***Natural Resource extraction with Reversible Stock Pollution***

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## Overview

Most analyses of pollution from industrial activities treat the pollution as ultimately irreversible (e.g., Hoel and Karp 2002, Newell and Pizer 2003). Policies are mainly directed at limiting the flow of pollution into the pollution stock by taxing flows. This paper considers the case of stock pollution that is reversible through the application of costly remediation. The application is coal mining in China, where mining results in heavy metal pollution of the soil on surrounding agricultural lands (Zhiyuan et al. 2014). Farmland lost to subsidence from underground coal workings is also prevalent. By examining the typical regulation requiring the mining firm to partially or totally reclaim the disturbed land after an operation shuts down, we find that the firm will delay the reclamation as long as possible because of the crucial role of discounting. The firm also has no incentive to contain the pollution during mining. If, on the other hand, the firm is also required to pay the pollution damages during operations, such as the opportunity cost of the stock of farmland made unavailable due to pollution, it will have no incentive to delay the reclamation under reasonable model parameterizations. It will also be incentivized to apply any available pollution control technologies during the mining operation. Numerical simulation shows that the application of efficient pollution taxes that match the opportunity cost of stock pollution during operations can result in a dramatically changed behavior by the firm, both in terms of extraction profile and total pollution emissions.

The paper is arranged as follows. After the introduction, in Section 2 the model for mineral extraction with externalities caused by the stock pollution is developed to examine the current regulation. We then add a new policy that requires ongoing taxes commensurate with the current opportunity cost of the polluted land. The mining firm’s strategies and resultant pollution paths are then analyzed and compared with the status quo case of requiring only reclamation. In Section 3, numerical simulation illustrates different practical cases. Conclusions are provided in Section 4.

## Methods

Profit maximization via deterministic two-stage optimal control with two state variables (resource stock and pollution stock), two control variables (production flow and pollution control including remediation) and numerical simulation. Various models are developed and analytically solved based on differing environmental rules and taxes. The analytic solutions provide some general insights. Simulations then examine outcomes for a stylized coal mine.

## Results

The first model, which examines a policy under which firms are only required to perform reclamation at the end of the mine life, explains why firms wish to delay reclamation at the end of mine life; the current environmental regulation that requires the mining firm to reclaim the disturbed land after an operation shuts down is contrary to their profit maximization, and so they delay as long as possible. This is a standard result that we observe repeatedly in the real world, and is a relatively trivial outcome to model.

Second, we introduce a new environmental policy designed to fix the incentive incompatibility of the current regulation by adding a pollution tax proportional to the environmental disturbance while in production. We show that under some parameterizations of the model immediate reclamation upon closure is in the firm’s best interest because by doing so it avoids the ongoing fixed cost of the environmental damage. The firm is also incentivized by this policy to make use of pollution control technologies that reduce the accumulation of pollution over the life of the mine. Strangely, most mining regulations throughout the world do not require firms to pay ongoing damages for stock pollution, setting up a mismatched incentive system that can be corrected by the addition of this simple tax. In China in particular, there is little or no incentive to apply pollution control technologies while the mine is in operation, other than to meet specified emission limits. Once one views the pollution damage as a growing but reversible stock pollutant it becomes clear that the current regulatory standards are inefficient.

Numerical simulation shows that under the new set of pollution taxes, which we assume match the temporal social damage during operations, the firm’s behavior can be dramatically changed. The addition of this quasi-fixed operating cost can increase extraction rates, shorten the mine life, and lower the stock of pollution at all points of the extraction process. It can also (optimally) sterilize reserves. An example of the numerical simulation is shown below. It shows the differing flows of pollution from the mining operation over the endogenous life of the mine as a function of whether it is required to pay only ongoing damages for the increasing stock pollutant, only reclamation of the stock pollutant, or both ongoing damages and reclamation. The different policies induce dramatically different pollution paths from the mine. The integral of the pollution paths is the stock of pollution at any given point. Note also the different mine lives under the different environmental policies.



Perhaps of most interest, if ongoing damages are high an environmental regulation only requiring mandatory reclamation at the end of mine life can result in a negative social surplus from mining, even if the mine operator is compliant. This appears to be the complaint of many environmental groups and NGOs. A requirement that the firm instead pay the socially efficient damages tax while in production can produce a positive social surplus from mining even if the firm avoids reclamation. The firm also continues to earn a profit and engage in the mining activity under this policy. This result comes from the presumed ability of the firm to alter its production profile and control some of its pollution via pollution control technologies. As such the availability of pollution control technologies provides even more motivation for an ongoing damage tax.

## Conclusions

In many real situations, the pollution from extractive industries does not naturally decay. Instead of modeling natural decay, which is the focus of most papers assessing the environmental impact of extractive activity, this paper models stock pollution which is reversible via the application of capital. Using a natural resource extraction model with externalities of stock pollution in surrounding farmland, we find why current mine regulations requiring the application of capital to stock pollution at the end of mine life may fail to incentivize firms to control and remediate pollution. Additionally taxing firms for contemporaneous environmental damages while in production provides a first-best outcome. Taxing firms for contemporaneous environmental damages at elevated rates can also provide a second-best outcome that takes into account the possibility of failed or delayed reclamation and that approximately matches the optimal pollution profile given no such failures. The results of the paper have implications for the optimal regulation of other stock pollutants like carbon dioxide that may be ultimately reversible through the application of remediation technologies like carbon capture and sequestration.

## References

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