
Mining and the Environment

Case Studies from the Americas



edited by Alyson Warhurst

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CHAPTER 8¹

COMPETITIVENESS, ENVIRONMENTAL PERFORMANCE, AND TECHNICAL CHANGE: A CASE STUDY OF THE BOLIVIAN MINING INDUSTRY

Ismael Fernando Loayza

This chapter analyzes the links between competitiveness, environmental performance, and technical change in the Bolivian mining industry. It develops a dynamic economic model of the mining firm and tests it empirically using a multiple-case study of four Bolivian mining companies and seven mining operations. This model combines an economic theory of depletion with a theory of pollution and comprises two sets of equations describing investment behaviour and pollution per unit of output. The model analyzes the ways companies compete through technical change and illustrates how competitive companies increase their production capacity and technological capability over time.

The principal finding of this study is that a mining firm's dynamic efficiency significantly affects its internalization of environmental costs. Dynamic efficiency — a firm's ability to innovate and gain economies of scale — is not only a significant influence on its ability to compete but also a principal deter-

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minant of its environmental performance. Increased competitiveness encourages investment in technological capability and production capacity, and this in turn reduces pollution per unit of output, whereas decreased competitiveness increases pollution per unit of output. The analysis illustrates how pollution results both from a market failure to adequately price environmental resources and from a lack of dynamic efficiency in firms. An implication for environmental policy is that regulatory initiatives to reduce pollution need also to address the dynamic inefficiency of firms, as well as considering externalities.

Theoretical and policy background

According to conventional environmental economics, some environmental degradation is an inevitable by-product of human activities. The critical issue for society is not to prevent pollution altogether but to determine the optimal level of pollution or pollution control by balancing the benefits of polluting activities against their associated costs (see, for example, Ruff 1970). According to economic theory, the independent actions of producers and consumers in competitive markets will, under certain conditions, determine these optimal levels of pollution or pollution control. For example, if the polluters and those with grievances about them are few and property rights are clearly defined, voluntary bargaining between the two parties may result in an optimal solution (Coase 1960). Real markets, however, fail to meet these conditions in several ways, and the literature on environmental economics highlights the significant role of externalities in generating excessive environmental degradation. Externalities occur when the actions of an economic agent affect (positively or negatively) the welfare of others and they are not compensated for the damage or receive benefits free of charge.

Externalities undoubtedly cause pollution levels beyond socially desirable limits but may not be the sole cause of excessive (suboptimal) environmental degradation. An emerging body of literature is therefore beginning to address the environmental effects of production inefficiencies in developing countries (Moore 1986; Barbier 1989, 1991; Pearce et al. 1990; Doleman 1991; O'Connor 1991; O'Connor and Turnham 1991; Simonis 1992; Warhurst 1992, 1994). This literature analyzes how low levels of investment inhibit the accumulation of non-resource capital and development of organizational capabilities and skilled human resources. As a consequence, developing countries undertake production processes with lower levels of efficiency than those in industrialized countries, which results in high levels of pollution per unit of output and leads the poorest populations of the Third World to exploit the natural environment without regard to its sustainability. O'Connor (1991) and Warhurst (1994) pointed out that in the mining

industry, low educational and skills levels of workers can negatively affect productivity and the maintenance of equipment. This reduces profit and constrains a company's capacity to invest. As a result, companies are unable to renew capital equipment or acquire state-of-the-art equipment that pollutes less per unit of output. Similarly, a principal characteristic of the many artisanal mining operations that prevail in developing countries is their underexploitation of ore deposits and overexploitation of the environment's capacity to receive waste. This situation is a result of high rates of time preference and a shortage of capital and technical knowledge.

By suggesting that a firm's level of pollution is related to its efficiency, this emerging literature makes a significant contribution to the analysis of excessive (suboptimal) environmental degradation. However, this analysis has two flaws. First, although it highlights the interface between the theory of pollution and the theory of production, it fails to systematically integrate them. Second, it fails to develop a dynamic model of the firm as an alternative to the conventional, static approach. This study seeks to address these shortcomings by developing and empirically testing a dynamic model of competitiveness and environmental performance in the mining firm.

The case studies of the Bolivian mining industry illustrate how dynamic investment in technologies and organizational forms that internalize and reduce environmental costs improve the competitive position of a company and improve its environmental performance. The formal hypothesis underpinning the research is that the externalization of a firm's environmental costs is determined by its competitive efficiency. Central to the analysis are two assumptions regarding the mining firm. First, competition between firms encompasses the capacity to innovate, which enhances a firm's ability to compete through technical change. Instead of simply maximizing their competitiveness within fixed constraints, mining firms improve it by changing the constraints. Second, competition operates as an evolutionary process that selects between successful and unsuccessful firms. As firms continually create and change products and modify the production process, the social mechanism of industrial competition influences the selection of many alternative approaches to the production of goods and services. The analysis shifts the focus from externalities to the negative environmental effects of companies facing competitive difficulties and examines the environmental payoff for companies and industries that can sustain and improve their competitive advantages. By demonstrating that pollution per unit of output is inversely related to a mining firm's competitiveness, this study lends empirical support to *a priori* arguments that competitiveness and environmental performance converge.

Toward a dynamic theory of the mining firm

This section establishes the analytic framework for the study by developing a dynamic economic theory of the mining firm. The static approach of conventional economic theories of depletion and pollution is highlighted to show how they neglect the interrelationship between production efficiency and environmental degradation. In this section, I develop a simple dynamic model of a mining firm to show that the degree of internalization of a mining company's environmental costs depends on changes in its competitiveness. The concept of dynamic competition highlights the process by which companies compete through technical change and changes in their production factors. This model therefore draws on Porter's (1990, p. 20) distinction between static and dynamic competition:

In a static view of competition, a nation's factors of production are fixed. Firms deploy them in the industries where they will produce the greatest return. In [dynamic] competition, the essential character is innovation and change. Instead of being limited to passively shifting resources to where the returns are the greatest, the real issue is how firms increase the returns available through new products and processes. Instead of simply maximising within fixed constraints, the question is how firms can gain competitive advantage from changing the constraints. Instead of deploying a fixed pool of factors of production, a more important issue is how firms and nations improve the quality of factors, raise the productivity with which they are utilised, and create new ones.

Competitive equilibrium and the mining firm

One of the major achievements of neoclassical economic theory has been its ability to abstract from specific differences among thousands of firms the common features underlying economic activities and the functioning of markets to explain these at a high level of generality. Competitive equilibrium, for example, is a concept based on the assumption that firms are driven by profit and select production levels to maximize their profit. Within this theoretical framework, the relationship of prices to costs is key to a firm's achieving equilibrium, as the shape or position of its cost curves will change only if the prices of the firm's production factors change.

Despite this tendency to universal abstraction, a specific theory of the mining firm and the economics of exhaustible resources has been developed to account for the concept of user cost. Hotelling (1931) established that because an ore deposit is an exhaustible resource and a unit of ore can be exploited only once, the competitive mining firm is not in equilibrium at the production level at which

price equals marginal cost. Whereas in manufacturing, for instance, today's production theoretically does not limit tomorrow's, in mining, today's production very much depends on yesterday's. The maximization of profit for a mining firm must therefore take into account this opportunity cost (commonly referred to in the literature as the user cost).

The allocation of mineral production over time is therefore fundamental to the maximization of a mining firm's profits. At any point in time, a mining firm has to allocate production over time to maximize the returns from natural capital. Yet, mining companies also have to consider capital-investment programs that could increase the present value of their profits through the development of technical and organizational change. Investment can improve exploration, project development, and extraction and processing technologies. Innovation, for example, can expand the stock of exhaustible natural resources that are economically exploitable by shifting mineral resources into mineral reserves.

Mineral production and environmental externalities

Minerals production requires, in addition to ore deposits, other environmental resources, such as land, water, and air. These environmental resources provide inputs to the production process and receive its waste streams. Under free-market conditions, most of these environmental resources have no price. Consequently, the mining company never internalizes these costs, and they are imposed on society instead. But these resources contribute to society's well-being because they provide production inputs and amenity services and support life. To maximize society's welfare over time, therefore, the right balance is needed between pollution and environmental protection, which the market fails to deliver as a result of externalities related to the exploitation of environmental resources.

In Figure 1, curve *B* represents the marginal social benefits (MSB) of mining pollution and the demand for pollution derived from the demand for minerals. (Pollution benefits society to the extent that it derives from the production of minerals, which contribute to the welfare of society.) Its negative slope reflects that fact that for each additional unit of mineral production, society's welfare is increased less than by the last unit produced. Curve *C* represents the marginal social costs (MSC) of pollution. Its positive slope illustrates that for each additional unit of mining pollution, society's welfare is decreased by a greater amount than the last unit of mining pollution because fewer environmental resources are available for other purposes. The areas below curves *B* and *C* define the MSC and MSB of pollution, and at pollution level P_2 society's welfare is maximized.

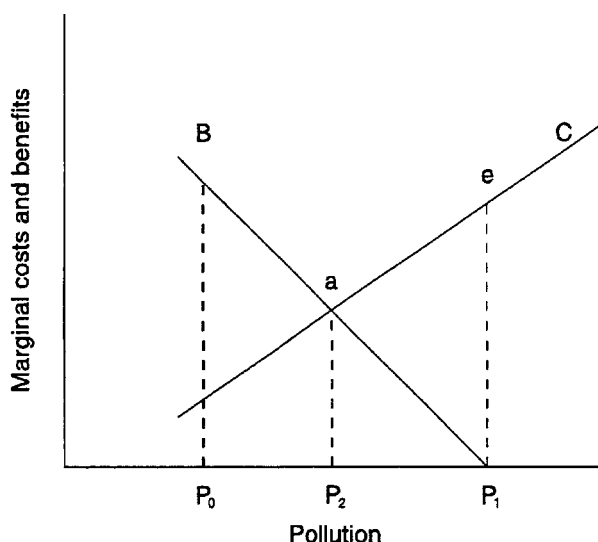


Figure 1. Optimal pollution level.

From the mining firm's standpoint, curve C coincides with the horizontal axis because pollution costs are external to the firm. Thus, mineral production will increase up to P_1 . At P_1 , the benefits to the mining firm are maximized. However, at these levels of pollution and production, the area P_1ae defines net social loss. The market fails to deliver P_2 because it is unable to price environmental resources and, therefore, unable to reflect the MSC of pollution (the area under curve C) adequately.

Figure 2 shows the effect on the firm of internalizing pollution costs to establish a level of environmental protection (such as set by government regulation). Under free-market conditions, X_0 is produced and there is no environmental protection. If, for example, a level of environmental protection (E_0) is required, the curve of marginal costs (which includes user costs) shifts from MC ($E = 0$) to MC ($E = E_0$). Accordingly, production is reduced from X_0 to X_1 , and the firm internalizes MC given by the distance AC .

The combined effect of pollution and user cost

A number of conclusions follow from the above discussion. First, as ore deposits are exhaustible, their exploitation involves a depletion cost (user cost), which is delivered by the market and is therefore internal to the mining firm. Second, under

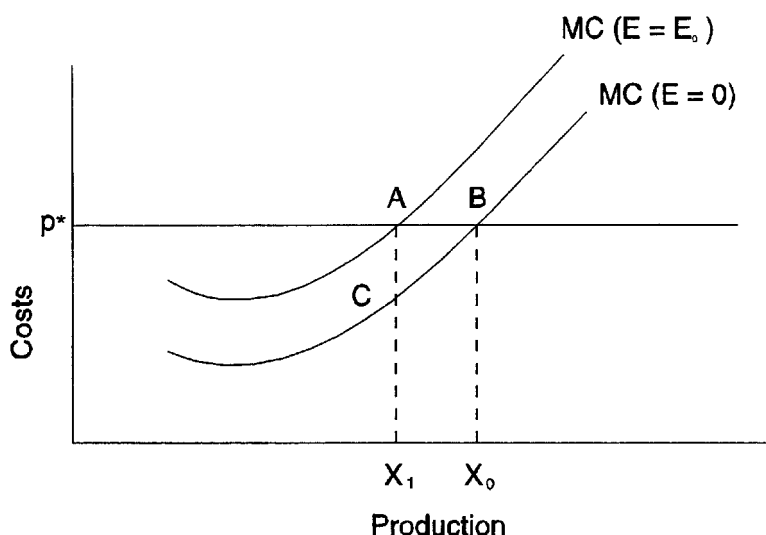


Figure 2. The firm's marginal cost (MC) of pollution.

free-market conditions, excessive pollution will take place because some environmental resources are inadequately priced by market mechanisms. Further, as production functions are constant under conditions of static competition, reductions in pollution take place only if an external agent (such as a governmental agency) encourages the mining firm to protect the environment. This lowers the mining firm's output. The mining firm's pollution costs include, therefore, both expenditures on production factors used for environmental protection and the income losses arising from a reduction in output. Third, a striking feature of this discussion is that user and pollution costs are both related to the exploitation of natural resources, although user and pollution costs have traditionally been analyzed independently.

To integrate both approaches, let us first assume, for simplicity, that firms are in equilibrium and that mineral production does not require capital but only labour. Labour can be employed either in the production of ore or in environmental protection. Thus, the marginal costs of the mining firm only include labour and user costs. Under these conditions, an increase in pollution costs resulting from changes in environmental regulations brings about two conservation effects. First, marginal reserves are changed into resources, and the total amount of ore to be exploited over a mining project's lifetime is reduced. Second, rising pollution costs

make the mining firm's initial production path no longer optimal. To maximize current profits, costs must be transferred from the present to the future because future costs have a smaller present value than current costs. Thus, environmental costs introduce a conservation effect as current output decreases in preference to future output. However, an increase in the interest rate raises the rate of growth of user costs and encourages a mining firm to bring forward future production. This modifies the optimal production path by increasing current production in preference to future production and by reducing the life span of the ore deposit. The amount of current pollution increases, although the total amount of pollution remains constant over the life span of the deposit. This may harm the environment if, in periods close to the present, environmental thresholds are close to being surpassed.

The introduction of capital complicates the analysis. On one hand, the increase in the interest rate promotes the expansion of ore production in the periods close to the present. On the other hand, it also increases capital costs and prevents an increase in present production. Thus, as the mining industry is capital intensive, it is uncertain whether a change in user cost will modify both the mining firm's production and its pollution paths. This suggests that introducing user costs into the analysis does little to help us understand the mining firm's pollution costs. It would appear, therefore, that under conditions of static equilibrium (and as conventional environmental economists implicitly conclude), the problem of pollution can be adequately analyzed independently of depletion. This means that if production functions are given and firms only compete through hiring the production factors that best fit their production functions, then the problem of depletion of natural resources is essentially independent of that of environmental pollution. The following section moves the discussion forward by analyzing the relationship between user and producer costs, assuming that mining firms also compete through changing their production functions. Under such dynamic-competition conditions, a mining firm may both increase ore production and internalize environmental costs through technical change.

Dynamic competition, production capacity, and technological capability

Thus far, the analysis has considered the mining firm a simple system, with production factors organized to produce ore concentrates. Two assumptions underlie this representation. First, it is assumed that a particular firm has technical relationships linking output levels with input specifications and combinations and that changes in output involve changes in the use of production factors, according to the technical possibilities given by the mining firm's production function. Second,

it is assumed that output levels, or the rates of ore extraction over time, are those that maximize the present value of the mining firm's profits. Therefore, changes in metal and production-factor prices prompt changes in output and in the use of production factors to maximize the current value of the firm's profits or to minimize the current value of its losses. Again, these changes conform to the technical possibilities given by the firm's production function.

In reality, however, firms are driven by profits, and the profits accrued by firms depend on their production functions. Thus, assuming that firms change and upgrade their production functions is more realistic than assuming that firms' production functions remain unchanged. Moreover, the many technical changes in the minerals industry in the last century indicate that competition involves innovation and that, consequently, firms relentlessly change their production functions. An analysis of the mining firm under conditions of dynamic competition is therefore empirically, as well as theoretically, justified.

The key feature of an industrial firm under conditions of dynamic competition is that it devotes its resources to producing not only final goods or services but also technical change to improve the efficiency of the production process and upgrade the firm's production function. As pointed out by Bell and Pavitt (1993), the firm has two stocks of resources: production capacity and technological capability. Technological capability incorporates the resources needed to generate and manage technical change, which is any change that modifies the levels of efficiency for a given production capacity. Technological capability includes mainly intangible assets, namely, knowledge, skills, experience, and institutional structures and linkages (in firms, such as collaboration among process-engineering departments; between firms, such as cooperation between the user and the supplier; and outside firms, such as connections with government research and development [R&D] departments). Consequently, the firm may accumulate two types of stock: production capacity and technological capability. Output and technical change are the respective outcomes of those stocks and are accumulated according to the profit-maximizing behaviour of the firm.

Because technical change seeks hitherto unachieved production results, the effects of accumulated technological capabilities are uncertain. When investment in technological capability is carried out, knowledge and experience are insufficient for one to adequately assess the overall effect of technical change. Nonetheless, technological accumulation is a key weapon in industrial competition. As Porter (1990) suggested, the fiercer the competition, the greater the incentive for companies to accumulate technological capabilities and to generate innovations. This causes firms to develop in an evolutionary fashion, which occurs for two

reasons. First, to survive, firms have to continuously adjust their stocks of production capacity and technological capability to meet changing production and competition conditions. Accordingly, firms strive for survival by accumulating production capacity and technological capabilities. Second, competition discriminates between the successful and unsuccessful firm strategies. Firms accrue profits according to their degree of success. In this way, successful firms increase over time their capacity to invest, which enables them to accumulate production capacity and technological capability, which further improves their competitiveness and strengthens their competitive advantage (Nelson and Winter 1982).

A dynamic model of the mining firm

The following model builds on the above theoretical framework and represents an original contribution to the study of environmental economics and exhaustible resources.

Because investment decisions modify a firm's stocks of production capacity and technological capability, the total investment of a mining firm in period t (I_t) can be expressed by the following equation:

$$I_t = I_t^Q + I_t^{TA} \quad [1]$$

where I_t^Q and I_t^{TA} are the investments in production capacity and in technological capability in period t , respectively. In period t , the investment in production capacity depends on the gap between the optimal production capacity and the actual production capacity in period $t - 1$ ($Q_{t-1}^{opt} - Q_{t-1}^a$); the interest rate (r_t); the firm's changes in profitability, which are estimated by its changes in competitiveness (dq_t) in period t ; and other determinants represented by the variable v_t . The larger the gap between optimal and actual production capacity in the last period, the greater the current rate of investment. If in period $t - 1$ there was excessive production capacity, $Q_{t-1}^{opt} - Q_{t-1}^a$ becomes negative, with the result that in period t reductions in production capacity are encouraged.

These changes in competitiveness in period t (dq_t) are a proxy for the variations in the firm's rate of return. It is assumed that if a company increases its market share, its profitability will also increase because the competitive success of a mining firm determines its profitability in the long run. The optimal production capacity over time is a function of the productivity levels attainable by the firm, given the technology and the firm's mineral resources (T_t^a), the prices of inputs used in the production process (P_t^i), the price of ore that is sold (P_t^o), changes in competitiveness (dq_{t-1}), and other factors such as mining policies (x_{t-1})

prevalent in period $t - 1$. Consequently, in period $t - 1$, the following function describes a mining firm's optimal production capacity:

$$Q_{t-1}^{\text{opt}} = o(T_{t-1}^a; P_{t-1}^i; P_{t-1}^o; dq_{t-1}; x_{t-1}) \quad [2]$$

In a given period, the mining firm's planned technological capability depends on its actual production capacity (Q_{t-1}^a), changes in its competitiveness during the same period (dq_{t-1}), and other factors (y_{t-1}). Thus, in period $t - 1$, the planned technological capability of a mining firm is described by the following function:

$$TA_{t-1}^{\text{wi}} = p(Q_{t-1}^a; dq_{t-1}; y_{t-1}) \quad [3]$$

The effect of changes in a mining firm's competitiveness (dq_{t-1}) on its planned technological capability and optimal production capacity is the kernel of the model of a decline occurs in the competitiveness of a mining company, changes in technological capability may conflict with variations in production capacity because of changes in anticipated user costs in relation to the planned user costs.² This is because a decline in competitiveness indicates that a firm cannot sustain its ability to compete and that capital losses may occur over time. In this situation, the firm minimizes its losses or maximizes its benefits by increasing its current production according to the anticipated decline in the growth rate of the user cost. However, because increased technological capability increases the profitability of future production only, the firm may reduce its investment in technological capability. Consequently, investments in production capacity may be encouraged in periods closer to the present as the firm's optimal production capacity increases, but investment in technological capability is greatly reduced as the firm finds the accumulation of technological capability less attractive.

In contrast, if a mining company is improving its competitiveness, the growth rate of its anticipated user costs increases faster than planned. An upward trajectory of a firm's ability to compete indicates that its production efficiency will be enhanced over time, and the firm can earn greater profits per tonne mined than when its competitiveness remains stable. As mineral resources can be exploited

² Planned and anticipated user costs are the user costs as perceived by a mining agent at two different moments. The planned-user-cost path is the one consistent with the optimal production path when an investment project is carried out. The anticipated-user-cost path is the one that at any point in time the mining agent anticipates will prevail in the future. Consequently, if planned- and anticipated-user-cost paths coincide, the mining firm's present production plan is optimal. However, if the anticipated-user-cost path differs from the planned-user-cost path, the production plan is then no longer optimal and has to be adjusted to maximize profits.

just once, the possibility of better exploitation of the mineral resources in the future — once production efficiency is enhanced — encourages a firm to transfer production from the present to the future. Therefore, the improvement in competitiveness of a mining firm increases its planned technological capability. This has no adverse effects on the accumulation of production capacity because of the complementary relationship between the incentives to invest in technological capability and those to invest in production capacity. Success prompts mining firms to increase their investments in exploration and the development of ore deposits and encourages them to accumulate production capacity as competitors are forced to leave the industry. This entails a steady increase in the optimal production capacity of successful firms.

The environmental-performance function

The environmental performance of a mining firm is defined by the pollution (environmental degradation) it generates per unit of output, rather than by the absolute level of pollution. It is important to consider production efficiency along with pollution. For example, if a smelter emits 100 t of SO_2 into the atmosphere in producing 1 000 t of metal/d, it emits 100 kg of SO_2 /t of metal. If, however, the smelter increases production to 3 000 t of metal/d but increases SO_2 emissions to only 150 t/d, its pollution per tonne of metal produced is reduced by half. Thus, changes in a mining firm's environmental performance can be described by changes in pollution per unit of output. In period t , the pollution per unit of output of a mining firm (Θ_t) is a function of the waste produced per unit of output (W_t), the way waste is disposed of (D_t), the toxicity of the waste (τ_t), and the consumption of complementary environmental services per unit of output (C_t). Thus,

$$\Theta_t = a(W_t; D_t; \tau_t; C_t) \quad [4]$$

The amount of waste per unit of output depends on the ore grade and the percentage of ore-grade dilution in the extraction. Ore grade is determined by the metal content per unit of ore, so decreases in ore grade will decrease metal recovery per unit of ore. The amount of waste per unit of metal output will thus increase as ore grade decreases. Unlike ore grade, which is a parameter given by nature, the degree of ore-grade dilution is a technical parameter, indicating the difference between ore grade and head grade (the grade of mined ore that is fed to a concentration plant). Ore-grade dilution results from imperfections in the blasting operation that increase the waste per tonne of ore extracted from the mine. Thus, if ore-grade dilution increases, the amount of waste also increases, and vice versa. Given a fixed amount of waste, the pollution per unit of output

varies with the system of waste disposal and the toxicity of the waste stream. Thus, dumping mining tailings directly into the environment has a greater impact than disposing of the same tailings in special reservoirs. The treatment and reuse of mine and mineral-processing water can reduce water consumption per unit of output and decrease the amount of water pollution.

The model assumes that two factors determine waste-disposal practices at mining operations: environmental regulations (g_i^{Re}) and the ability of the environment to assimilate waste (S_i^w). In the absence of regulations requiring the internalization of environmental-damage costs, mining firms minimize costs by maximizing the use of the environment as a receiver of waste. For a given set of environmental regulations, changes in a mining firm's waste-disposal practices are related to the ability of the environment to assimilate waste. The environment's ability to assimilate waste is limited, so the greater the amount of waste produced in a given period, the more quickly the assimilation limit is reached. Therefore, changes in the ratio of firm's production capacity to the ability of the environment to receive waste (Q_i^a/S_i^w) will lead to changes in the waste-disposal practices of mining firms. Thus,

$$D_i = c(Q_i^a/S_i^w; g_i^{Re}) \quad [5]$$

Toxicity of mining wastes is assumed to be a function of environmental regulations (g_i^{Re}) that are mainly related to environmental-quality standards; metal recovery in mineral-processing activities (σ_i); loss of reagents per unit of output (ϕ_i); and the natural properties of the ore, particularly those that determine acid mine drainage. As the metal-recovery rate decreases, more metal is discharged into the environment. Similarly, reagents lost during mineral processing can leach into groundwater, surface water, and soils. Therefore, the degree of toxicity of waste generated by a mining firm can be described by the following function:

$$\tau_i = d(\sigma_i; \phi_i; Fe_i; g_i^{Re}) \quad [6]$$

This assumes that consumption of environmental resources per unit of output is determined by their degree of scarcity and by existing environmental regulations. Scarcity discourages consumption, and consumption increases scarcity. Natural availability and the effects of demand from a firm and from other consumers determine the availability of these resources at the mining site (S_i^o). Consequently,

$$C_i = e(Q_i^a/S_i^o; g_i^{Re}) \quad [7]$$

Thus, in period t , changes in a mining firm's environmental performance can be described as follows:

$$d\Theta_t = f[d(Q_t^a/S_t^o); d(Q_t^a/S_t^w); d\delta_t; d\sigma_t; d\phi_t; dFe_t; d\Gamma_t; dg_t^{Re}] \quad [8]$$

This model is consistent with the results of a conventional environmental-economics analysis because it demonstrates that under conditions of static competition, changes in a mining firm's environmental performance will result only from changes in environmental regulations. Under conditions of static competition, actual production capacity is optimal (all other things being equal), so production capacity will not change over time. Similarly, environmental properties are assumed to be stable over a firm's life span, so $d(Q_t^a/S_t^o)$, $d(Q_t^a/S_t^w)$, dFe_t , and $d\Gamma_t$ are therefore equal to zero. Under conditions of static competition, the firm's production function and technical parameters are given, so $d\delta_t$, $d\sigma_t$, and $d\phi_t$ are also equal to zero. Under conditions of static competition, equation [8] can therefore be simply expressed as follows:

$$d\Theta_t = g(dg_t^{Re}) \quad [9]$$

Under conditions of dynamic competition, however, production capacity and the technology used in the production process vary along the evolutionary path of the mining firm. Thus, the variables are not equal to zero, and equation [8] can be restated as

$$d\Theta_t = h(dQ_t^a; d\delta_t; d\sigma_t; d\phi_t; dFe_t; d\Gamma_t; dg_t^{Re}) \quad [10]$$

Technical change and environmental performance

Under conditions of dynamic competition, a mining firm has incentives to improve its environmental performance. Improvements that increase metal-recovery rates or decrease ore-grade dilution and reagent losses not only increase profits but also reduce pollution per unit of output. Thus, a mining firm's investment in technological capability favours its environmental performance. Each variable can therefore be modeled as a function of investment in technological capability. For example, changes in metal-recovery rates are a function of investments in technological capability and of changes in other factors, such as head grade and concentrate grade. Similarly, changes in reagent losses are a function of investment in technological capability and of changes in other factors, such as the complexity of the ore. Because changes in production capacity are equal to investment (either positive

or negative) in production capacity, changes in environmental performance can be described by the following function:

$$d\Theta_t = h(dq_{t-1}; dq_t; r_t; P_{t-1}; W_{t-1}; d\xi_t; dg_t^{Re}; d\mu_t) \quad [11]$$

This equation describes how, in period t , changes in pollution per unit of output are a function of several factors:

- Changes in a mining firm's competitiveness ($dq_{t-1}; dq_t$), both in period t and in period $t - 1$;
- The interest rate in period t (r_t);
- The prices of inputs and outputs in period $t - 1$ (P_{t-1});
- The stocks accumulated by the firm until period $t - 1$ (W_{t-1}), which include the firm's production capacity and technological capability;
- Changes in some technical parameters that are caused not by technical changes but mainly by changes in the natural properties of the ore deposit ($d\xi_t$);
- Changes in environmental regulations (dg_t^{Re}); and
- Changes in residual factors ($d\mu_t$).

The key feature of equation [11] is that changes in a mining firm's pollution per unit of output correlate negatively with changes in its competitiveness. This relationship has been neglected in the literature on environmental economics because researchers have assumed static competition. In contrast, the model developed here predicts that under conditions of dynamic competition, if a mining firm's ability to compete (competitiveness) is improved, its pollution per unit of output is reduced and vice versa. This is because, other things being equal, under conditions of dynamic competition the improvement in a mining firm's competitiveness increases its investments in production capacity and technological capability. Technological capability increases as the rate of growth of user costs rises over time, the efficiency of production improves, and profits increase, giving the firm easier access to investment funds. The increase in technological capability

improves the firm's environmental performance by reducing ore-grade dilution and losses of reagents and increasing metal-recovery rates.

Although it is uncertain whether reductions in production capacity will occur if the competitiveness of a mining firm declines, the downward trend in the rate of growth of user costs can lead to increases in pollution per unit of output. This is because investments in technological capability are drastically reduced, and the firm attempts to minimize natural capital losses by maximizing current output. This has a negative effect on production efficiency; consequently, ore-grade dilution and reagent losses are likely to increase, and metal-recovery rates may drop. Furthermore, as financial difficulties become more serious over time, the mining firm either has to shut down or has to scale down its operations. The latter negatively affects its waste-disposal practices and consumption of complementary environmental resources per unit of output.

It is important to stress that the validity of the relationship between changes in competitiveness and changes in environmental degradation per unit of output relies on the assumption that the technological capabilities of a mining company relate to the generation and management of incremental (as opposed to radical) technical change. This is because incremental technical change underlies the properties described in the equations and relates to improvements in the process that reduce inputs (reagents and complementary environmental services) or increase outputs (overall metal-recovery rates) over time. Radical technical change, on the other hand, might relate to the development of a new process, using, for instance, new and more toxic reagents to improve metal-recovery rates. The total effects of radical technical change on pollution per unit of output are thus uncertain. The assumption that a mining firm's technological capability generates and manages incremental technical change is based on the fact that mining is a scale-intensive industry and one in which incremental improvements of process technology dominate technical development. It must be emphasized that the dynamic model in no way suggests that technological development in mining has been protective of the environment. However, as long as incremental technical change dominates the pattern of technical change in a firm, the model demonstrates that improvements in a firm's competitiveness can result in improvements in its environmental performance and vice versa.

The interface of user and pollution costs revisited

A mining firm's investment in technological capability can modify the amount of economically exploitable ore over time and therefore can affect a mining firm's user costs. Incremental technical changes that enable a firm to economically exploit lower grade ore and increase recovery rates, for example, can reduce both

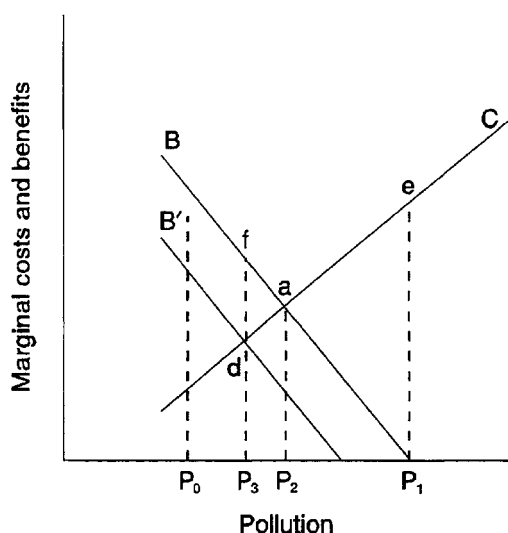


Figure 3. Excessive pollution resulting from externalities and dynamic inefficiency.

present user costs and pollution per unit of output. Thus, under conditions of dynamic competition, the theory of depletion and the theory of pollution appear to be significantly related, whereas this is not so under conditions of static competition. The overlap of theories makes it evident that excessive environmental degradation originates not only in the inability of the market to appropriately price environmental resources but also in competitive inefficiency. In other words, firms unable to accumulate technological capability and production capacity mismanage the environment, both as a source of raw materials and as a receiver of waste.

Figure 3 illustrates how excessive environmental degradation is related both to externalities and to competitive inefficiency. Curve B shows the demand for pollution derived from the demand for minerals, and curve C shows the marginal costs of pollution to society; P_2 represents the optimum pollution level under conditions of static competition. Under conditions of dynamic competition, however, improvements in production efficiency cause curve B to shift to B' , as a result of incremental technical change and the enlargement of successful firms' production capacity. These improvements further reduce pollution per unit of output, from P_2 to P_3 . At P_3 , society's betterment increases by the amount given by the area afd . Conversely, if the pollution level is at P_1 , society's excessive pollution level — P_1P_3 — comprises two parts:

- P_1P_2 is the level of suboptimal environmental degradation resulting from externalities associated with the use of environmental resources; and
- P_2P_3 is the excessive level of environmental degradation resulting from dynamic inefficiency, which discourages reductions in the mining firm's pollution per unit of output.

Testing the model

The main prediction of the model — that, *ceteris paribus*, pollution per unit of output is inversely related to a mining firm's competitiveness — was evaluated in the context of the Bolivian mining industry. The Bolivian mining industry provides a good case study because it satisfies two conditions for a simple empirical test of this study's hypothesis:

- The absence, in practical terms, of a systematic framework of environmental regulations relating specifically to mining; and
- Clear signs that the structure of the mining industry has dramatically changed since the 1980s, after a period of relative stability during the 1960s and 1970s.

Thus, the main effects of a company's investment decisions on its competitiveness and environmental performance are likely to emerge from the analysis.

Structure of the Bolivian mining industry

Bolivian mineral producers can be classified into three types, based on their ownership structure and size:

- The state-owned mining company, Corporación Minera de Bolivia (COMIBOL), which comprises all mining operations nationalized in 1952 and has been for more than three decades the largest single mining company in Bolivia;
- Privately owned large- and medium-scale mining operations; and
- Privately owned small-scale mining operations and mining cooperatives, which are typically labour intensive.

Table 1. Bolivia's zinc, tin, silver, and gold production, 1960–92.

	Share of national production (%)		
	State mining (COMIBOL)	Large- and medium- scale mining	Small-scale mining
Zinc			
1960	80	15	5
1971	69	—	31
1980	60	33	7
1990	24	61	15
Tin			
1960	65	12	23
1970	64	22	14
1980	68	22	10
1990	34	11	55
Silver			
1960	85	3	12
1970	81	4	15
1980	84	11	5
1990	36	48	16
Gold			
1960	—	48	52
1970	2	30	68
1980	—	21	79
1992	1	90	9

Note: COMIBOL, Corporación Minera de Bolivia.

In 1990–92, zinc, tin, silver, and gold production represented 90% of total nonferrous-minerals production by value, with antimony, bismuth, copper, lead, and wolframite (tungsten) accounting for the remainder.

Table 1 shows how the structure of Bolivia's zinc, tin, silver, and gold production changed between 1960 and 1992. COMIBOL was the most significant producer of zinc, tin, and silver until the early 1980s, but its importance declined by 1990 as the private mining operations increased their share of national production. Because the structure of the Bolivian mining industry changed dramatically during the 1980s, one might expect to find significant changes in both the competitiveness of the companies and in the ways they carry out production. The Bolivian mining industry is therefore a suitable case for testing whether, in the absence

of environmental regulations, a mining firm's trajectory of pollution per unit of output will correlate inversely with its trajectory of competitiveness.

Indicators of a company's environmental performance

The environmental performance of a mining company was assessed by reference to the firm's pollution per unit of output. Pollution was evaluated by changes in the following parameters: metal-recovery rates; reagent consumption; and solid- and liquid-waste-disposal practices at the mining site.

Metal recovery and head grade

Mineral production involves the processing of large amounts of ore to obtain small amounts of metals. Because 10% of the metal content cannot be economically recovered, a proportion of the metal content is disposed of in the environment. The ratio of metal recovered to total content in the feed ore is the metal-recovery rate, expressed as a percentage.

Water recycling and treatment

Water is a very important input in the mining industry. All mining operations in Bolivia use water to process minerals, and most of these operations take place in areas where water is scarce. Cations of heavy metals and chemical substances used in the dressing process often contaminate mine and mineral-processing water. The pollution caused by a mining operation is, therefore, heavily affected by its water- and waste-management practices.

Disposal of waste

Mining operations generate a variety of solid wastes. Waste (barren rock, coarse material, overburden, tailings) comes out of mines and ore-dressing plants; and scrap comes from mining and mineral-processing equipment. Because pollution per unit of output relates not only to the quantity and toxicity of the waste but also to waste-disposal practices, three categories of disposal were considered:

- The absence of disposal systems, or the unrestricted use of the environment's sink function;
- The disposal of waste but failure to undertake reclamation at the closure of the operation; and
- Waste disposal and reclamation.

Reagent consumption

Thiosalts and other chemical substances (such as sulfuric acid, sodium cyanide, sodium hydroxide, zinc sulfate, diesel oil, amine, and pine oil) are used in processing minerals and are ultimately discharged into the environment. Because water and soils at Bolivian mining operations are not systematically analyzed, I estimated the loss of reagents in tailings from reagent consumption per tonne treated.

Trajectories of competitiveness

This section presents the results from empirical analysis of the relationship between competitiveness and pollution per unit of output for selected mining companies. I used least-squares regression analysis and analysis of variance (ANOVA) to distinguish periods in which a company's competitiveness remained constant from those in which competitiveness either rose or fell. I then matched these trajectories of competitiveness to trajectories of pollution per unit of output to ascertain whether there was a significant correlation between competitiveness and environmental performance.

Empresa Minera Inti Raymi

Empresa Minera Inti Raymi exploits gold and silver in its Kori Kollo deposit in Oruro, about 200 km from La Paz. Although Kori Kollo has been exploited since colonial times, its development was limited until the 1980s because production of sulfide concentrates was not commercially feasible. However, massive oxidized and sulfide gold-silver deposits were discovered in the early 1980s, and in 1982 Empresa Minera Inti Raymi was founded to exploit these deposits. To exploit the oxidized deposit, Inti Raymi successfully introduced a heap-leaching operation, which expanded from 400 t/d to 4 000 t/d by 1987. A 14 500 t/d agitation-leaching project was initiated in 1993 to exploit the sulfide deposit. Figure 4 illustrates that Inti Raymi has followed an upward trajectory of competitiveness. Whereas world gold production increased 58% between 1984 and 1992, Inti Raymi's market share rose by 2 150%, from 0.004 to 0.090.

Corporación Minera de Bolivia

COMIBOL was established to exploit mining concessions belonging to Patiño, Hochschild, and Aramayo, three corporations that were nationalized in 1952. Until the middle of the 1980s, COMIBOL underwent few changes. As part of the structural adjustment of Bolivia's economy that began in 1986, COMIBOL was gradually restructured: some of its operations were transferred to cooperatives, and

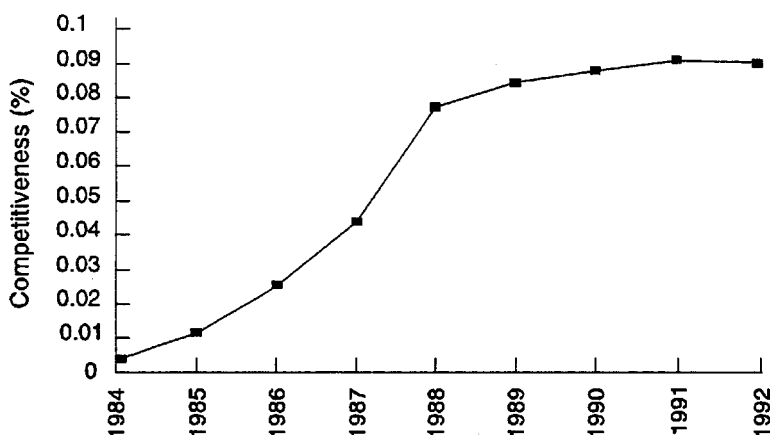


Figure 4. Inti Raymi's trajectory of competitiveness in gold.

COMIBOL actively sought joint-venture partners for other operations. Although minerals continued being significant to the Bolivian export economy (44% in 1990), COMIBOL's contribution decreased from 70% in the 1950s to around 10% by 1990. For 1970–92, COMIBOL's trajectories of competitiveness in tin, zinc, and silver were fairly similar.

Figure 5 illustrates the case for tin. Although competitiveness increased in 1970–77, it fell severely in 1978–87 in response to falling commodity prices. In 1988–92, however, COMIBOL's competitiveness in tin, zinc, and silver began to improve, although its market-share levels were lower than in the 1970s.

I took the trajectories of competitiveness and broke these down into sub-trajectories of increasing or decreasing trends in competitiveness. I then used least-squares regressions to evaluate these trends and used an ANOVA to distinguish periods in which competitiveness remained statistically constant from those in which competitiveness statistically rose or fell. The analysis showed that COMIBOL's competitiveness in tin, zinc, and silver production decreased significantly in 1978–87.

I evaluated COMIBOL's environmental performance at three mining operations: Catavi, Colquiri, and Unificada. Until the tin crisis in 1987, Catavi was COMIBOL's largest tin operation, and all COMIBOL interviewees regarded Catavi as COMIBOL's best-organized mine. I selected Catavi for analysis because it best represents COMIBOL's severe decline in competitiveness in tin. Colquiri is a major tin–zinc operation that improved its mining and ore-dressing operations

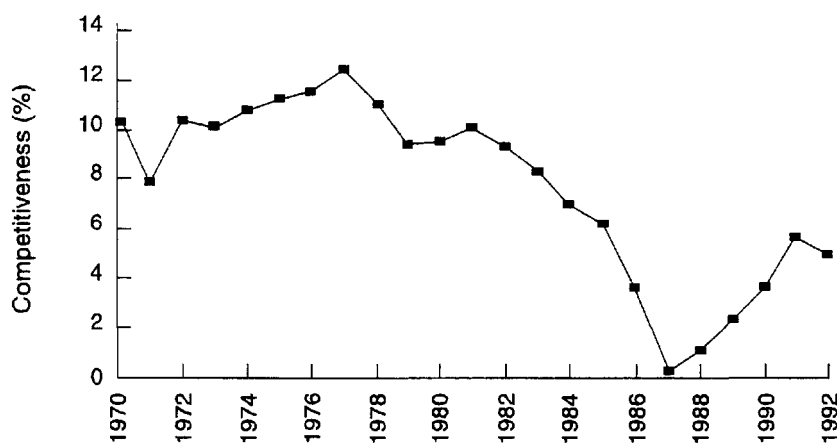


Figure 5. COMIBOL's trajectory of competitiveness in tin.

in 1988 and 1989 by introducing sublevel stoping and redesigning the concentrator. I selected Colquiri for analysis not only because it is COMIBOL's largest zinc producer but also because it made considerable efforts to improve the efficiency of its operations. Unificada, a significant producer of tin, silver, and zinc, illustrates COMIBOL's attempt to diversify production away from tin. Unificada is also the location of one of COMIBOL's major technical changes — tin volatilization. The failure to manage this technical change was one of the main causes for COMIBOL's decline in competitiveness in tin.

Compañía Minera del Sur

Compañía Minera del Sur (COMSUR) is a composite mining corporation, comprising a number of companies and operating sites. Founded in 1968, it enlarged and diversified its tin operations in the 1970s and 1980s, establishing a basis for becoming Bolivia's most important producer of zinc and lead in the 1990s. Zinc accounts for 75% of total production value, and in 1990 Rio Tinto Zinc acquired 30% of the company's equity.

The trajectories of competitiveness for COMSUR's zinc and silver production appear to have two general trends: no significant change (in 1974–82, for zinc, and in 1977–85, for silver) and a steady rise in competitiveness (in 1982–92, for zinc, and in 1985–90, for silver). Figures 6 and 7 illustrate the remarkable improvement (more than 300%) in COMSUR's competitiveness in zinc and silver, respectively.

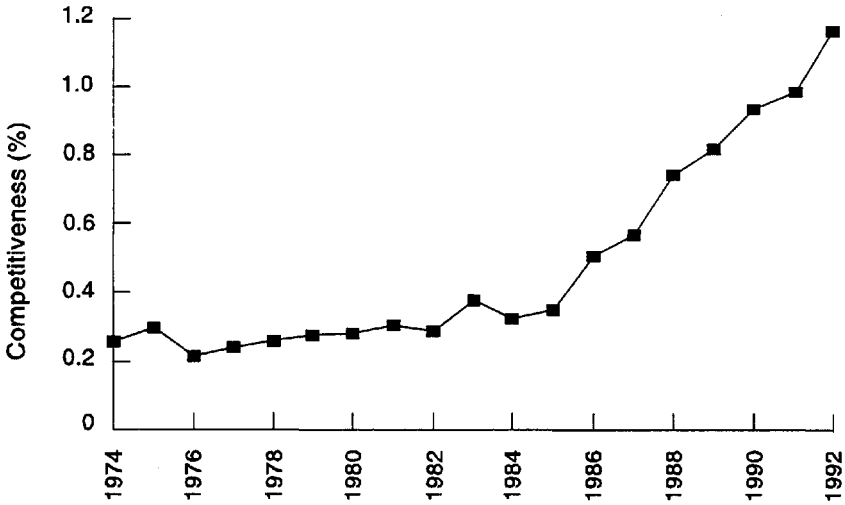


Figure 6. COMSUR's trajectory of competitiveness in zinc.

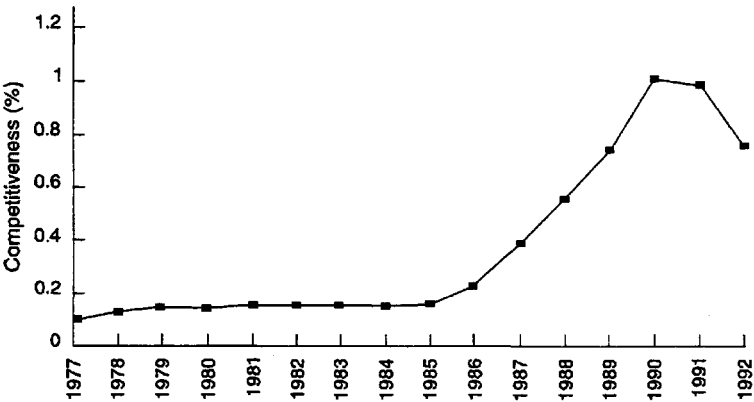


Figure 7. COMSUR's trajectory of competitiveness in silver.

An ANOVA of COMSUR's competitiveness in zinc and silver showed that the increases in competitiveness in 1982–92 for zinc and in 1985–90 for silver were statistically significant. In the case of COMSUR (as well as in the case of Inti Raymi), only periods of improved competitiveness were analyzed in relation to environmental performance. I selected the mining operations of Porco and COMCO for this. Although COMSUR's upward trajectories of competitiveness

in zinc and silver may have been related to COMCO's development (at the end of the 1980s) and the acquisition and sustained production growth of Caballo Blanco S.A. (bought in 1980) and Quioma S.A. (bought in 1986), the case of Porco (COMSUR's leading mining operation) encapsulates COMSUR's success. Until the early 1980s, Porco was a fairly small operation (350 t/d), but by 1992 its zinc production had risen by 150%. In 1992, an enlargement project, from 800 t/d to 1 200 t/d, was completed, and Porco is now Bolivia's largest zinc mine (1 200 t/d). COMCO is a 1 000 t/d heap-leaching silver operation, reprocessing old oxidized tailings since 1989. COMCO may represent a turning point in COMSUR's development: technical operations represent a departure from the traditional production methods of the Bolivian mining industry (gravimetric concentration and flotation), and COMCO is the only project that COMSUR developed from scratch.

Central Local de Cooperativas Mineras Cangallí

When the state took over the largest mining groups in 1952, mining concessions in the Tipuani-Tora region were nationalized and divided into 10 sectors, with 2 200 mining concessions. The cooperatives located in the 9th sector established the Consejo de Cooperativas Cangallí, which in 1982 became the Central Local de Cooperativas Mineras Cangallí (CECOCA). CECOCA is the legal owner of more than 800 mining concessions, distributed among 12 cooperatives, and each cooperative freely controls the concessions it has. Although CECOCA coordinates activities that require the cooperatives to collaborate (such as negotiating an agreement to drag the Tipuani river) and provides technical and financial support to the cooperatives, it neither formulates corporate policies nor interferes in any individual cooperative's business.

I selected one of CECOCA's cooperatives — the Cooperativa Aurífera Rosario California Ltda — for detailed study because it pioneered the major technical changes (surface mining and mechanization) that were diffused throughout the region during the early 1980s and is one of the gold cooperatives that has achieved the highest degree of economic success.

Figure 8 shows Rosario California's "shadow trajectory" of competitiveness in gold. Most of CECOCA's cooperatives make no systematic records of production parameters, not even of output. The shadow trajectory was therefore calculated using data from the Federación Regional de Cooperativas Auríferas (regional federation of gold cooperatives), which has since 1982 estimated the cooperatives' total gold production on the basis of archives and oral reports. In a period in which world gold production rose by 80%, Rosario California's shadow trajectory of competitiveness increased in 1978–86 but decreased in 1986–91. An ANOVA showed that both the increase and the decrease were statistically significant.

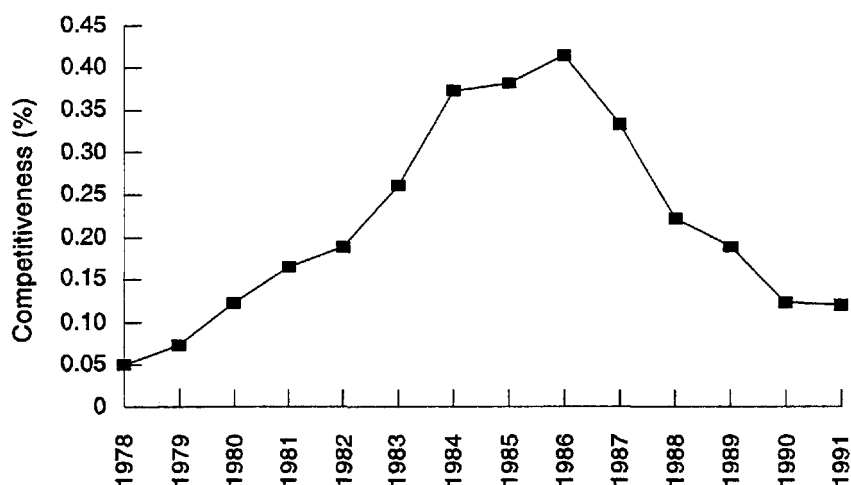


Figure 8. CECOCA's shadow trajectory of competitiveness in Cooperativa Aurifera Rosario California.

Table 2. Trajectories of competitiveness of the four study firms, 1977–92.

Competitiveness	Firm	Mineral	Period	Operation
Decline	COMIBOL	Tin	1977–92	Catavi (Sn)
		Zinc	1978–87	Colquiri (Sn, Zn)
		Silver	1978–92	Unificada (Sn, Zn, Ag)
	CECOCA	Gold	1986–91	Rosario California (Au)
Improvement	Inti Raymi	Gold	1984–92	Kori Kollo (Au)
	CECOCA	Gold	1978–86	Rosario California (Au)
	COMSUR	Zinc	1982–92	Porco (Zn, Ag, Pb)
		Silver	1985–92	COMCO (Ag)

Note: CECOCA, Central Local de Cooperativas Cangalli; COMIBOL, Corporación Minera de Bolivia; COMSUR, Compañía Minera del Sur.

Summary

The trajectories of competitiveness for the four study firms are summarized in Table 2, which includes the mining operations at which the firms' environmental performance was assessed.

Comparison of environmental performance

I divided the multiple-case study into two sets of mining operations by testing for a negative correlation between a firm's competitiveness and its pollution per unit of output. One set comprised operations for which the hypothesis of a negative correlation was not rejected; the other set comprised operations for which either the hypothesis was rejected or a correlation (positive or negative) was indeterminate. The criteria for deriving the trajectories of pollution per unit of output were based on the following:

- Variation by more than 10% in quantitative variables, such as metal-recovery rates and reagent consumption, would be deemed significant; variation of 0–10%, less significant.
- Changes in metal-recovery rates would be adjusted according to changes in head grade, based on the assumption that significant increases and decreases in head grade are equal to less significant decreases and increases, respectively, in recovery rates. If there were significant increases in metal-recovery rates and head grade, the total increase in metal-recovery rates would therefore be regarded as less significant.
- Changes in qualitative variables would be considered significant only if the firm had made major changes in water management or waste disposal (for example, the introduction of water-recycling or reclamation programs).
- Variations in pollution per unit of output due to changes (variables) in recovery rates, in reagent consumption, in water consumption, and in waste disposal would be scored to obtain aggregate indicators of changes in a mining operation's pollution per unit of output. Significant and less significant variations in a variable would score 2 and 1, respectively; no variation and indeterminate changes would score 0. A score of 4 would mean that an operation had experienced less significant changes in all four variables, so an operation scoring more than 4 would be considered as having made significant changes in pollution per unit of output. Scores of 1–4 would be considered less significant. Operations scoring 0 would be considered as having made no significant changes. The relative nature of an operation's overall score would be emphasized: if two operations scored 5 and 7, respectively,

all that could be said about their environmental performance is that both had undergone significant variations, and it would be incorrect to conclude that the operation scoring 7 performed better than the one scoring 5.

Correlations of changes in competitiveness with changes in pollution per unit of output

Table 3 shows the relationship between changes in competitiveness and changes in pollution per unit of output for the eight operations examined. In only one case did the changes in a mining company's competitiveness not correlate with changes in its pollution per unit of output (Rosario California, when CECOCA's competitiveness improved). In six cases, changes in competitiveness correlated negatively with changes in pollution per unit of output as predicted by the model, and in five of these (Inti Raymi, Porco [COMSUR], Rosario California [when CECOCA's competitiveness decreased], Catavi [COMIBOL], and Unificada [COMIBOL]), the negative correlation was significant. Moreover, in all these operations, changes in pollution per unit of output due to variations in recovery rates, reagent consumption, water consumption, and waste disposal had the same direction. This initial evidence supports the model's prediction that these variables will follow similar trends because changes in competitiveness reflect complementary changes in technological capability and production capacity.

In the cases of COMCO (COMSUR) and Colquiri (COMIBOL), some variables followed opposing trends, calling into question the causal linkage suggested by the model. Moreover, because of the contradictory trends in reagent consumption, water consumption, and waste disposal, the direction of COMIBOL's trajectory of pollution per unit of output at the Colquiri operation was uncertain. I therefore assessed the robustness of the model by its ability to explain not only the contradictory trends in Colquiri and COMCO but also the main reasons underlying the lack of correlation between changes in CECOCA's competitiveness and changes in pollution per unit of output at the Rosario California cooperative (1978–86).

Environmental advantages from technical changes to enhance the production process

The data in Table 3 were used to examine the role of incremental technical change in enhancing a company's competitiveness and environmental performance and the relationship between technical change, production capacity, and environmental performance.

Table 3. The relationship between firms' competitiveness and their pollution per unit of output.

	Inti Raymi	COMSUR			CECOCA		COMIBOL				
		Porco		Comco	Rosario California		Catavi	Unificada		Colquiri	
		Au	Zn	Ag	Ag	Au	Au	Sn	Sn	Ag-Zn	Sn
Competitiveness	84-92 I	82-92 I	85-92 I	85-92 I	78-86 I	86-91 D	77-92 D	77-92 D	78-92 D	77-92 D	78-87 D
Pollution per unit of output	D(S)	D(S)	D(S)	D(L)	k	I(S)	I(S)	I(S)	I(S)	I(S)	?
Recovery rates	86-92 D(S)	88-92 D(L)	88-92 D(L)	89-92 k	80-86 k	86-91 I(?)	77-85 ?	77-85 I(L)	89-92 k	77-92 ?	78-85 k
Reagent consumption	88-92 D(S)	88-92 D(S)	88-92 D(S)	89-92 D(S)		86-91 I(S)	88-92 I(?)	77-85 NA	89-92 I(S)	90-93 D(L)	90-93 D(L)
Water consumption	86-92 k	88-92 D(L)	88-92 D(L)	89-92 k	80-86 k	86-91 k	77-92 I(S)	77-92 I(S)	77-92 I(S)	77-92 D(L)	77-92 D(L)
Waste disposal	87-93 D(S)	88-92 D(S)	88-92 D(S)	89-92 I(L)	80-86 k	86-91 I(S)	77-92 I(S)	77-92 I(S)	77-92 I(S)	77-92 I(S)	77-92 I(S)
Correlation	-(S)	-(S)	-(S)	-(L)	0	-(S)	-(S)	-(S)	-(S)	?	?
Hypothesis rejected	No(S)	No(S)	No(S)	No(L)	Yes(S)	No(S)	No(S)	No(S)	No(S)	?	?

Note: CECOCA, Central Local de Cooperativas Mineras Cangallí; COMIBOL, Corporación Minera de Bolivia; COMSUR, Compañía Minera del Sur. D, decrease; I, increase; L, large; S, small.

Table 4 summarizes the technological performance of Inti Raymi and COMSUR. Improved metal-recovery rates and reagent consumption indicate a link between environmental performance and technological performance at these sites. For example, sodium cyanide (NaCN) consumption fell by 29% at the COMCO heap-leaching operation as a result of systematic control and monitoring. The activities of a small R&D department at the Inti Raymi leaching project resulted in even more dramatic reductions in NaCN (73%) and zinc (79%) per unit treated. The COMCO and Inti Raymi operations highlight the important fact that in leaching operations, economic and environmental considerations favour the careful management of cyanide. As an executive of Inti Raymi stated during an interview, "it will be the end of the operation if a disaster takes place because of the mismanagement of the cyanide solution." Furthermore, the profitability of the project depends very much on minimizing solution losses, not only because of the cost of cyanide but also because of the fact that metal is lost, as well as the solution.

COMSUR also achieved significant reductions in reagent consumption per tonne treated at Porco, although the operation uses different mining and mineral processing methods. In 1988–92, the Porco operation reduced its consumption of complex cyanide, CuSO_4 , Dowfroth 1014, lime, and SF 114 by 21, 22, 33, 37, and 22%, respectively, per tonne treated. These reductions resulted from new technology and expertise in process engineering. For example, COMSUR redesigned Porco's mining operations and constructed a new and enlarged (from 800 t/d to 1 200 t/d) zinc–silver and lead-flotation plant in 1988–92. COMSUR also installed equipment embodying new technology, such as a semiautogenous grinding mill, column-cell cleaning of concentrates, and computer-based process control. In addition to the modification of the original design (from lead–zinc differential float to bulk flotation for zinc, lead, and silver), these changes made the flotation process much more efficient. The optimization of variables — such as pH levels, liquid–solids ratio, and the feed of reagents — brought about reductions in reagent consumption and increases in the grade of zinc and lead concentrates. Increasing the lead-recovery rates by 11% also significantly reduced the amount of lead per unit of output discharged into the environment.

So far, an important result has emerged: the optimization of the production process through incremental technical change has a beneficial effect on both a mining company's ability to compete and its level of pollution per unit of output. In comparison with Porco and Inti Raymi, COMCO made only a modest improvement in environmental performance, because there was less technological dynamism at that site. COMCO's ore reserves did not increase over time (in contrast

Table 4. Technological performance of Inti Raymi, Porco, and COMCO.

	Inti Raymi	COMSUR	
		Porco	COMCO
Successful radical technical changes	• Oxidized deposit: open pit and heap leaching • Sulfide deposit: agitation leaching		• Oxidized tailings: heap leaching
Successful incremental technical changes	• Induced polarization and magnetic prospecting in exploration • Improvement of the heap design • Reduction of the size of mineral grain • Improvement of the watering of heaps • Optimization of the cycle and the grade of the gold-bearing solution	• Change in explosives • Column-cell cleaning • Automatic computer-based process control • Semi-autogenous grinding heaps • Bulk flotation, instead of lead–zinc–differential float	• Redesign of the crushing and comminution circuit
Unsuccessful incremental technical changes	• Reduction in the evaporation of the gold-bearing solution		• Replacement of dry- with wet-grinding

Note: COMSUR, Compañía Mineral del Sur.

to those at Porco and Inti Raymi), and because of this shortage of reserves, COM-SUR was unable to commit itself to changing from dry grinding to wet grinding, which would have significantly reduced its costs. In addition, political opposition to COMCO from the civic institutions of Potosi magnified the long-term risks of this project.

Thus, the analysis shows that technological performance is linked to competitiveness and environmental performance — the discharge of wastes such as heavy metals and reagents per unit of output decreases with improvements in production efficiency. The output–waste ratio, just like the output–input ratio, is an indicator of the production efficiency of an industrial operation. Improvements in the production efficiency of a mining company result in more efficient use of the environment and involve greater internalization of pollution costs.

Misuse of environmental resources due to unsuccessful technical change

Increased pollution per unit of output is also related to the mismanagement of technical change (innovation inefficiency). On one hand, because of unsuccessful technical change, the decline in metal-recovery rates cannot be arrested, and the waste generated per unit of output increases. On the other hand, unsuccessful technical change has negative effects on a company's competitiveness. This brings about significant reductions in production capacity, which result in greater externalization of costs to the environment. COMIBOL's Catavi and Unificada operations and CECOCA's Rosario California cooperative (1986–91) illustrate these processes well.

CECOCA's Rosario California

By the second half of the 1980s, sands bearing coarse gold at the Tipuani river were depleted. CECOCA's cooperatives approached this problem in two ways. First, they developed new operations downstream, at the Kaka river. Second, they altered the course of the Tipuani river to exploit the sand that had settled on the bedrock (Table 5).

The sands at the Kaka river bear significant amounts of fine gold, and mercury was used for gold recovery. However, to recover the mercury from the amalgam, CECOCA used rudimentary techniques. This brought about a significant discharge of mercury vapour into the atmosphere and increasing losses in efficiency in reusing the mercury. Upstream, CECOCA's first attempts to alter the course of the Tipuani river were successful because they were carried out where the riverbank is quite wide. However, for subsequent work where the Tipuani river

Table 5. Unsuccessful technical changes at Catavi, Unificada, and Rosario California.

COMIBOL		CECOCA
Catavi	Unificada	Rosario California
1970–85	1970–85	1986–91
• Cassiterite flotation (fine tin tailings)	• Tin volatilization	• Channeling of the river
	1987 to present	• Mercury and gold amalgamating
1987 to present	• Diversification from tin to zinc–silver	• Exploration of the old river bed
• Exploitation of mill tailings		

Note: CECOCA, Central Local de Cooperativas Mineras Cangalli; COMIBOL, Corporación Minera de Bolivia.

enters a very narrow valley between steep hills, channeling the river would require specialized knowledge of hydraulics, rock mechanics, and other branches of engineering to channel the river appropriately, knowledge that had not been accumulated by CECOCA or the Rosario California cooperative. Thus, at Huarachani, Rosario California made unsuccessful attempts to alter the course of the Tipuani river. Landslides could not be prevented, and the mining activities originally planned to occur over 4 years could only partially succeed for about 6 months. This had a devastating effect on Rosario California's income and competitiveness. From 1988 to 1992, production capacity fell by 66%, from 2 400 t/d to 800 t/d. Furthermore, because of the failure to channel the river, the increase in waste per unit of output discharged into the river was up to six times higher than anticipated. Between 1986 and 1991, pollution increased significantly at Rosario California, as the operation produced greater amounts of barren rock and toxic wastes (mercury) per kilogram of gold.

COMIBOL's Catavi and Unificada

At its Catavi and Unificada operations, COMIBOL introduced cassiterite flotation and tin volatilization between 1978 and 1985 in an effort to deal with a long-term decline in tin-recovery rates. From 1977 to 1985, tin head grade fell by 39% at Catavi and by 26% at Unificada. Significant increases in recovery levels can be obtained by using gravimetric and flotation methods to produce low-grade concentrates (assaying Sn at up to 5%), which the volatilization process can subsequently upgrade. In the 1960s, COMIBOL embarked on the acquisition and development of cassiterite-flotation and tin-volatilization technologies (Garret 1968). By the early 1970s, the Instituto de Investigaciones Minero Metalúrgico (IIMM, institute for the study of mining and metallurgy), an R&D institution supporting Bolivian mining and mineral-processing activities, had developed an industrial cassiterite-flotation process specifically for Bolivian ores.

The introduction of cassiterite flotation into COMIBOL's operations failed because of delays and a lack of capability to optimize the process at the plant site. COMIBOL established an industrial cassiterite-flotation plant at Colquiri in 1979, about 2.5 years after its original deadline and 8 years after it installed a 100-t/d semi-industrial plant. COMIBOL was unable to improve or even maintain the contribution of the cassiterite-flotation plant to total recovery rate. For example, after a peak in production (1977) at the El Kenko cassiterite plant at Catavi, the amount of ore treated, the recovery rate, and the concentrate grade greatly decreased, declining from 14% of Catavi's total production in 1977 to 2% by 1983.

However, COMIBOL's inability to formulate and introduce coherent plans adapted to the specific technical problems of its tin operations prevented it from fully exploiting the advantages of this technical change in Catavi. From 1977 on, the underground high-grade reserves in the Catavi mine were severely reduced, and surface low-grade reserves from old tailings increased in importance. The tin content of these surface resources was similar to that of the ore mined and fed to the sink-and-float plant. Because stripping, blasting, and crushing are unnecessary for exploiting old tailings, COMIBOL could have significantly reduced its costs if it had had the technical capacity to process these surface resources. Further, this would have provided an opportunity to reclaim tin tailings and greatly reduce acid mine drainage. Cassiterite flotation has been viewed as a promising technology for reprocessing the millions of tonnes of ore accumulated in Bolivian tin tailings. However, the Catavi operation had none of the organizational and technological capabilities required to manage cassiterite flotation in the context of a radical transformation from an underground to a surface operation, so COMIBOL was unable to change these low-grade reserves into economically exploitable resources.

COMIBOL's lack of ability to manage technical change also explains its failed attempt to introduce tin-volatilization technology at Unificada. This case, however, highlights the key role of management, rather than technical ability. COMIBOL undertook three major activities to introduce tin-volatilization at La Palca (Unificada): managing the user-supplier relationship in the context of a turnkey contract with a Russian firm, Machino Export; locating the plant and building the plant base; and developing mineral resources to supply low-grade concentrates to the plant.

MANAGING THE USER-SUPPLIER RELATIONSHIP — The investment at La Palca suffered badly because of deficiencies in the relationship between COMIBOL and Machino Export. In particular, the original contract had to be supplemented with covenants for the procurement of parts and equipment that had been overlooked. Almost 2 years after it signed the contract, COMIBOL realized that the 242-t/d

plant was unprofitable, so it increased the plant capacity, first to 350 t/d and then to 400 t/d. By 1980, La Palca had been delayed by 6 years and investment expenses had increased from 25 to 68 million United States dollars [USD] (Canelas 1981).

LOCATING THE PLANT — Originally, COMIBOL intended to locate Unificada's volatilization plant at the site of an old volatilization plant (Taitón), built in the 1940s. However, 3 or 4 years into development, COMIBOL found the site inadequate because of a limited water supply and changed the location from Taitón to La Palca, instead of attempting to increase the supply of water. Although La Palca has an abundant supply of water, the local geological structure cannot support a 400-t/d volatilization plant. This was identified by COMIBOL's geological department, but COMIBOL was unable to assess the time and cost trade-offs involved in moving the plant to La Palca and fortifying the geological structures, rather than maintaining the plant at Taitón and undertaking work to increase the water supply (Canelas 1981).

DEVELOPING THE MINERAL RESOURCES — COMIBOL was unable to ensure an adequate supply of tin concentrates from Unificada for the volatilization plant. After 9 years' delay, La Palca started its operations in 1983. Utilized capacity of the operation averaged only 50% in the mid-1980s. Although Unificada produced low-grade concentrates for La Palca, it could supply only 35% of La Palca's capacity, at best, and because of the difficulty in acquiring low-grade concentrates from other sources after the collapse of tin prices on the London Metal Exchange, COMIBOL closed La Palca at the end of 1985. Thus, as a result of COMIBOL's mismanagement of cassiterite flotation and tin volatilization, it was unable to arrest the decrease in tin-recovery rates, and this increased the discharge of metals into the environment per tonne of treated material (see Table 3). At Catavi, tin-recovery rate fell by 13% between 1977 and 1985. At Unificada, the recovery rate decreased by 9% between 1977 and 1980, but it rose in 1981 upon completion of the La Palca volatilization plant. However, COMIBOL was unable to sustain this improvement, and the recovery rate fell again between 1981 and 1985. In addition, because COMIBOL did not make the required technical changes to feasibly exploit its low-grade reserves, the potential of its natural-resource base went unrealized during the period of advantageous market conditions in the 1970s and the first half of the 1980s. As a result of innovative inefficiency, COMIBOL actually increased its pollution per unit of output and wasted a great opportunity to reduce contamination through reprocessing and reclaiming old tin tailings.

The effects of changes in production capacity

The weakening of a mining firm's competitiveness may further increase pollution per unit of output because it encourages the firm to reduce its production capacity. This adjustment process is well represented by COMIBOL's environmental performance in 1986–92. After 1986, a fall in tin prices and the reduction of public credit to state enterprises, as part of a structural-adjustment program, put strong pressure on COMIBOL to adjust its operations.

Following its failure to manage cassiterite flotation and tin volatilization, COMIBOL adopted the short-term measure of selective mining in a desperate attempt to survive its crisis of competitiveness. Selective mining is the exploitation of only the highest-grade block reserves or the richest part of the mineral vein. This practice boosts productivity and income in the short term but reduces a mining operation's life span.

When operations were scaled down and employment fell, there was a significant externalization of environmental costs (see Jordan and Warhurst 1992). For example, with scaled-down operations, water-recycling and waste-management practices became redundant. Until 1985, the Catavi and Unificada operations disposed of their tailings in impoundments, from which water was recovered for processing. This internalization of environmental costs was justified by the volume of material handled. This put a premium on water supply, and the physical limitations of rivers and streams for disposal were exceeded. In scaling down operations (from 5 000 t/d to 360 t/d at Catavi and from 1 500 t/d to 350 t/d at Unificada), water demand was reduced (by up to 95%), eliminating the need for water recycling. Lower production levels reduced the risk of blocking the nearby Vetilla and Pailaviri river systems, so tailings were discharged into the rivers. As water recycling was no longer required, the costs of COMIBOL's adjustment to the new competitive conditions were transferred to the natural environment: reduced investment and operational costs were exchanged for greater environmental costs.

COMIBOL's crisis of competitiveness, in addition to its direct environmental effects, caused the firm to dismiss more than 90% of its work force at Catavi. Although Bolivia offers no unemployment benefits, the social cost of this adjustment was partially alleviated by the formation of cooperatives, with ex-COMIBOL employees, to exploit the Catavi mine. About 10 000 people work in the Catavi cooperatives, using artisanal methods. These artisanal operations have destroyed the infrastructure needed to recycle industrial water, and freshwater is now contaminated by chemical reagents, such as xanthates, sulfuric acid, and frothers, and is discharged, along with tailings, directly into the Vetilla river. Downstream, the water is heavily polluted and highly acidic: the pH fluctuates between 2.9 and 3.0 (Empresa Minera Catavi 1993).

Table 6. Scale of Operation at Inti Raymi, Porco, and COMCO.

Inti Raymi		COMSUR			
		Porco		COMCO	
(Years)	(t/d)	(Years)	(t/d)	(Years)	(t/d)
1985	400	1974–84	350	1989– present	1 000
1986	1 200	1985–90	800		
1987–92	4 000	1992– present	1 200		
1993	14 500				

Source: For Inti Raymi, Perú et al. (1992).

Note: COMSUR, Compañía Minera del Sur.

Thus far, the evidence presented (from COMIBOL in particular) provides strong support for the causal linkages postulated by the dynamic model of the mining firm. A decline in a mining firm's competitiveness causes an increase in its pollution per unit of output because it affects a company's investment expenses and, therefore, its stock of technological capability and production capacity. The Catavi case also illustrates that decreases in production capacity reduce not only a firm's nonnatural capital but also its labour force. In this situation, unemployed miners and their families have no choice but to resort to selective and artisan mining practices, which lowers production costs, but at the expense of incremental increases in environmental costs.

Internalization of environmental costs

Let us now return to the environmental performance of Inti Raymi and COMSUR and address the mechanisms by which an increase in competitiveness leads to the accumulation of production capacity, resulting in reductions in pollution per unit of output as water and waste management are improved.

The increase in production capacity at Inti Raymi and COMSUR's Porco and COMCO operations is summarized in Table 6. The increase in production capacity at a time of increased competitiveness reflects both an increased capacity to invest and a reduction in a firm's risk premium to the point at which the firm can make investments with uncertain returns.

Between 1987 and 1992, Porco's proven and probable reserves rose by 60 and 40%, respectively, as a result of systematic exploratory work to develop new ore veins at Las Santas. This enabled COMSUR not only to continue Porco's mining activities but also to enlarge its operations, from 800 t/d to 1200 t/d. While

this expansion was happening, RTZ acquired 30% of COMSUR's equity. This move reflected RTZ's interest in Bolivia's mining potential and COMSUR's interest in having a partnership with a multinational to increase its own capacity to invest. The relationship between COMSUR and RTZ has had positive effects on COMSUR's environmental performance. In the case of Porco's expansion, for example, COMSUR replaced the old dressing plant with one embodying new, more efficient technology (Sutill 1993). This enabled COMSUR to reduce Porco's consumption of water per tonne treated by up to 13%. Whereas tailings at Porco were formerly dumped along the river, they are now discharged into a new tailings impoundment that complies with developed countries' standards — an impermeable layer of argillaceous and coarse material covering the dam prevents the contamination of groundwater (from acid mine drainage and the leaching of flotation reagents).

At the time of writing, Porco had not yet developed an environmental-protection program, which was to have included mitigation of pollution from its old tailings dam; environmental assessment of its current operations; and decommissioning and reclamation programs.

The striking expansion in production capacity at Inti Raymi, 3 500% between 1985 and 1993, reflects the development of an oxide heap-leaching project from 1985 to 1992 and the commissioning of a sulfide agitation-leaching project in 1993. Despite Inti Raymi's significant expansion of its heap-leaching project, it did not change its waste-disposal methods because the area has abundant land and low population density and the toxicity of the tailings is relatively low. Further expansions were rejected after an evaluation of ore reserves showed that additional economically exploitable, oxidized reserves were unavailable. Instead, Inti Raymi set out to find a partner (Battle Mountain Gold Company) to provide the capital and technology needed to develop and exploit its sulfide deposit. To exploit the sulfide deposit, Inti Raymi needed to introduce (for the first time in Bolivia) agitation leaching and enlarge its operation to 14 500 t/d (Ugalde 1992). The agitation-leaching project was expected to generate about 120×10^6 t of waste, 13 times the amount produced by the heap-leaching project. This sulfidic waste has a greater potential for producing acid mine drainage than the oxidized material does, and its management therefore merits special consideration. Inti Raymi prepared a plan for decommissioning, waste management, and reclamation, including reprocessing of the heap-leaching tailings (see Pero et al. 1992).

Two conclusions emerge from this analysis. First, significant improvements in firms' competitiveness — like those experienced by COMSUR and Inti Raymi in the 1980s — are likely to lead to these firms' forming partnerships with companies that have incorporated more efficient environmental practices into their

mining operations. Thus, along its evolutionary path, a firm may be positively influenced in its environmental management by having a partnership with a more competitive company (such as COMSUR's partnership with RTZ). Second, the relationship between changes in pollution per unit of output and changes in production capacity resembles a discontinuous function. Incremental changes in a firm's production capacity have, at best, less significant effects on its pollution per unit of output. For example, Inti Raymi's water-management and waste-disposal methods did not change significantly as a result of the expansion of its heap-leaching project; and the same applies to COMSUR's introduction of flotation at Porco. However, a major change in a firm's production capacity (usually including a radical change in the production process) can significantly affect the firm's use of the environment (for example, Inti Raymi's agitation-leaching project). Reductions in pollution per unit of output in the mining industry may result not only from incremental technical change (as considered in the introductory sections) but also from radical technical change.

Lessons from contradictory evidence

The cases of CECOCA's Rosario California cooperative (1978–86) and COMIBOL's Colquiri operation (1977–92) provide contradictory evidence that fails to support the model. Although CECOCA's competitiveness increased between 1978 and 1986, this did not affect the pollution per unit of output of its Rosario California cooperative. This was principally because Rosario California had accumulated negligible technological capability and so achieved no increases in gold-recovery rates. Rosario California's failure to accumulate technological capability was due to its corporate strategy. The cooperative's main objective — to guarantee that all of its members work and partake of its profits equally — discouraged labour specialization and, in particular, the accumulation of knowledge and technical expertise. The cooperative developed only those work processes that its unskilled members could carry out. Moreover, as Rosario California's corporate strategy was formulated by the members' assembly, the cooperative suffered from a lack of leadership and was inefficiently managed. This type of development was reinforced by the policies of the technical and financial institutions that supported mining cooperatives' activities, such as the Mining Bank. These institutions granted loans according to appraisals that only considered investment in production capacity and had as their main concern a project's cash flow. The Mining Bank's technical assistance to the cooperatives was limited to corroborating the availability of reserves and a project's economic feasibility. Evidence from CECOCA indicates that a firm's reduction in pollution per unit of output requires

not only an increase in its competitiveness but also minimal organizational conditions for the firm to accumulate management and technological capabilities.

At COMIBOL's Colquiri operation, pollution per unit of output has shown some rather paradoxical trends. Although COMIBOL's competitiveness declined, reagent-consumption and tin-recovery rates at Colquiri decreased or remained constant in 1990–92. The average water consumption per tonne treated was 30% less in 1989–92 than it had been in 1977–85. However, water recycling in the dressing process decreased only slightly in 1989–92 from that of 1977–88. Furthermore, Colquiri disposed of 13% less tailings in its tailings impoundment, thereby increasing the discharge of waste per tonne treated into natural streams. These contradictory trends were due to the advantageous environmental effects of incremental technical change and the negative effects of COMIBOL's reduction in production capacity, a result of its decline in competitiveness.

Although the reduction in production capacity at Colquiri (from 2 200 t/d to 1 000 t/d) was not as severe as that at Catavi or Unificada, it was nonetheless severe enough to make the need for water recycling less pressing than it had been in 1978–85. COMIBOL's environmental performance at Colquiri improved because of the redesign of Colquiri's concentrator between 1988 and 1989. This new mineral-processing circuit enabled the firm to reduce its energy and water consumption per tonne treated. The fact that technical change occurred despite the firm's decline in competitiveness and despite severe reductions in its investment in technological capability does not mean we have to reject the model, because technical change and reductions in pollution per unit of output may result from a firm's previous technological accumulation as well as its current investments in technological capability.

Summary of findings

The comparative analysis of the case study showed that the model's main prediction — that pollution per unit of output is inversely related to a mining firm's competitiveness — was not rejected. Empirical evidence confirmed that variations in the stocks of technological capability and production capacity are the primary transmission mechanisms between changes in competitiveness and changes in environmental performance. The case studies also showed, however, that these relationships involve more factors than anticipated by the model — in particular, the flow of foreign technology, management, and capital into the domestic economy and social factors such as unemployment are important. Accordingly, as long as actual competition resembles dynamic competition, a mining firm's efficiency in exploiting ore deposits significantly influences the extent to which it externalizes environmental costs.

Environmental costs and competitive efficiency

The principal result of this study is that a mining firm's ability to compete significantly affects its internalization of environmental costs. A mining firm's trajectory of competitiveness, therefore, conditions its trajectory of pollution per unit of output over time. Other things being equal, an improvement in a mining firm's competitiveness tends to reduce its pollution per unit of output, and a decline in its competitiveness tends to increase its pollution per unit of output. Thus, excessive environmental degradation originates not only from the inability of the market to adequately price environmental resources but also from a mining firm's competitive inefficiency. Moreover, the analysis showed that, under conditions of dynamic competition, the problem of the depletion of natural resources (user cost) is essentially related to the problem of environmental pollution (pollution costs). Figure 9 illustrates these findings. According to the conventional economics of static competition, the externalization of environmental costs is caused by the market's failure to adequately price environmental resources. In this study, by contrast, two variables determine a particular level of externalization of environmental costs: market failure and a mining firm's competitive efficiency.

Market failure prompts excessive environmental degradation in at least two ways. First, as identified in conventional economic theory, the market's failure to adequately price environmental resources may induce a firm to externalize some of its environmental costs. Second, the market's failure to provide insurance against the risks involved in the development of innovations and appropriation of technological assets embodied in human capital makes a firm underinvest in technological capability. Because technological accumulation is crucial to a firm's competitive efficiency and to internalizing environmental costs, such underinvestment in technological capability may aggravate environmental degradation. A firm's ability to compete also determines the degree to which it internalizes its environmental costs. This is because improvements in competitiveness encourage investment in technological capability and production capacity. A firm's lack of accumulated technological capability weakens its ability to innovate, which increases waste and losses of harmful substances per unit of output. Moreover, improvements in competitiveness and technical change prompt increases in a firm's production capacity, which encourage improvements in its management of the natural environment as the scarcity effects related to the use of environmental resources become more acute. Increases in a firm's production capacity will therefore lead to improvements in waste-disposal methods and reductions in the use and pollution of complementary environmental resources.

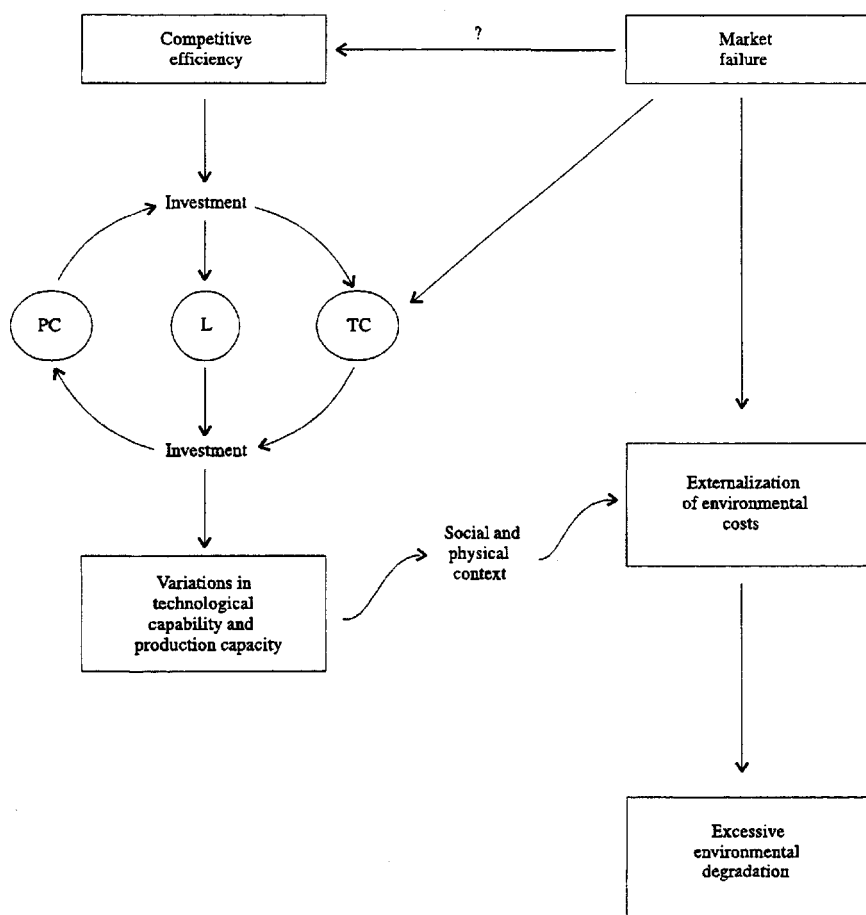


Figure 9. Factors underlying excessive environmental degradation. Note: ?, indeterminate; PC, production capacity; L, leadership; TC, technological capability.

The negative effect that a mining firm's inability to innovate has on its environmental performance is well illustrated by COMIBOL's failure to introduce cassiterite flotation and volatilization to recover tin. In the first stage, COMIBOL was unable to arrest the decline in its tin-recovery rates, and it lost the opportunities for accumulating production capacity and diversifying production that had been opened by the rising prices for tin and other metals in the 1970s. In the second stage, during the first half the 1980s, COMIBOL's decline in competitiveness (aggravated by the reduction in tin prices) led to a severe shrinkage in its production capacity. Catavi and Unificada, two of the most important of COMIBOL's tin operations, scaled down their operations dramatically and decreased

their consumption of water. With water recycling no longer a necessity and the nearby rivers' capacities for receiving mining tailings no longer at risk of being overloaded, both operations discharged tailings directly into the river. Moreover, the severe reduction in COMIBOL's production capacity caused unemployment and thus encouraged the emergence of artisan mining operations. A significant increase in pollution per unit of output was the result — these new operations discharged tailings and toxic substances, such as sulfuric acid and fuels, into natural streams.

Conversely, evidence from Inti Raymi clearly illustrates how a mining firm's internalization of environmental costs may follow improvements in its competitiveness. In 1982–85, Inti Raymi started using a 400-t/d heap-leaching operation to exploit a massive gold and silver deposit. At that time, the firm had no reclamation plan at all. When heaps were exhausted, the firm neither thoroughly rinsed out the cyanide nor reclaimed the heaps. In 1986, Inti Raymi established an R&D department, which introduced several incremental technical changes. As a result, the firm optimized the size of the mineral grain, improved the watering of heaps, and greatly enhanced the cycle of the cyanide solution, including thoroughly retrieving the solution from the old heaps. Overall, these changes positively affected Inti Raymi's environmental performance. They significantly increased gold-recovery rates and reduced cyanide consumption per tonne treated by 70%. The remarkable improvement in Inti Raymi's competitiveness led it to enlarge its production capacity from 4 000 t/d to 14 500 t/d. Inti Raymi increased its reserves by 1 200%, and it developed a new mining project (agitation leaching). This project was a watershed in the Bolivian mining industry because, for the first time, a project had included, from the project-feasibility stage, the design for a comprehensive mitigation and reclamation program.

Investment efficiency

The case study indicates that the model is limited by its failure to distinguish between investment and investment efficiency. It fails to consider the possibility that a particular amount of money invested in production capacity and the same amount invested in technological capability might produce quite different outcomes. The variable *L* (leadership; referring to a firm's ability to manage its investments) is introduced in Figure 9 to handle this distinction. A mining company's ability to manage its investments is essential to its competitive efficiency. This is particularly true of investments in technical change, as successful technical change involves management of complex processes over time. The case study showed that a firm's capabilities to adapt to technical change to continually improve its technologies at the operation site were deciding factors in the firm's

competitive success. For instance, the change in COMSUR's Porco plant design, from lead-zinc differential float to bulk flotation, was vital to reaping the advantages of its new concentrator. Moreover, the remarkable improvements in the heap-leaching project at Inti Raymi were possible because of further investments in technological capability to improve the production parameters at the mining site and to deal with bottlenecks and problems. In contrast, COMIBOL and CECOCA were unable to reap the potential benefits of the technical changes they introduced into their production processes. COMIBOL mismanaged tin volatilization and cassiterite flotation, and CECOCA lost significant amounts of fine gold for lack of technical changes to improve gold-recovery rates. Thus, both firms failed to continually improve the production process at the operation site, and this was due to a lack of knowledge, expertise, and appropriate institutional linkages.

It seems that to manage technical change, a mining firm requires efficient management and coordination of all its activities at the corporate level. In the heap-leaching project at Inti Raymi, for example, the efficient coordination of ongoing production activities and investment projects was crucial to accruing the advantages of the incremental technical changes introduced by its R&D department. Moreover, efficient management was a key factor in the successful completion of the agitation-leaching project. In contrast, the failure of the cassiterite-flotation process at COMIBOL's Catavi operation was due to the management's lack of leadership and commitment to organizational change, such as redeploying personnel, reducing the work force, training human resources, finding financial sources, and making long-term plans to transform Catavi from an underground to a surface operation. So, although the cassiterite-flotation process was technologically accomplished, it had minor economic benefits for COMIBOL. At Unificada, the cause of failure was not a lack of the technical expertise and knowledge needed to manage the tin-volatilization process but a lack of the expertise and knowledge required to negotiate with technology suppliers; arrange the tasks of a complex investment plan according to a schedule; cope with pitfalls and unforeseen circumstances; and coordinate the supply of low-grade tin concentrates. In short, the failures of the tin-volatilization process at Unificada and the cassiterite-flotation process at Catavi were largely due to management shortcomings.

As COMIBOL and CECOCA illustrate, the impact that investments in technical change have on a firm's ability to compete depends on leadership, knowledge, expertise, and institutional linkages related to the management of not only technical processes, such as product design, process engineering, and R&D, but also organizational procedures, such as marketing, finance, planning, and human-resource development.

Implications for policy and further research

Although this study is based on the Bolivian mining industry, it has policy implications of a much wider scope, as the causal relationships and factors identified are likely to be relevant in other industries and in other countries. An important policy implication of this research is that a nation needs to integrate environmental, technological, and industrial policies if its economy is to follow an environmentally sensitive pattern of development (which reinforces the conclusions of Warhurst [1993, 1994] in reviewing environmental regulations in the mining industry). Understanding the factors underlying companies', industries', and the economy's abilities to compete is of great importance in designing policies that in the long run promote the rational use of the natural environment as well as economic growth. Thus, a study of a mining firm's ability to compete is needed to develop a long-term environmental policy for the mining industry, which may be the main policy implication of this study.

Reconsidering the model

To improve the model, one must consider at least two issues. First, the model deals with changes in competitiveness as an exogenous variable, so its predictive value (and potential usefulness for policy design) is limited: investments in production capacity and technological capability affect not only a firm's pollution per unit of output but also its competitiveness. This limitation means that the evolutionary features of dynamic competition are defined *a priori*, rather than arising from the dynamic effects of competition itself. If this variable is made internal to the system of equations, one will be able to systematically consider the influences of science, technology, and market contexts on competitiveness and environmental performance. This might provide a tool for designing long-term environmental and mineral policies and open a different perspective on the analysis of economic processes.

Second, the model leaves uncertain the effect of radical technical change on the relationship between a mining firm's changes in competitiveness and changes in its pollution per unit of output. Because radical technical change may have a significant influence on the development of the mining industry in the long run, a historical study of the technological development of the mining industry is advisable. This work should aim to assess the long-term effects of radical technical change on competitiveness and pollution per unit of output, rather than its immediate (short-term) effects. This will also be relevant to policy design — policies can be tailored to promote both the innovations that are potentially the

most beneficial to the environment and the competitive and regulatory conditions that will allow these technologies to fulfil their potential.

Competitive efficiency and the pollution-prevention principle

The inability of market forces to properly price environmental resources has been the main justification for government intervention through environmental policy. Environmental policy has, therefore, mainly regulated the disposal of industrial residues and wastes. Under the static approach to competition, the trade-off between environmental protection and the promotion of industry has been considered a major constraint on pollution reduction. The recent shift toward the pollution-prevention principle has been accompanied by a shift from policies designed to ameliorate pollution toward those based on a preventive agenda. The intention is for industry to reduce or eliminate waste at source, rather than merely treating and disposing of it (see, in the context of the minerals sector, Anderson and Purcell [1994]).

Although the pollution-prevention approach is an advance in dealing with environmental degradation, there are two constraints on the development of a still more efficient environmental policy. First, the analysts tend to consider environmental policy a social mechanism for internalizing externalities, as it is thought that environmental degradation originates in the market's inability to appropriately price environmental resources. Second, the policymakers have not considered the need for technology policies to complement environmental policies, as it is assumed that competition is static. Accordingly, environmental policy has neglected the relationship between a company's ability to innovate and its environmental performance (Warhurst 1993).

This study provides empirical evidence for the relationship between a company's ability to innovate and its environmental performance. Further, it shows that at least for the mining industry, excessive environmental degradation is also caused by competitive inefficiency, which so far the pollution-prevention approach has not considered. Policy mechanisms should be developed to prevent pollution arising from the decline in competitiveness of industrial activities (such as COMIBOL's Catavi operation). Although this study suggests that progress toward the optimal use of the environment is compatible with industrial development, this does not imply a blind confidence in spontaneous or automatic mechanisms of any kind. Industrial evolution is a social rather than natural process, so the challenge will be to establish institutions, practices, and policies to make such progress feasible. In this regard, this study has identified promising new avenues to explore and examine, rather than providing solutions or answers.