.anra.gov.au/topics/land/landuse/index.html, accessed 20 April 2011.

New Zealand Government (2010). *Some Facts about Mining in New Zealand (Press Release Wednesday, 24 March 2010)*. New Zealand Government, Wellington, New Zealand.

NSW Ombudsman (2010). *Responding to the Asbestos Problem: The need for Significant Reform in NSW*, NSW Ombudsman, Sydney, NSW, http://www.ombo.nsw.gov.au/publication/PDF/specialreport/SR_AsbestosProblem_Nov10.pdf, accessed 20 April 2011.

Omar, P.J. (2010). Disclaiming onerous property in insolvency: a comparative study, *International Insolvency Review* 19, 41–63.

Ormsby, W.R., Howard, H.M. and Eaton, N.W. (2003). Inventory of abandoned mine sites: progress 1999–2002. Geological Service of Western Australia, Record 2003/9, Perth.

Peck, P. and Sinding, K. (2009). Financial assurance and mine closure: stakeholder expectations and effects on operating decisions, *Resources Policy* 34, 227–233.

Perrings, C. (1989). Environmental bonds and environmental research in innovative activities, *Ecological Economics* 1, 95–110.

Pesaran, M.H. (1990). An econometric analysis of exploration and extraction of oil in the UK continental shelf, *The Economic Journal* 100, 367–390.

Shogren, J.F., Herriges, J.A. and Govindasamy, R. (1993). Limits to environmental bonds, *Ecological Economics* 8, 109–133.

Solow, R. (1971). The economist's approach to pollution and its control, *Science* 173, 502–511.

© 2012 The Authors
AJARE © 2012 Australian Agricultural and Resource Economics Society Inc. and Blackwell Publishing Asia Pty Ltd

Statistics New Zealand (2010). *National Accounts Year Ended March 2010 – Tables*. Statistics New Zealand, Wellington, New Zealand.

Tinbergen, J. (1952). *On the Theory of Economic Policy*. North-Holland Pub. Co., Amsterdam, the Netherlands.

Tirole, J. (2010). From Pigou to extended liability: on the optimal taxation of externalities under imperfect financial markets, *Review of Economic Studies* 77, 697–729.

White, B. and Doole, G.J. (2011). *Environmental Bonds and Environmental Policy for Mining in Western Australia*. Discussion Paper. School of Agricultural and Resource Economics University of Western Australia.

World Bank (2009). *Financial Surety*. World Bank, Washington, DC.

Xabadia, A., Renan, U.G. and Zilberman, D. (2006). Control of accumulating stock pollution by heterogeneous producers, *Journal of Economic Dynamics and Control* 30, 1105–1130.

Mathematical Appendix

The Lagrangian for this problem is:

$$L=\sum_{t=0}^{T-1}\delta^t\left\{\begin{array}{l} p_t(\sum_{k=1}^{K}Q_{k,t})-\sum_{k=1}^{K}\Big(w(X_{k,t},Q_{k,t})+c_k(E_{k,t})+d_k^s(Y_{k,t})+d_k^f(Q_{k,t},Y_{k,t})\Big) \\ -\sum_{k=1}^{K}\delta\lambda_{k,t+1}\left[X_{k,t+1}-X_{k,t}+Q_{k,t}\right]-\sum_{k=1}^{K}\delta\gamma_{k,t+1}\left[Y_{k,t+1}-Y_{k,t}-hQ_{k,t}+E_{k,t}\right] \\ -\sum_{k=1}^{K}\mu_{k,1}Q_{k,t}-\sum_{k=1}^{K}\mu_{k,2}E_{k,t} \end{array}\right\}$$
$$-\delta^T\sum_{k=1}^{K}s_k(Y_{k,T}) \qquad \text{(A1)}$$

The Kuhn Tucker (KT) conditions are applied as equations 1–6 contain inequality constraints and the constraint set satisfies standard regularity conditions. The KT conditions are given by equations 2–5 and:

$$\frac{\partial L}{\partial X_{k,t}}=\delta\lambda_{k,t+1}-\lambda_{k,t}=w_X(X_{k,t},Q_{k,t}) \text{ for } k=[1,2,...,K] \text{ and } t=[0,1,...,T-1], \qquad \text{(A2)}$$

$$\frac{\partial L}{\partial Y_{k,t}}=\delta\gamma_{k,t+1}-\gamma_{k,t}=d_k^{sY}+d_k^{fY} \text{ for } k=[1,2,...,K] \text{ and } t=[0,1,...,T-1], \qquad \text{(A3)}$$

$$\frac{\partial L}{\partial Q_{k,t}}=\left\{\begin{array}{l} Q_{k,t}>0\Rightarrow p_t-w_Q(X_{k,t},Q_{k,t})-d_k^{fQ}-\delta(\lambda_{k,t+1}-\gamma_{k,t+1}h)=0 \\ Q_{k,t}=0\Rightarrow p_t-w_Q(X_{k,t},Q_{k,t})-d_k^{fQ}-\delta(\lambda_{k,t+1}-\gamma_{k,t+1}h)-\mu_{k,1}\leq 0 \end{array}\right\}$$
$$\text{for } k=[1,2,...,K] \text{ and } t=[0,1,...,T-1], \qquad \text{(A4)}$$

$$\frac{\partial L}{\partial E_{k,t}} = \left\{ \begin{array}{l} E_{k,t} > 0 \Rightarrow -c_{k,E}(E_{k,t}) - \delta\gamma_{k,t+1} = 0 \\ E_{k,t} = 0 \Rightarrow -c_{k,E}(E_{k,t}) - \delta\gamma_{k,t+1} - \mu_{k,2} \leq 0 \end{array} \right\}$$

$$\text{for } k = [1, 2, ..., K] \text{ and } t = [0, 1, ..., T-1], \tag{A5}$$

$$\mu_{k,1} Q_{k,t} = 0, \mu_{k,1} \geq 0, \mu_{k,2} Q_{k,t} = 0, \mu_{k,2} \geq 0, \tag{A6}$$

$$X_{k,0} = a_k \forall k,\ Y_{k,0} = b_k \forall k,\ \lambda_{k,T} = 0, \forall k, \text{ and } \gamma_{k,T} = \delta^T s_k^Y(y_{k,T}) \forall k. \tag{A7}$$

© 2012 The Authors
AJARE © 2012 Australian Agricultural and Resource Economics Society Inc. and Blackwell Publishing Asia Pty Ltd