Non-renewable Resource Extraction under Financial Incentives to Reduce and Reverse Stock Pollution

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Sept 11, 2018

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Abstract

This paper examines the impacts of financial incentives on non-renewable resource extraction that produces reversible stock pollution. A particular emphasis is the timing of reclamation. We show that traditional standards-based regulation incentivizes operators to delay reclamation. A policy that instead requires the operator to pay ongoing damages from the pollution stock via a Pigouvian stock tax is not only socially optimal but provides the operator with the correct incentives to reclaim the pollution stock. A Pigouvian pollution flow tax, which has been a popular recommendation in the stock pollution literature, does not generate these reclamation incentives. The financial incentives embodied in regulatory reform in the United States, China and Western Australia have no explicit intention of implementing a Pigouvian stock tax. They are therefore unlikely to incentivize optimally timed reclamation by the firm, even though the policy reforms have been driven by a recognition that past policies were ineffective at incentivizing reclamation.

JEL classifications: Q32; Q53; Q58
Keywords: Mining; Hotelling; Reclamation; Pigouvian taxes; Stock pollution; Financial assurance; Superfund; CERCLA 108(b).

1 Introduction

The optimal regulation of pollution stocks has been well studied. Little has been done, however, to investigate the incentive effects of the de facto policies that governments create to regulate such stocks. This paper studies the historical and newly proposed regulation
in the United States, Australia, and China of the large stocks of surface waste created by mining. These stocks not only diminish amenity values in the immediate vicinity of the mine via degradation of scenic quality, they also contain toxic substances. In the United States metal mining is the largest polluter of the 29 industrial sectors tracked, being responsible for 37 percent of toxic releases (US EPA, 2015). The four most common environmental contaminants from mining are the heavy metals lead, arsenic, zinc, and cadmium (US EPA, 2004). Importantly, these metals impact the environment mainly through their accumulated stocks, rather than flows (Nobbs and Pearce, 1976; Hong et al., 1995). The only negative effect of the concurrent flow is to augment the damaging stock. Most of these releases are onto land within the mine perimeter, what we refer to as on-site pollution. However, during and after the completion of mining, these toxic substances can contaminate surrounding lands and waterways via fugitive dust and drainage (US EPA, 2016b), what we call off-site pollution.

Historically, mine operators have not been charged for the negative visual impacts or other non-market damages from their operations. Nor have they been charged for contemporaneous damages from the accumulating stock of toxic wastes. Instead, they are simply held responsible for reclaiming their operations at the termination of the mine.1 Yet due either to lack of incentives or finances, mine waste stocks are sometimes left untouched by the operator when the mine is abandoned. In 2004 the EPA identified 156 active mining and processing sites that had the potential to cost the Agency $15 billion in cleanup costs due to operator negligence (US EPA, 2004). Through 2011 the EPA spent over $4.6 billion reclaiming abandoned hardrock mining and mineral processing waste (US EPA, 2016a). From 2010 to 2014 it spent $1.1 billion.2 The US Bureau of Land Management estimates that it will cost the US government an additional $35 billion to clean up contaminated hardrock mining sites on Bureau lands (US EPA, 2004).

The failure of environmental standards to incentivize reclamation is an ongoing problem

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1Operators are also typically limited in the amounts of pollution that can escape the permitted mine boundary, though as we will note substantial off-site effects can still occur.
that has been recognized by the courts and the regulators themselves. After reviewing the
evidence, the US Court of Appeals in 2016 declared that “It is a common practice for [mine]
operators to avoid paying environmental liabilities by declaring bankruptcy or otherwise
sheltering assets” (US Court of Appeals, 2016, p. 10). Muehlenbachs (2015) documents this
same behavior by Canadian oil and gas operators. The Court then observed that “this limits
the incentive to adopt best practices, and in some circumstances may encourage operators to
take on greater risks knowing they will never have to pay the costs” (US Court of Appeals,
2016, p. 10). The failure to reclaim then leads to toxic releases onto surrounding lands. The
EPA itself finds that “despite changes in regulations and practices, the release of CERCLA
hazardous substances as a result of mining and mineral processing activities is an ongoing
issue” (US EPA, 2016b, p. 5). The off-site damage caused by mining is not limited to the
United States. On the mainland of China, 19.4% of farmland, about 57.5 million acres (an
area the size of Idaho), has been polluted (China, 2014, p. 3). Heavy metals resulting from
mineral and coal mining are a main contaminant (Shi et al., 2013). In addition, communities
surrounding coal mines in China express significant dissatisfaction with air quality, water
safety, and health (Li et al., 2017). In Ghana, Aragon and Rud (2016) find that farmers
located near large-scale gold mines have lost 40% in total factor productivity due to pollution
from mining.

Regulatory agencies in mining nations are in response introducing new regulations in the
form of financial incentives. There are currently three types of financial incentives being
proposed. The United States considered a rulemaking that would require mine operators to
post federal financial assurance to cover the anticipated cost of reclamation upon closure.
Western Australia is requiring operators to pay a rehabilitation levy proportional to the
current stock of on-site pollution such that government reclamation of abandoned mines will
be funded. China is imposing taxes on off-site flows of coal gangue, tailings, smelting slags
and water and air pollutants in an effort to fund mine reclamation efforts (China, 2016).

In this paper we develop a simple model of non-renewable resource extraction with re-
versible stock pollution to provide an intuitive analysis of how mine operators’ extraction,
abatement and final reclamation efforts are affected by current regulations, and how these efforts may change under these new financial incentives. Our analysis shows that historical regulations provided virtually no incentive to reclaim. Requiring financial assurance does incentivize the operator to reclaim at some point, but not necessarily at the optimal time. It also reduces the stock of pollution created during operations by incentivizing abatement activities. But since the policy does not internalize all stock damages, mine operators will continue to pollute too much and underemploy the very abatement technologies that regulators wish them to adopt. Taxes on the current stock of damage, as in Australia, or on the flows creating those stocks, as in China, are optimal when charged at the appropriate level and over both on-site and off-site pollution. As implemented, neither type of tax appears to be achieving this goal.

We finally compare the choice of an optimal stock tax with the optimal flow taxes that have been proposed in the literature on stock pollutants (e.g., Farzin 1996). A tax on the current stock of damage has much to recommend it. Both types of tax incentivize the mine operator to reduce the pollution stock via production and abatement decisions, but when the stock is reversible through the application of investment the stock tax also incentivizes the firm to promptly reclaim the now smaller stock of pollution at the end of the mine life when such reclamation is socially optimal. A flow tax provides no incentive for the operator to reclaim the waste stock, and must as a result also generate enough revenue to fund what becomes the government’s effort in this regard. A stock tax is also likely to be the easier to administer because of reduced informational requirements on the part of the regulator.

2 The advent of financial incentives for mine regulation

There is no shortage of faith in the need for and effectiveness of financial incentives when it comes to mine reclamation. Though ultimately rejected, the United States EPA’s consideration of federal-level financial assurances for mine reclamation is a case in point.3 In response

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3These considerations took place during the final term of the Obama administration. On February 21, 2018, during the first year of the Trump administration, the EPA reversed itself and announced its decision not to require financial responsibility at the federal level, leaving such incentives up to the states (US EPA 2018).
to a toxic release at Love Canal in upper New York state and the subsequent cleanup costs borne by the federal government, the United States Congress enacted CERCLA, the Comprehensive Environmental Response, Compensation, and Liability Act of 1980. Informally known as Superfund, the act was “to promote the timely cleanup of hazardous waste sites and to ensure that the costs of such cleanup efforts were borne by those responsible for the contamination.” Section 108(b) of CERCLA then directed the EPA to “develop requirements that classes of facilities establish and maintain evidence of financial responsibility consistent with the degree and duration of risk associated with the production, transportation, treatment, storage, or disposal of hazardous substances.” The EPA identified hardrock mining facilities as solution ponds, tailing piles and heap leach piles as those for which it would first develop these requirements. After a series of bureaucratic and legal delays, and after decades of Superfund cleanups funded by the federal government, the EPA posted its proposed financial responsibility rule for mining in January of 2017 (US EPA, 2017). The proposed rule, broadly called CERCLA 108(b), would require mine operators to financially guarantee estimated waste stock reclamation costs, calculated as being proportional to the size of the disturbed area. The EPA intended that its financial assurance rule would “create effective incentives for regulated entities to manage the hazardous substances present at their facilities more carefully and thereby minimize the threats of future releases” and create “a culture of responsible behavior among the regulated community that will minimize the need for future Superfund actions.” (US EPA, 2017, p. 3400). They also anticipated that the rule will incentivize more prompt restoration of lost ecosystems (US EPA, 2016d, p. 7-2). The Courts, who were previously called upon to compel the EPA to act, also noted that the financial assurances within CERCLA would provide incentives; “basic economic self-interest means the operator will take cost-effective steps to minimize hazardous releases in order to minimize their environmental liabilities” (US Court of Appeals, 2016, p. 10). Of particular note in the proposed rulemaking was the allocation of responsibility for the act of cleanup to the firm and the expectation that such cleanup will be timely. This will be a key emphasis of our paper, since the existing stock pollution literature allocates the responsibility for
reclamation to the government.

Western Australia and China are pursuing a second type of financial incentive. In 2012 Western Australia enacted The Mining Rehabilitation Fund Act (MRF Act), which repealed reclamation bonding requirements and replaced them with an annual levy on unreclaimed mine site waste stocks so as to fund government reclamation of abandoned mine sites (Western Australia, 2012). China is imposing a flow tax on additions to off-site mine waste stocks via its new Environmental Protection Law (China, 2016). The fee for off-site mine tailings, for example, is 15 yuan ($2.30) per ton produced. Of interest to this paper is whether these financial incentives will improve practice regarding abatement and final reclamation at mining operations.

The literature on the management of waste stocks from non-renewable resource extraction reflects the recent move towards financial incentives. Traditional economic models of mine operator efforts originate from the historical standards-based regulations of fugitive pollution flows, whereby the resultant stock of off-site pollution must be held below some environmental limit (Roan and Martin, 1996; Cairns, 2004). The models allow for continuous reclamation of pollution stocks. They also assume that there is substantial natural decay of the stock of pollution, in the spirit of the earlier models by Forster (1975), Hoel and Kverndokk (1996) and Keeler et al. (1971) on the optimal control of stock pollutants, but contrary to the fact that the main stock pollutant from hardrock and coal mining, heavy metals, has no appreciable natural decay. The analysis solves for the optimal amount of reclamation during operations in order to maximize profits while meeting these standards. Given the constraint that stocks be below the standard at the termination of the mine, and given the prospect for natural decay, final and complete reclamation of on-site and off-site waste stocks is not considered and nor required in these models. Moreover, as evidenced by the billions of dollars of Superfund reclamation obligations in the United States and the more than 10,000 abandoned mining facilities in Western Australia (Western Australia, 2014), in practice physical standards have not been effective in incentivizing the levels of reclamation

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4We define abatement as activity that reduces the concurrent pollution flow to a lower bound of zero. Reclamation reverses the quantity of an existing waste stock to a lower bound of zero.
activity presumed by these models.\textsuperscript{5}

Farzin (1996) introduces financial incentives via a Pigouvian tax on pollution flows, but assumes that stock damages are irreversible and so does not include the possibility of reclamation. White et al. (2012) examine Pigouvian stock taxes under stochastic insolvency and policy constraints, and allow for reclamation upon closure, but continue to assume continuous reclamation during operations. Reclamation at closure is not emphasized, and nor is its timing given the finite planning horizon in their model. In a closely related paper Doole and White (2013) also allow for continuous reclamation and find that the mine optimally reclaims all toxic wastes as they are produced, avoiding any need to examine reclamation decisions or reclamation timing after closure.

In an effort to make clear the different incentive effects of these various financial instruments on production, abatement, reclamation, and reclamation timing, and to embed some additional real-world constraints and flexibilities, our paper assumes away stochastic insolvency and policy constraints. It makes the extraction period endogenous such that the effect of regulation on speed of extraction and quantity of reserves can be determined. In the spirit of Farzin (1996), we assume that the stock of on-site pollution is irreversible during operations and allow only costly pollution abatement activities during that period. However, in keeping with mining engineering practice and in a break from the current literature we allow reclamation of the on-site stock of pollution to happen at or after closure. For off-site pollution we allow repeated, lumpy reclamation actions during operations. An innovation of our paper is to model the specific disincentive that mine operators currently have over immediate reclamation upon closure and whether incentive compatibility over prompt reclamation can be achieved through these financial instruments.

The rest of the paper is arranged as follows. In Section 3 we develop a simple model of mineral extraction with externalities related to on-site pollution. Section 4 uses the model to provide a theoretical examination of operator choices over output, abatement and reclamation under current regulations and the new financial incentives. In that section the

\textsuperscript{5}The EPA Comprehensive Report (2016b) provides some insights into reasons for the ineffectiveness of US Federal and State environmental standards with respect to mine waste stocks.
model is also extended to the case of off-site pollution. In Section 5 a numerical example is used to illustrate the mine operator’s choices under of the different types of regulation. Conclusions are provided in Section 6.

3 The model

To bring out the main points of the paper in the simplest way possible we restrict our model to contain only the bare essentials. Our base case model refers to stock pollution contained on the mine site through effective regulation of fugitive emissions. There is a finite homogeneous mineral reserve $R_0$ that is extracted by a private, price-taking, profit-maximizing operator over some finite but free time horizon. The extraction path is $q(t)$ (the quantity of mineral extracted at time $t$) and total extraction cost is $c_1(q)$ ($c_1(0) = 0$, $\frac{\partial c_1}{\partial q} > 0$, $\frac{\partial^2 c_1}{\partial q^2} > 0$). For ease of analysis the price of the mineral is fixed at $p$, which is not an unreasonable representation of most commodity prices over the long run. Mineral extraction generates a flow of a polluting waste $a(t)$ and an accumulating stock of that polluting waste $A(t)$, $\dot{A}(t) = a(t)$. One can think of the polluting waste stock on the mine site as the acres of “land or surface water that has been altered for purposes of accommodating mining and/or processing activities” (US EPA, 2017, p. 3503). The social damage is assumed to be a finite amount $DA(t)$ in each period, reflective of the growth of disturbed acreage over time. Given that the pollutants from mining are mainly disturbed lands and other effects with no natural attenuation, we do not allow for natural attenuation of the stock of pollution. We also do not include a separate flow externality emanating from production or from the stock of pollution itself since it is mainly the quantity of disturbed land that affects society negatively in any period.

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6This same cost function is used in Roan and Martin (1996) and Cairns (2004). The inclusion of a depletion effect, $c_1(q, R)$, which is common in the literature of non-renewable resource extraction as an attempt to reflect resource heterogeneity within an ore deposit, is an unnecessary complication that we elect to avoid. Cairns and Davis (2015) provide a trenchant critique of such cost functions for their inconsistency in simultaneously modeling the resource as both homogeneous and heterogeneous. Stock effects will nevertheless be present in our model when the firm is liable for the stock of pollution it creates.

7The assumption of a linear damage function is consistent with Farzin (1996) and White et al. (2012) and reflects the contiguously spreading footprint of the mining operation. We do not model threshold effects, whereby damage only occurs once the stock reaches a certain level (Nobbs and Pearce, 1976; Farzin, 1996). We also ignore the possibility that $D$ goes to infinity as the stock reaches a second threshold, and that changes in the level of stock could inflict adjustment costs.
Because there is no depletion effect in the mining cost function, in the absence of regulation the mine extracts the whole resource in finite time (Hotelling, 1931). Hotelling rent is positive. However, under regulation the increasing stock of pollution as extraction proceeds induces an effect similar to a depletion effect, whereby the resource may not be exhausted due to rising costs associated with taxation of the stock of pollution over time. Specifically, when the mine is faced with a tax $DA_t = DA_{t-1} + D_a t$ during operating period $t$, operations involve a U-shaped average cost curve because of the fixed cost component resulting from previous operating decisions. As the resource is extracted through time the minimum of the curve rises, eventually exceeding the fixed price $p$. In essence, the pollution stock effect replaces the extraction stock effect in terms of possibly rendering some units of the orebody uneconomic to extract. When the operator is instead faced with a financial assurance requirement to reclaim the stock of pollution at closure the rising liability with cumulative extraction is a charge that can eventually makes the project’s cumulative net present value decline, again possibly warranting termination prior to full exhaustion of the resource.

There are two technologies, abatement and reclamation, that can be used by the operator to affect pollution stocks. Focusing first on reclamation, we assume that it can only happen at or after mine closure.\footnote{There are three reasons that mine reclamation tends to happen only at the end of the life of the mine. First, the land disturbed during mining for use as process ponds and reservoirs, waste rock piles, tailings dams, and open pits, is an input to production. It cannot be restored while production is ongoing. Second, there are no empirically observable diseconomies of scale in restoration that would make smaller, incremental efforts optimal (US EPA, 2017, p. 3505). Finally, restoration often employs the same heavy equipment used for mining, and so the opportunity cost of restoration prior to closure is high.} We assume that there is only a single, lumpy technological choice available for reclamation, and that reclamation restores the land back to its initial state. As such, we will hereafter refer to the action as restoration rather than reclamation. The average cost of instantaneously restoring a unit of land contaminated with waste stock is $c_3$. The total cost of restoration thus only depends on the current state of pollution, not the initial state to which the action returns the land.\footnote{While we feel that this is a reasonable representation of the costs and technologies available to mine operators, relaxing these assumptions would create additional policy choices for the regulator as to how to incentivize the right amount of reclamation (Phillips and Zeckhauser, 1998).}

The operator also has the opportunity to reduce $a(t)$ by undertaking more sophisticated operating procedures that abate the pollution flow. These abatement procedures raise total
operating costs by $c_2(q,a)$ \(\frac{\partial c_2}{\partial q} > 0, \frac{\partial^2 c_2}{\partial q \partial a} < 0, \frac{\partial^2 c_2}{\partial a^2} > 0, c_2(0,0) = 0\) and \(c_2(q,0) \to \infty\), the function implicitly linking production with waste flows. For example, at an added cost underground mines can bind tailings with cement and pump them into underground voids, reducing dust generation, visual impact, and surface water contamination. Coal mines can use water trucks for dust suppression. Note that under any abatement strategy during operations \(\dot{A} > 0\) given \(0 < a < \infty\), reflecting the irreversibility of the stock while operations are underway. We assume that all operating costs reflect full opportunity costs of inputs, and that restoration has no impact on mineral prices or other production costs.\(^\text{10}\)

In the model the decisions the operator faces include how much production \(q(t)\) to undertake in each period, how much polluting waste to emit in each period net of abatement, \(a(t)\), when to terminate production, \(T\), and the period \(T', T' \geq T\), in which it cleans up the final pollution stock \(A(T)\), all in the effort to maximize profits net of any financial incentive. We distinguish between the time that production ceases and the time when the operator would like to undertake restoration to allow us to probe the firm’s timing decisions on production and restoration in the absence of regulation that effectively enforces \(T' = T\).

With its focus on simplicity our model abstracts from the irreversible capital expenditures to build the mine and the irreversible capital expenditures to install abatement technologies (Cairns, 2004). Irreversible capital expenditures to build the mine are immaterial for the subsequent marginal decisions that are the focus of this paper other than through their creating the cost functions for operations, abatement, and restoration. Capital expenditures for abatement technologies may seem more relevant, but from an engineering perspective abatement costs are mainly operating decisions such as backfilling tailings, using water trucks for dust suppression, or collecting and processing runoff and are thus more appropriately modeled as an increase in operating costs than the sinking of capital costs. Moreover, the capital used in abatement is more like rented capital (water trucks for dust suppression) than sunk capital (e.g., expenses on specialized equipment). These rental costs are best treated as increased operating costs (Davis and Cairns, 2017). There may be natural capacity.

\(^{10}\)For analyses as to how land restoration may affect the macroenvironment, see Lin et al. (1976) and Schlottmann and Spore (1976).
constraints on production and abatement related to terrain, as in Roan and Martin (1996), and these could be relaxed through additional investment, but we assume, as in Roan and Martin (1996), that these constraints do not bind.

4 Results

In this section we will use various versions of the model to derive insights for operator decisions and the resultant on-site pollution generated under different regulatory and financial incentives. We then extend the analysis to off-site pollution. Finally, we compare the information requirements for an optimal flow versus stock tax in this modeled environment.

4.1 Historical policy mandating restoration of the disturbed mine site

Our first implementation of the model caricatures the historical regulatory environment that requires mining operators simply to restore the disturbed mining area after they declare an operation permanently closed. Under this policy, in addition to paying the extraction cost $c_1(q)$ from periods 0 through actual closure time $T$ the operator has to pay a cost $c_3$ to reclaim the on-site pollution stock at declared closure time $T'$. It can also elect to spend $c_2(q,a)$ on abatement during operations. The operator will maximize the profit from extraction while minimizing the cost of restoration:

$$\begin{align*}
\text{Maximize} & \quad \int_0^T [pq - c_1(q) - c_2(q,a)]e^{-rt}dt - c_3A(T)e^{-rT'} \\
\text{subject to} & \quad \dot{R} = -q(t) \\
& \quad \dot{A} = a(t) \\
& \quad R(0) = R_0 \text{ and } A(0) = 0, 
\end{align*}$$

(1)

where $r$ is the discount rate and $c_3A(T)$ is the total restoration cost at time $T'$. The terminal time $T$ is free.
The simplicity of our model reveals profit-maximizing behavior under this historical policy that is consistent with observed practice. From equation (1), in the absence of effective penalties that charge the operator for damages caused by the current stock of waste either during operations or after operations close, the operator will seek to minimize $c_3 A(T)e^{-rT'}$ for any $A(T)$. As $T' \to \infty$ the restoration cost is minimized at zero, $c_3 A(T)e^{-rT'} \to 0$. The operator will strategically seek to put off declaring closure as long as possible so as to let the restoration cost be discounted away. Given imperfect information on the part of the regulator there is effectively no bite in a requirement to reclaim damaged lands at actual closure time $T$. The fight to clean up uranium mines in Colorado reveals a typical case. By switching to “intermittent status” and staying “open with minimal activity,” with the stated reason of waiting for the price of uranium to rise again before restarting operations, operators can delay the restoration of the land by ten or more years, even though they are financially solvent (Frosch, 2013). An empirical analysis by Muehlenbachs (2015) of reclamation actions in the oil industry, which is subject to regulations similar to those outlined here, concludes that “the option to temporarily close is being widely used to avoid environmental remediation of oil and gas wells in Canada.” Correspondingly, since the stock of damage no longer affects present value profits, the operator will have no incentive to invest in any abatement during operations, and $c_2 = 0$. From equation (1), given our assumption about the absence of depletion effects in $c_1(q)$ the standard Hotelling result obtains; the shadow price of the resource is positive and rises at $r\%$ and the whole resource will be extracted in finite time $T$.

That the extraction program is unaffected by regulation in this model exaggerates the ineffectiveness of current regulation. Even so, evidence of the failure of this historical regulation to incentivize reclamation is everywhere. There are as many as 500,000 abandoned mine sites in the United States (Berger et al., 2011). It is these outcomes that the move to policies with financial incentives intends to change.

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11 Many operators do willingly reclaim waste stocks at mine closure (e.g., Freeport-McMoRan). Our model abstracts from other incentives for restoration such as maintaining the social license to operate concurrent and subsequent mining operations (White, 2015).
4.2 Policy that requires financial assurance of restoration costs

Recognizing the inadequacy of the historical regulatory environment, regulators at the local and regional level have in some cases required that mining firms post bonds to pay for restoration of damaged on-site lands upon closure. In the United States, the proposals under CERCLA 108(b) were a major federal initiative in this regard and is prototypical. By requiring financial assurance proportional to the quantity of stock of pollution created (US EPA, 2017), CERCLA 108(b) would have effectively charged the operator an unavoidable cost \((c_3 + d)A(T)\) at time 0, where \(d \approx 0.5c_3\) is the added indirect costs associated with the EPA, rather than the operator, restoring the disturbed land.\(^{12}\) Given the resources available to the regulator it can now start reclamation activities at a time of its choosing, \(T^* \geq T\). If the operator itself restores the land it receives a refund of its financial assurance, with interest, and spends \(c_3A(T)\). From the results in the previous section the operator’s decision is the action [abandon, restore] that minimizes present value costs \([- (c_3 + d)A(T), -(c_3 + d)A(T)e^{r(T^* - T)} - c_3A(T)e^{-rT^*}]\), where the terms in the second argument include the initial assurance amount, the returned assurance amount with interest, and the final restoration cost, all in present value. The optimal action is to restore, independent of the level of stock pollution.\(^{13}\) However, because of the effect of discounting the optimal time of restoration from the firm’s perspective is not at closure, but in some finite time approaching infinity. The firm will face a constraint on restoration timing due to the ability of the government to threaten to reclaim on the firm’s behalf, in effect setting \(T^* = T^*\). We will show in the next section that the optimal time of restoration in this model is either at closure or never. Where there are the information asymmetries introduced in the previous section, it is unlikely that governments will have information as to the optimal time of restoration, and firms will still have an incentive to postpone reclamation through temporary closure.

\(^{12}\)CERCLA 108(b) in fact only requires operators to file enough financial assurance to reclaim the current stock of pollution (US EPA, 2017), and so the time zero value of the bonding amount is in practice \([c_3 + d]\int_0^T a(t)e^{-rt}dt = [c_3 + d]A(T)\). This does not change the analysis as long as \(d > 0\) and \(a(t) > 0\) for some \(t < T\).

\(^{13}\)This is the case for firms that are able to self insure. Firms with weaker balance sheets would have been required to use third-party instruments like trusts, insurance, or letters of credit, with annual fees in the range of 1.1% to 4.0% of the financial assurance amount depending on firm creditworthiness (US EPA, 2016d, p. 5-5). We have not examined the incentive effects of these third-party instruments.
The operator’s maximization problem is now:

$$\begin{align*}
\text{Maximize} & \quad \int_{0}^{T} [pq - c_{1}(q) - c_{2}(q, a)]e^{-rt} dt - c_{3}A(T)e^{-rT^*} \\
\text{subject to} & \quad \dot{R} = -q(t) \\
& \quad \dot{A} = a(t) \\
& \quad R(0) = R_{0} \text{ and } A(0) = 0.
\end{align*}$$

Given $T^* < \infty$ the operator is affected by the level of the pollution stock that it creates and will take pollution into account when it chooses the extraction path. It may also spend effort on abatement during operations.\textsuperscript{14} With the now growing costs of restoration as production proceeds the finite resource may no longer be completely exhausted. The operator will continue to ignore the impacts of stock pollution during operations; in a type of “solution neglect” (Berger et al., 2011), financial assurance schemes such as CERCLA 108(b) do not charge mine operators for ongoing stock damages or for stock damages after their operations are suspended. We will illustrate the suboptimality for the case of $T^* = T$ (no information asymmetries) in a numerical exercise below. The policy also continues to ignore the restoration of off-site lands that have been damaged, which we will also address below.

### 4.3 Policy that internalizes the damages from ongoing stock pollution

Under a Pigouvian stock tax the mining operator would maximize its after-tax profits from extracting the resource and restoring the damaged land:\textsuperscript{15}

$$\begin{align*}
\text{Maximize} & \quad \int_{0}^{T} [pq - c_{1}(q) - c_{2}(q, a) - DA(t)]e^{-rt} dt - \int_{T}^{T'} DA(T)e^{-rs} ds - c_{3}A(T)e^{-rT'}
\end{align*}$$

\textsuperscript{14}We thank an anonymous referee for pointing out that if the marginal lower bound of $\left|\frac{\partial c_{2}}{\partial a}\right|$ is always higher than $c_{3}$, then there would be no abatement.

\textsuperscript{15}As Farzin (1996) notes, “static” Pigouvian taxes are typically used to address marginal flow damages. Here there are no marginal flow damages, and the tax is set to address the stock externality costs. White et al. (2012) call the tax a modified Pigouvian tax.
subject to\[ \dot{R} = -q(t) \]
\[ \dot{A} = a(t) \]
\[ R(0) = R_0 \text{ and } A(0) = 0. \]

There are three planning periods. In the first period the stock of pollution net of abatement starts to immediately accumulate up to time \( T \), when the operator ceases extraction. In the second period the pollution stock is positive and stationary while the operator waits to restore the land. In the third period, which is instantaneous, the operator restores the land to its original state. The second integral in equation (3) suggests that if the operator delays the restoration after the reserve is depleted it has to pay for the ongoing pollution damage in each period. Intuitively, by charging the operator for ongoing pollution damage it will have less incentive to delay ultimate cleanup.

Equation (3) is a separable two-stage optimal control problem. The second stage begins at an arbitrary time \( T \), whereby for any level of stock pollution \( A(T) \) from stage one the operator minimizes the cumulative post-closure damage charges plus the restoration cost by choosing the optimal restoration time \( T' \):

\[
\text{Minimize} \quad C = \int_{T}^{T'} DA(T)e^{-rt}dt + c_3 A(T)e^{-rT'}
\]

or simply,

\[
\text{Minimize} \quad C = \frac{D}{r}(e^{-rT} - e^{-rT'}) + c_3 e^{-rT'}.
\]

Because of the linearity of the damage function, \( A(T) \) ceases to enter the optimization calculus, facilitating the recursive analysis.

**Proposition 1.** For any \( T \) and \( A(T) \), if the mining operator is required to pay pollution damage \( DA(T) \) in each period after closure but before restoration starts, its actions are bang-bang. The operator will optimally begin the restoration immediately upon closure.
when \( D > rc_3 \) and will optimally defer restoration indefinitely when \( D < rc_3 \).

**Proof.** In Equation (5), taking derivative of \( C \) with respect to time \( T' \) we obtain \( \frac{\partial C}{\partial T'} = (D - rc_3)e^{-rT'} \). When \( D > rc_3 \), the total cost \( C \) will be greater as restoration time \( T' \) is pushed further into the future. In other words, only if the unit stock damage is relatively small \( (D < rc_3) \) it is optimal to pay the damage at each period and put off the restoration cost in perpetuity \( (T' \rightarrow \infty) \). Given the linearity of the problem the result is independent of the level of \( A(T) \).

The intuition of this result is clear: for each period that the operator delays spending \( c_3 \) on a unit of restoration it (and society) gains \( rc_3 \) in interest on the avoided restoration costs while incurring \( D \) in ongoing pollution damages. When damages are small and restoration costs are large restoration is not optimal. The fact that immediate restoration may not be uniformly optimal, per Proposition 1, has not been considered in the CERCLA regulatory process.

Given Proposition 1, the operator’s two-stage optimization problem in equation (3) can be rewritten as the more tractable problem

\[
\text{Maximize} \quad \int_0^T \left[ pq - c_1(q) - c_2(q,a) - DA(t)\right]e^{-rt}dt - \int_T^\infty DA(T)e^{-rs}ds
\]

when \( D < rc_3 \), or

\[
\text{Maximize} \quad \int_0^T \left[ pq - c_1(q) - c_2(q,a) - DA(t)\right]e^{-rt}dt - c_3A(T)e^{-rT}
\]

when \( D > rc_3 \),

subject to \( \dot{R} = -q(t) \)

\( \dot{A} = a(t) \)

\( R(0) = R_0 \) and \( A(0) = 0 \).

Proposition 1 is an essential insight in the quest to regulate firms to promptly undertake
restoration themselves at mine closure. While Pigouvian taxes have been promoted as internalizing externalities, in this case when imposed as a stock tax it also prompts optimal timing of the action to reverse the stock of pollution. The emphasis is that for reversible stock pollution, charging an ongoing stock damage fee while a stock pollutant exists is superior to financial assurance requirements not only because of the optimality of fully internalizing stock damages during operations, but also because it provides the operator with the correct incentive as to when and whether to undertake restoration. Even when the mine closure time and restoration cost is the firm’s private information and unknown to the regulator, an ongoing damage fee will incentivize the firm to make a socially optimal timing choice for both the length of operations and the timing of restoration. Of note, immediate restoration upon mine closure is not necessarily optimal and nor does this policy command it. For example, mining industrial minerals in desert areas may produce land disturbances that are costly to reclaim but present little ongoing damage to the environment.¹⁶

The notion that stock externalities are best internalized via an ongoing stock damage fee has been lost on regulators. For example, with the goal of creating Western Australia’s own “Superfund” the MRF Act charges operators an annual levy of 0.01c₃A(t), where c₃ varies with the type of stock pollutant (Western Australia, 2013). It is intended as a revenue tax, the proceeds of which are to be used by the Australian government to reclaim past and current mine waste sites. Though it is of the form of a Pigouvian tax on stock damages, it is unlikely that in setting the tax there was any consideration of internalizing the current stock damage and providing the incentives that such a tax creates. For instance, in reviewing the success of the tax over its first two years the Western Australian Government notes that an “unanticipated” outcome is that the tax “encourages early and ongoing environmental rehabilitation of minesites operating under the Mining Act as this reduces the levy payments” (Western Australia, 2014). Moreover, with $D = 0.01c₃ < rc₃$, from Proposition 1 the stock tax is not sufficient to incentivize operators to immediately reclaim waste stocks upon closure

¹⁶The restoration timing problem can be generalized to situations where unit damage costs, unit restoration costs and interest rates are rising or falling over time, generating an interior stopping point for $T'$ reflecting the type of $r$-percent rule developed in Cairns and Davis (2007). Prior to stopping the firm pays damages, while at stopping the firm restores the damaged land. Under this formulation of the problem the optimization is not separable, which is the reason we have chosen the simplified formulation that we model.
for reasonable commercial interest rates; in the absence of additional penalties or effective regulatory enforcement firms will likely prefer to pay ongoing damages tax in perpetuity even where immediate closure is socially optimal. In Western Australia mine-site waste stocks were reportedly down 7% in 2014-2015, the first year the MRF was implemented, compared with 2013-2014 (“Innovative fund lifts mine rehabilitation rate”, 2015). But under this tax we have no reason to think that the reduction is optimal, and nor that the number of abandoned mines will decrease.

4.3.1 Operator decisions when immediate restoration is optimal

We focus in the rest of the paper on the case \( D > rc_3 \), where restoration immediately upon closure is optimal. This would seem to be the most prevalent market circumstance given social preferences for immediate cleanup of mine wastes (e.g., Burton et al., 2012).\(^{17}\)

We know from Proposition 1 that the stock tax incentivizes the operator to restore the polluted land at closure. The current value Hamiltonian under internalized stock damages is now:

\[
H = pq - c_1(q) - c_2(q, a) - DA(t) + \lambda_1(-q(t)) + \lambda_2(a(t)).
\]  

Taking first order conditions,

\[
\frac{\partial H}{\partial q} = p - \frac{\partial c_1}{\partial q} - \frac{\partial c_2}{\partial q} - \lambda_1 = 0 \tag{9}
\]

\[
\frac{\partial H}{\partial a} = -\frac{\partial c_2}{\partial a} + \lambda_2 = 0 \tag{10}
\]

\[
\dot{\lambda}_1 = r\lambda_1 \tag{11}
\]

\[
\dot{\lambda}_2 = r\lambda_2 + D. \tag{12}
\]

\(^{17}\)Specific studies that measure benefits and costs have found that immediate land restoration can be optimal (Burton et al., 2012; Randall et al., 1978). After qualitatively reviewing restoration and damage costs for oil and gas wells in Alberta, Muehlenbachs (2015) comes to the conclusion that immediate restoration is optimal for that industry as well.
If the terminal condition \( R(T) \) is not zero due to the cost effects of the rising pollution stock the mine faces economic exhaustion and the shadow value of the mineral in the ground, \( \lambda_1 \), will be zero. From equation (9) production will be such that price equals marginal production cost in each period of the finite mine life. If \( R(T) \) is zero the mine is instead physically depleted.

Since the terminal condition \( A(T) \) is free, the transversality condition reflecting the preference for immediate restoration upon closure is

\[
\lambda_2(T) = -c_3, \tag{13}
\]

irrespective of whether the mine faces economic or physical depletion. From equations (12) and (13),

\[
\lambda_2(t) = -\frac{D}{r}(1 - e^{-r(T-t)}) - c_3e^{-r(T-t)}, \tag{14}
\]

where \( \frac{D}{r}(1 - e^{-r(T-t)}) \) is the present cost of the flow of damages from an addition to the pollution stock and \( c_3e^{-r(T-t)} \) is the present cost of the restoration technology available to the firm for that unit of pollution. \( \lambda_2 \) represents society’s shadow loss on adding one more unit to the stock of pollution. In other words, \(-\lambda_2\) represents the shadow value of reducing the stock of pollution by a unit. From equation (10) it equals the marginal cost of abatement \( \frac{\partial c_2}{\partial a} \) in each period. This is a standard result in models of stock pollutants, though in this case the tax explicitly reflects the ability to reverse the pollution in finite time and the costs of such reversal.

Now that immediate restoration upon closure is the optimal action for the mine operator it is forced to make a trade-off between paying those restoration costs and spending on pollution abatement. If the cost of pollution abatement is high and damage and restoration costs are low, the operator will choose to create a larger stock of pollution and pay an increased ongoing damage tax and restoration cost. If the cost of pollution abatement is low and payments for damage and stock restoration are high, the situation matching Ben Franklin’s axiom that “an ounce of prevention is worth a pound of cure,” the operator will
invest more in pollution abatement in order to create a smaller damage tax and smaller stock of pollution by the close of operations.

An important and generalized intermediate outcome is evident:

**Proposition 2.** If the pollution damage is internalized via a tax \( DA(t) \) on the stock of pollution, under the condition that cleanup immediately after mining is optimal \( (D > rc_3) \) the operator applies declining marginal abatement cost to control the pollution flow over time. There is an increasing pollution flow and an exponentially increasing pollution stock over time.

**Proof.** The absolute value of the marginal cost of pollution control is \( |c_{2a}| = -\frac{\partial c_2}{\partial a} = \frac{D}{r}(1 - e^{-r(T-t)}) + c_3e^{-r(T-t)} \). Under the condition \( D > rc_3 \), we have \( \frac{\partial |c_{2a}|}{\partial t} < 0 \), which shows that the absolute marginal pollution control cost is decreasing over time. Since \( -\frac{\partial c_{2a}}{\partial t} = -\frac{\partial^2 c_2}{\partial a^2} \frac{\partial a}{\partial t} < 0 \), under the assumption \( \frac{\partial^2 c_2}{\partial a^2} > 0 \), the pollution flow is increasing over time, \( \frac{\partial a}{\partial t} > 0 \). The stock of pollution exponentially rises \( \frac{\partial \dot{A}}{\partial t} = \frac{\partial a(t)}{\partial t} > 0 \) until closure, when it drops non-continuously to zero as a result of restoration. As \( t \to T \), the marginal abatement cost \( |c_{2a}| = -\frac{\partial c_2}{\partial a} = \frac{D}{r}(1 - e^{-r(T-t)}) + c_3e^{-r(T-t)} \to c_3 \).

Intuitively, given the linear damage function the earlier the pollution the more cumulative pollution tax the operator has to pay over the life of the mine. The operator will therefore devote more effort towards pollution abatement in the early periods of extraction. An observation by regulators that pollution flows and stocks are increasing over time should not necessarily be taken to imply policy failure. It does, though, provide another case where policies that rely on private intertemporal discounting may not be intergenerationally equitable.
4.4 Policy that also internalizes the damage from stock pollution adjacent to the mining site

In this section we consider the additional damage caused by off-site stock pollutants. This can include negative effects from toxic releases and lost amenity value from visual disturbances (e.g., “Rosemont Copper is Not Telling Us the Whole Story”, 2010). Berger et al. (2011) give some examples of how large these off-site damages can be, whether willful or not, and how in some cases they are likely to overwhelm the profitability of the mining activity itself.

We assume that the damages from off-site pollution are internalized via a tax on the stock of waste, and that the firm can avail itself of two technologies to lessen the damages, abatement and restoration. Unlike the on-site pollution that can only be reversed at the end of mining due to technical constraints, we assume the off-site stock pollutants can be reversed while the mine site is in operation. Without economies of scale for restoration, for one unit of newly generated stock pollutant the firm would compare the present value of lifetime damage with the current restoration cost and the action would be bang-bang: either restore immediately or never. This is the case modeled in Doole and White (2013). When there are diseconomies of scale, restoration is ongoing (White et al., 2012). However, with economies of scale for restoration the action is lumpy. This is the case we model in keeping with observations of firms’ actual restoration efforts are lumpy.

Suppose mineral extraction is generating a toxic pollutant flow \( a_2(t) \) that cumulatively pollutes \( A_2(t) \) acres of land adjacent the mining site in year \( t \) and that causes annual damage \( D_2(A_2) \). To remove the toxic pollutants from the polluted land, a restoration cost \( c_4(A_2) \) has to be applied. We assume \( c_4(A_2) \) has economies of scale. The firm can invest in abatement cost \( c(a_2) \) to control the off-site pollution flow and can even stop the flow \( (a_2 = 0) \) if enough abatement effort is applied; \( c(0) \) is finite. If the firm is charged an ongoing stock damage fee \( D_2(A_2) \) the firm will undertake effort to abate the flow of off-site pollution. There may also exist a trigger point \( A_2(T^1) \) where the firm would remediate the stock of off-site pollution.
at time $T^1 (T^1 < T)$. When this is the case, the firm incurs an additional present value cost $C^1$ related to pollution taxes, pollution controls, and reclamation of emissions onto adjacent lands between time zero and time $T^1$:

$$ C^1 = \int_0^{T^1} [D_2(A_2(t)) + c(a_2(t))]e^{-rt}dt + c_4(A_2(T^1))e^{-rT^1} \tag{15} $$

subject to $\dot{A}_2 = a_2(t)$. It makes choices over the amount of abatement and the timing of restoration to minimize this cost.

The off-site pollution problem in equation (15) for the case of a stochastic, perpetual, constant exogenous flow $a_2$, abatement with increasing marginal costs, and a fixed “destination-driven” restoration cost $c_4(A(T^1)) = C_4$ has been solved by Keohane et al. (2007). Keohane et al. (2007) find that the firm applies a rising and then falling amount of abatement effort, with periodic restoration of the off-site waste stock when the stock gets high enough. Because the problem is autonomous this “pollute first, clean up later” process is repeated at regular intervals $T^1, T^2, ..., T^N, ...$

The mineral extraction problem that we model is different from that considered in Keohane et al. (2007). It has a finite terminal time and an endogenous, time-varying flow of pollution related to extraction, making the solution of the problem more difficult as the firm juggles production decisions with abatement and restoration decisions. The general intuition that the firm will apply a variable level of abatement still holds, but there is no longer a guarantee that the stock of pollution will get high enough during the mine life to warrant restoration.\(^{18}\) The termination of the polluting flow at finite time, when the mine closes, also changes the perpetual nature of restoration cycles where periodic restoration is optimal. After some time $T^N < T$, the present-value lifetime damage from the newly generated pollution stock net of abatement, $\int_{T^N}^{\infty} D_2(A_2(t))e^{-rt}dt$, may be less than the present value cost of the next optimally timed restoration charge $c_4(A_2(T^{N+1}))e^{-r(T^{N+1}-T^N)}$. In this case there will be a final restoration at time $T^N$ at cost $c_4(A_2(T^N))$ and a final abatement cost

\(^{18}\)In Keohane et al. (2007), allowing the restoration to be costly at the margin, as we assumed in our base case model, also removes any assurance that restoration will be part of the optimal actions of the firm.
\[ \int_{T_N}^{T} [c(a_2(t))] e^{-rt} dt \] over the remaining periods of mine operation. A residual, unreclaimed stock pollutant will exist upon mine closure, for which the firm will pay a perpetual damage tax.

If we allow that the extraction of minerals creates both on-site and off-site pollution flows, and assuming that periodic but not necessarily regular restorations of the off-site stock of pollution are optimal, the firm's problem becomes:

\[
\begin{align*}
\text{Maximize} & \quad \int_0^T \left[ pq - c_1(q) - c_2(q,a) - DA(t) \right] e^{-rt} dt - c_3 A(T) e^{-rT} - C^1 - \ldots \\
& - C^N - \int_{T_N}^{T} [c(a_2(t))] e^{-rt} dt - \int_{T_N}^{\infty} D_2(A_2(t)) e^{-rt} dt.
\end{align*}
\]

(16)

Activities of the firm will be expanded to include abating off-site pollution flows, with periodic restoration of the off-site pollution stock where warranted. The production profile will be modified accordingly to reflect these additional costs. The additional complexity makes the problem less tractable than our base model of only on-site pollution, but at its simplest can be seen to modify the problem in a way that adds additional variable costs to production that are proportional to the stock of off-site pollution. In extreme cases, these additional costs will not only exaggerate the endogeneity of the resource stock due to rising stock-effect costs over time, they may cause extraction to become entirely unprofitable. Where extraction is still profitable, and given that the levels of \( A_2 \) and \( A \) are likely to be highly correlated, sufficient intuitions about the effect of additional off-site pollution on the base-case extraction problem can be gained by increasing \( D \) in the base model to account for the additional costs of the off-site pollution that accompanies the generation of on-site waste stocks during extraction. Section 5 of the paper undertakes a numerical solution to this problem and compares results under low and high levels of \( D \).

4.5 Implications of restoration for optimal taxation

In the model thus far we have assumed that the firm has the property right over on-
site and off-site restoration and will self-fund the restoration effort when incentivized to do so. The optimal Pigouvian stock tax in this case is straightforward; the government simply charges the firm for concurrent on-site and off-site stock damages while they exist. If the firm, given its private information over restoration costs, finds it optimal to restore the land it will do so. If the firm instead finds it optimal to leave a stock of pollution unreclaimed it will pay a perpetual stock tax. Because of incentive compatibility, the government, seeing an absence of restoration, will know that restoration is suboptimal.

There may be situations where the government holds the property right over restoration, either for efficiency or political reasons. This is the assumption in Keohane et al. (2007), for example. The optimal tax becomes more complicated, as the government will have to tax the firm not only for ongoing damages, but also to fund the government’s restoration effort presuming that such restoration is optimal. Insights as to how to tax the firm in this situation can be gained from our model of on-site pollution:

**Theorem 1.** When the government holds the property right over restoration, and when immediate restoration upon closure is optimal, it is optimal to impose a unit tax on the flow of pollution $\alpha(t)$ at rate $-\lambda_2(t)$, which per equation (14) includes two components: the present value of the cumulative social damage before restoration of that unit addition to the pollution stock; and the present value of the restoration cost for that unit. From equation (10) and Proposition 2, the flow tax falls monotonically over time.

Most of the previous literature on stock pollution has assumed that governments assess a flow tax on additions to the stock of pollution. It is well known that a flow tax on a stock pollutant needs to take into account the sustained effects of the flow (Farzin, 1996; Hoel and Kverndokk, 1996). As a result the flow tax is set to the shadow price of flow pollution, in our case $-\lambda_2(t)$. Theorem 1 points out that charging such a tax presumes that the government funds the restoration. This has been the default assumption in the literature and has been
part of the motivation for a flow tax rather than a pollution stock tax.\textsuperscript{19}

If the firm has a credible incentive to restore damaged land and the government nevertheless wishes to implement a flow tax rather than a stock tax, the following theorem applies:

**Theorem 2.** *When the firm* has a credible incentive to restore damaged land, *the optimal unit tax rate for the flow of pollution is* $-\lambda_2(t) - c_3e^{-r(T-t)} = \frac{D}{r}(1 - e^{-r(T-t)})$. *This flow tax is decreasing over time. During the extraction period the flow tax is identical to charging an ongoing stock tax since for one unit of newly polluted land at an arbitrary time* $t < T$, charging the flow tax $\frac{D}{r}(1 - e^{-r(T-t)})$ *at time* $t$ *is identical with charging an ongoing damage tax* $D$ *on that unit from time* $t$ *to* $T$, $\int_t^T De^{-rs}ds = \frac{D}{r}(1 - e^{-r(T-t)})$.

The shadow price of pollution takes into account the cost of eventually reversing that pollution, and that cost must be deducted from the flow tax when the firm is held liable for that restoration expenditure.

The time path of optimal flow taxes has received much interest in the stock pollution literature. In general, the path is indeterminate and depends on the assumptions of the model. Factors that affect the time path include the assumed convexity of the damage function, the presence of intertemporal discounting, the presence of threshold damage effects, abatement possibilities, and the degree of pollution reversal through natural decay and restoration. Under different models the tax has been shown to optimally rise over time (Falk and Mendelson, 1993), rise over time and then level off (Farzin, 1996; Plourde, 1972), or rise and then fall over time (Farzin and Tahvonen, 1996; Hoel and Kverndokk, 1996; Keohane et al., 2007; Ulph and Ulph, 1994). A continuously falling tax was only noted to be possible when there is no intertemporal discounting and no natural decay of the stock pollutant (Ulph and Ulph, 1994; Hoel and Kverndokk, 1996). While our model allows no natural decay, it does have a positive interest rate. Nevertheless, the flow taxes in Theorems 1 and 2 are monotonically

\textsuperscript{19}The exception is White et al. (2012) and Doole and White (2013), who assess a stock tax and assume that the firm undertakes restoration, though on an ongoing basis.
decreasing over time. Our model is closest to that of Keohane et al. (2007), who allow for abatement and restoration and obtain an initially rising flow tax due to convexity of the damage function. The specific aspects of our model that cause the pollution flow tax to always fall are 1) the ability to reverse the pollution stock in finite time at the end of the mine life, causing emissions near the restoration period to have less impact on the program than emissions in the early phase of the operation, as in Keohane et al. (2007), but 2) a linear damage function whereby later additions to the pollution stock do not have higher marginal damage. Again, we feel that the linear damage assumption better represents the spread of the stock of pollution as mining proceeds, whereby more valuable units of land are not necessarily contaminated first.

The analysis thus far reveals that there are three main differences between a flow tax and a stock tax when restoration is possible. The first is that a stock tax will be constant when damages are linear, while the equivalent flow tax must be time-varying. While the optimal level of each is site-specific, the latter is likely to be more difficult for a regulator to administer for any given site. The second difference is the incentive effects for restoration. A flow tax provides no restoration incentive, even if the tax is modified to fund the firm’s restoration actions, since once the flows are produced the taxes paid are sunk. A stock tax, because it is ongoing, fully incentivizes the firm to restore, and also funds them to do so. As a result, when flow taxes are preferred the appropriate allocation of the property right for restoration is with the government and the full opportunity cost should be charged, as in Theorem 1. Third, a stock tax is superior to a flow tax when there are information asymmetries. From Theorems 1 and 2 and equation (14) the optimal flow tax requires that the government know the timing of mine closure and reclamation, which implicitly requires knowledge of the social damage function, the extraction, abatement, and restoration cost functions, price projections, and reserve quantity. The stock tax requires only knowledge of the social damage function and the measure of the current stock of pollution.

Finally, we return to the current concern that the property right for restoration may in the end fall on the government. In the absence of additional incentives a flow tax does
not incentivize restoration by the firm. China’s flow tax is therefore likely to be funding government restoration of fugitive mine wastes, and should be set at the full shadow price $-\lambda_2(t)$. Stock taxes, such as that in Australia, do incentivize restoration by the firm when set at high enough level. Bankruptcy risk aside, and in the light of its superior administrative attributes, we would advocate a stock damage tax on both on-site and off-site pollution stocks because it will incentivize and fund the operator to restore the land if and when this is socially optimal. However, given the risk of operator bankruptcy, adding to this stock damage tax financial assurance based on the current cost of restoration (see fn 11), is a simple mixed policy that is likely to be relatively efficient when immediate restoration is optimal.\(^{20}\) Where no restoration is optimal, the financial assurance should cover the present value of the perpetual damage tax on the unrestored land rather than the cost of restoration.

5 Numerical example

The above sections have modeled a mine operator’s strategies across different regulatory policies. We now illustrate the effects of those strategies on production and pollution flows using a numerical example. For our base case the parameters in the model are assumed as follows: $r = 0.05$, $p = 30$, $R(0) = 20$, $c_1 = 0.8q + 5q^2$, $c_2 = \log_{1.2}(a^{-1}q^2)$, $c_3 = 100$, and $D = 10$, whereby the condition for cleanup incentive compatibility $D > rc_3$ is satisfied. Since this is a qualitative analysis, the units for the parameters are not specified. The abatement cost function $c_2$ is specified in this way so as to allow for a direct relationship between $a$ and $q$ when $c_2 = 0$. The base on the log function allows for scale effects.

A case with four identical single-asset mining firms facing four different regulatory policies is considered. Firm 1 pays stock pollution damage during the extraction period but avoids

\(^{20}\)White et al. (2012) have undertaken a comprehensive examination of the optimal mixed policy when the mining firm is subject to bankruptcy risk and there is ongoing and continuous reclamation. The policy menu comprises a restoration bond, a production tax, a damaged land tax, and a carbon tax. Because of the complexity of their model closed-form solutions to the optimal control problem are not possible. They estimate from a numerical exercise based on mineral sands mining in Western Australia that if the government is constrained to using only one instrument, that instrument can be programmed to be relatively efficient. We presume the same efficiency is possible for the combination of a stock damage tax and financial assurance. White (2015) similarly recommends a combination of a stock pollution tax and a restoration bond when immediate restoration is optimal.
restoration and damage fees after closure, even though immediate restoration is socially optimal given our parameterization of the model. Firm 1 is representative of weak balance-sheet firms in Western Australia under an optimally set MRF Act levy. Firm 2 pays no stock damages but dutifully reclaims the stock of pollution immediately at closure, representative of US firms operating under EPA’s proposed CERCLA financial assurance requirements and where the government has full information on closure time. Firm 3 pays both stock damages and the stock restoration cost at closure, representative of strong balance-sheet firms in Western Australia under an optimally set MRF Act levy. Firm 3 reflects operator behavior under fully internalized pollution costs, the operator referred to in Proposition 2. Firm 4, like Firm 2, is only liable for restoration costs but finds it advantageous to avoid restoration by placing operations in permanently suspended mode because of the absence of financial assurances. One could argue that Firm 4 represents historical mining firm behavior under the usual, non-enforceable mandate that restoration begin upon mine closure.

In the following sections the pollution and extraction paths, the profits of the firms and the benefits to society are compared for each firm. To conduct the simulation we solved equation (7) for the state and control parameters annually using Solver in Excel. The optimal mine life was chosen from a grid search of life/NPV outcomes given optimality for each sampled mine life.

5.1 The pollution flows and stocks

Figures 5.1 (a) and (c) show the pollution flows and pollution stocks of the four firms. A corresponding plot of the average cost spent on pollution control, \( \frac{c_2}{q} \), is given in figure 5.1 (b). Because Firm 4 avoids the liabilities associated with pollution, it will operate with \( c_2 = 0 \). From our abatement cost function, the pollution flow for this firm will be \( a = q^2 \), which is too large to be plotted for all periods. Thus, we only plot the first few periods for Firm 4 in figures 5.1 (a) and (c), and Firm 4 does not appear in figure 5.1 (b).

From figure 5.1(a), the pollution flow of all firms that pay pollution damage or restoration costs is lower than that of Firm 4. For Firm 1, whose only environmental liability is
(a) The pollution flows

(b) The average cost of pollution control \( \frac{C}{q} \)

(c) The pollution stocks

Figure 5.1: Pollution flows, pollution stocks and the average pollution control cost under different policies

The payment of pollution damage during the extraction period, the pollution flow increases slowly at the beginning but rises sharply at the end of the production period. Its corresponding average cost of pollution control declines over time, as shown in 5.1 (b). Pollution control declines because later pollution expenditures avoid fewer cumulative damage payments. Conversely, Firm 2, which pays restoration cost but no ongoing damage cost, has a rising average pollution control cost with a view to minimizing the present value of these costs by delaying them. The resultant pollution flow declines over time. As in Proposition 2 the pollution flow of Firm 3 increases over time as it applies less and less pollution control effort, as in 5.1 (b). The marked difference of the pollution flows and pollution control costs
between Firm 1 and Firm 3, both of which are subject to ongoing damage charges but which differ in intent to reclaim the pollution stock at the end of mining, suggests that under a regime that charges ongoing pollution stock damages monitoring pollution control effort may be a useful mechanism for determining when a firm intends to avoid its ultimate restoration costs. That is, charging damage costs sets up a useful signaling mechanism where there are information asymmetries.

Figure 5.1(c) shows the pollution stocks $A(t)$. Firm 1 generates the largest (and sustained) terminal pollution stock of the three regulated firms, though in this simulation the stock of pollution is lower in the early stages of the operation than that of Firm 2, whose only obligation is restoration. A policy of paying ongoing damages, even for a firm who avoids restoration, can thus produce a less polluted environment in the near term. Firm 3 will always generate the least stock pollution because it takes liabilities associated with both the stock damage and restoration cost into account.

Comparing Firms 4 and 2, which stylistically represent mine operator behavior both before and after the proposed CERCLA 108(b) rulemaking, requiring restoration via financial assurance does indeed reduce the stock of pollution at termination, as desired, by incentivizing expenditure on pollution controls during operations.\textsuperscript{21} If there are ongoing damages from stock pollution during operations, which is likely, CERCLA 108(b) would still have resulted in pollution stocks that are larger than socially optimal (compare Firms 2 and 3).

5.2 The extraction path and remaining reserves

Figures 5.2 (a) and (b) show the extraction paths and the remaining reserves of the four firms. In each case in this example the firms physically exhausts the resource, as shown in figure 5.2 (b); the areas under the curves in figure 5.2 (a) are the same. The path for Firm 4, which acts as if there are no environmental liabilities, is the traditional Hotelling extraction path under increasing marginal costs, no depletion effect, and a constant price. In this example the other firms all have shorter extraction times.

\textsuperscript{21}The reduced stock of pollution could also be achieved via mine design changes, though to model this we would need to model choice over production technologies.
That the regulated firms extract more quickly is not a generalizable result. There is one general effect in our model of regulation that slows down extraction and one that speeds it up compared with the unregulated firm (Firm 4). In first effect firms can decrease the present value of restoration by slowing production and extending the time of closure. In the second, under a pollution charge of \( D \) during operations the firm has an incentive to increase the rate of production so as to reduce the project time over which \( D \) is paid. There are also specific effects associated with the explicit functional form assumed for the cost of abatement \( c_2 \) that can shift the marginal cost curve by \( \frac{\partial c_2}{\partial q} \) and that can thereby incentivize less or more rapid production. In the examples in Figure 5.2 the increased production effects win out, introducing a green paradox when there are other pollutants from mining like carbon emissions.\(^{22}\)

Figure 5.2: The extraction paths and reserve states under different strategies

5.3 The profit path and social benefit

Figure 5.3 (a) shows the cumulative present value profits for each firm over time. Firm 4 has the highest cumulative profit since none of the externalities are internalized. Because Firm 3 internalizes more liabilities than any other firm it has the lowest cumulative profit.

\(^{22}\)We have confirmed that by changing the abatement cost function the optimal mine lives of Firms 1, 2, and 3 under regulation can exceed that of Firm 4. We have also confirmed that under higher damage costs or under more costly abatement and restoration costs there is economic rather than physical exhaustion for the regulated mines.
Figure 5.3 (b) shows the cumulative present value social benefit for each firm, equal to the mining firm’s profit less the present value cost of externalities generated by its activities. For Firm 1, which pays only pollution damages, at each period the cumulative social benefit equals Firm 1’s cumulative profit reduced by $c_3A(t)e^{-rt}$, the cleanup cost of the stock pollution incurred by the government should the firm abandon operations at that time. For Firm 2, the social benefit equals profit less the present value of the accumulated ongoing damage $\int_0^t DA(t)e^{-rs}ds$ that is not paid at each period. Firm 3, which internalizes both the pollution damage and the land restoration cost, naturally creates more cumulative social benefit than the other two firms. In the case of Firm 4, which takes no environmental liabilities into account, the pollution stocks it creates while pursuing profit maximization are so large that the social losses from both the stock damage and the government-financed restoration cost are too great to be offset by the rents from extraction. These are the cases that Berger et al. (2011) highlight in their paper.

The example shows that under this parameterization the social benefits from requiring firms to pay pollution damages during production and for which the government steps in 

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23 We assume that the government steps in to remediate the stock of pollution because it is socially optimal to do so given $D > rc_3$. 

and funds restoration (Firm 1) are less than under a policy where the firm does not pay stock damages but cannot avoid reclaiming the stock at the end of the planning period due to financial assurances (Firm 2). This is because in this example the restoration cost is relatively expensive compared with abatement in the first place, and the firm that is not liable for restoration and subject to only a charge for ongoing damages tends to abate less than the firm that is liable for restoration. In the next section we show a case where the social benefits of these two policies are reversed.

5.4 The Case of Off-site Damages

In this section a case with relatively greater pollution damage, $D = 30$, is analyzed, representative of mining that creates both on-site and off-site stock damages (see Section 4.4). This might represent the case of China, where coal mines are mainly co-located with agricultural lands, and the 6% of mine sites in the US that are within 3 miles of federally designated “critical habitat” (US EPA, 2016c). We assume that this greater stock damage is internalized in the Pigouvian stock damage tax charged to Firms 1 and 3. Firms 2 and 4 are unaffected, and do not alter their behavior. Figure 5.4 (a) shows that Firm 1 now produces less stock pollution than Firm 2. This is because the stock pollution damage is so great that Firm 1 spends more effort at pollution control. Figure 5.4 (b) shows that in this case Firm 1 creates a larger social benefit than Firm 2, even though the government must step in and fund Firm 1’s restoration costs. In fact, even though Firm 2 is incentivized to comply with restoration laws the concurrent stock pollution externality from its operations is so large as to wipe out the surplus from its production.
Though this is only a numerical example, the result is insightful. It is quite likely that when mining laws were designed the concurrent stock damage from operations was low and there was no thought of internalizing those costs. Mines were in remote areas and the local stocks of pollution that were created did not greatly affect surrounding land use activities. The focus, even in 1980 when CERCLA was passed into law, was simply on restoration, the case of Firm 2. Today, mining can have severe negative impacts on neighboring lands while the mine is active. Continuing simply to require restoration, or even to incentivize restoration via financial assurances (Firm 2), may well result in negative cumulative social benefits from mining. A policy of instead charging firms for ongoing damages will incentivize firms to apply additional pollution control technologies during operations and remediate promptly upon closure so as to avoid ongoing damage costs (Firm 3). Even for cases where the mining firm intends to avoid its restoration obligations given an absence of financial assurance (Firm 1), requiring payments for ongoing damages can reduce the final stock of pollution left for the government to reclaim compared with rules that focus only on restoration.
6 Conclusion

This paper considers the effect of financial incentives, as opposed to environmental standards, on the extraction of a non-renewable resource that creates a reversible stock pollutant. We first caricature a current regulation that requires the mining firm to reclaim the stock of pollution upon shut down. We find that the firm will put off the restoration as long as possible to reduce the present value of the restoration cost because of the crucial role of the discounting. The higher the interest rate the higher this incentive. The modeled behavior is consistent with actual industry behavior. A proposed regulation in the United States that would have required firms to post federal financial assurance for restoration does incentivize restoration, but only in order to pre-empt reclamation by the government using the firm’s funds. To that effect, the firm will continue to put off reclamation as long as possible.

We then examine a policy that requires the firm to pay ongoing stock pollution damage, the Pigouvian solution. Western Australia has imposed this type of tax, though to raise revenue rather than to internalize pollution. Unlike financial assurance a stock tax eliminates the firm’s incentive to delay restoration after closure when prompt restoration is socially optimal. It also induces the firm to perpetually delay restoration where that is socially optimal. Due to the force of interest the firm applies less and less pollution control over time, which results in an exponentially rising stock of pollution.

We also show how pollution flow taxes, as applied in China, can achieve the efficient outcome during operations, but do not incentivize restoration by the firm. The best policy option from an administrative point of view would appear to be financial assurance of restoration, as proposed in the United States, combined with a stock damage tax, as in Western Australia.

A numerical example of the model shows the effects of the various regulatory policies on production and pollution profiles. Incentivizing the mine operator only to restore the damaged land upon closure, as embedded in financial assurances, absolves the operator of any responsibility for ongoing social damages from pollution stocks and can result in negative
social benefits from mining when the ongoing stock damage is large. In fact, in the example a higher social welfare can be achieved by removing the financial assurance requirement and instead requiring the operator to pay a current period stock damage tax only until closure, leaving an unfunded restoration upon closure to the government to deal with. The example shows that a stock tax can also result in a smaller stock of waste during operations via the incentives for enhanced pollution abatement. Remarkably, the efforts at regulatory reform that we review have no explicit intention of implementing a Pigouvian stock damage tax that internalizes both on-site and off-site pollution and are therefore unlikely to reduce stock pollutants to their optimal levels. Nor will they incentivize optimal private sector actions around closure and restoration timing.
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