Working Paper

The Resource Economics of Environmental Absorption Capacity

Edgar G. Hertwich

WP-96-156
December 1996

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Abstract

This paper uses an economic framework to investigate the depletion of heavy metal absorption capacity of soil. Specifically, the Hotelling model for the allocation of exhaustible resources across time is applied to Cadium deposition onto agricultural soil in the Rhine basin. The Hotelling model requires a knowledge of the resource as well as the demand function for the resource. The resource of absorption capacity is limited because above a certain Cd concentration in soil agriculture is not allowed; accumulation of Cd above this maximum acceptable soil concentration is not allowed. The demand function for absorption capacity corresponds to the cost function of avoiding deposition of heavy metals. According to the Hotelling model calculations, 0.2 DM should be spent to avoid the deposition of 1 kg Cd at a discount rate of 5% and 600 DM at 1%. The optimal level of Cd control expenditure increases at the discount rate. The paper also presents a modified Hotelling model that takes the replenishment of the resource by removal of heavy metals from the soil (leaching and plant uptake) into account. Using a simple donor-controlled outflow model of Cd behavior in soil and a residence time of 1000 years, the optimal initial expenditure level for Cd control in the Rhine basin is etermined to be 0.0006 DM/kg (3% discount rate). For the Katowice district, the optimal level is 20 DM/kg. A net input of Cd into the soil of the Rhine basin is allowed for 400 years in the Rhine basin and for 200 years in Katowice. This paper finds the modified Hotelling model to be a useful heuristic for understanding the time dimension of absorption capacity; specific recommendations cannot be derived, however, because they depend on tenuous inputs such as the cost curve for pollution control, the discount rate, and the maximum acceptable soil concentration.

Bibliographic Sketch

Edgar G. Hertwich is a Ph.D. student at the Energy and Resources Group, University of California, Berkeley (http://violet.berkeley.edu/~manerg/). He holds a B.A. in physics from Princeton University and an M.S. in Energy and Resources from Berkeley. He is interested in research at the environment/industry interface. His dissertation investigates how life-cycle assessments and similar tools are or can be used to reduce the environmental impacts of industrial society. He has published in the area of life-cycle impact assessment, with a focus on human health impacts and the development of trade-off methods. Hertwich is an alumni of the IIASA Young Scientists Summer Programme.

The Resource Economics of Environmental Absorption Capacity

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Introduction

The IIASA IND project has investigated the deletion of the soils' absorption capacity for heavy metals. In this paper, an economic framework is used to treat the pollution absorption capacity of soil as a depletable resource. I presents a general framework for the application of the Hotelling model--originally developed in resource economics to describe the optimal allocation of a depletable resource across time--to environmental absorption capacity. Cadmium deposition onto agricultural soils is used for a case study, although a number of the "Chemical Time Bomb" issues presented by Stigliani (1988) could be used as well. The Hotelling model is used as a heuristic to provide a better understanding of the time dimension of the chemical time bomb. The physical sciences have difficulty in dealing with time; economics uses discounting. It serves to judge the magnitude of the problem; due to the many assumptions the results presented here are not to be taken literally.

After a short introduction of the Hotelling model, the problem of Cd deposition onto soils is described in terms of resource economics. The cost curve of avoiding Cd deposition--the equivalent of the demand curve for absorption capacity--is derived from data on the cost of removing Cd from phosphate fertilizer and reducing atmospheric emissions, as well as on the source of Cd deposited onto arable land in the Rhine basin. For illustrative purposes, this demand curve is also scaled to the deposition of Cd in the Katowice voivodship. The size of the resource is derived from the maximum allowable and the current concentrations of Cd in agricultural soil. In the first exercise, the absorption capacity is treated as a purely depletable resource with no restoring through removal of Cd from the soil. In the second exercise, Cd is assumed to have a fixed residence time. The "resource" is the opportunity of depositing Cd above the steady-state rate that corresponds to the maximum allowable concentration in soil.

The Hotelling Model

In 1931, Harold Hotelling published a paper on "The Economics of Exhaustible Resources" in which he uses a partial equilibrium analysis to describe the optimal allocation of a depletable resource across time and to prove that--assuming perfect information and zero transaction costs--a free market with private resource ownership would provide just such an allocation (Hotelling, 1931).

The basic result of the model is that the resource rent--the price of the resource above exploitation costs--rises at the exogenously defined discount rate. Today, this insight is referred to as the "Hotelling rule". (Dasgupta & Heal 1979, p.156).

The Hotelling model has been superseded by a general equilibrium model presented by Howarth and Norgaard (1992, 1995), who show that the allocation obtained by the Hotelling model is only one of many efficient allocations and each efficient allocation--represented by a specific discount rate--corresponds to a different distribution of rights among generations; the choice of a specific discount rate is therefore a question of intergenerational equity.

I do not attempt a general equilibrium formulation, because the cost of reducing Cd deposition to the critical load is not large enough to significantly deteriorate general welfare. If instead of stopping at the maximum allowable concentration a large-scale contamination of soil were allowed (and hence safe food production impaired) or if Cd deposition could not be mitigated at reasonable cost the Hotelling model would not be applicable.

The exponential increase of the resource rent at the rate of discount can be explained as follows: a resource owner has the option of either taking a resource out of the ground and putting the rent into a bank account, or of keeping the resource in the ground. The rent of the resource in the ground has to grow as much as the rent of the exploited resource alternatively invested for the resource owner to be indifferent to the time of exploiting the resource. Hence, the rate of price increase is determined. The initial price has to be set so that through time all of the resources will be used; it depends on the size of the stock, the demand function, and of course, the cost of resource extraction. The consumption path will depend on the demand curve and can be derived from the price path. The Hotelling model has been extensively applied in energy and resource economics after 1973 (Griffin & Steele 1980, Dasgupta & Heal 1979).

Cd Deposition as an Economic Problem

Through the lens of economics, several aspects of Cd deposition can be distinguished:

1. damage (costs) resulting from the immediate exposure to deposited Cd;
2. damage resulting from the delayed exposure, when Cd is stored in the ground and released later;
3. the allocation of absorption capacity.

Analysts have previously related current damage (exposure) to current deposition looking only at aspect (1), thereby neglecting that the soil may not be at steady state but may be accumulating Cd. Aspect (2) includes two features: one, in a simple linear, donor-controlled outflow model (investigated further below), the current deposition might correspond to a higher steady state soil concentration than the current, i.e., the system has not yet reached steady state. In this case, evaluating the (health and ecological) costs resulting from a constant release, as is frequently practiced in the evaluation of chemicals for policy making and LCA (Jager and Visser, 1994; Guinée and Heijungs, 1993), would include both effects. Two, delayed effects can occur through nonlinearities of the type described by Stigliani (1988). In this chapter, I assume that nonlinearities such as buffering capacity and a nonlinear relationship between the plant uptake and soil concentration are not only well known but considered in the definition of a critical load. Hence the issue of nonlinearities is pushed into aspect (3).

If the soil has a lower concentration than the maximum acceptable concentration, it is able to absorb pollution in excess of the critical load until the maximum is reached. The allocation of this absorption capacity is treated in exercise 2.

The ability to deposit more Cd in soils for a limited amount of time presents an opportunity; depositing Cd now causes opportunity costs because the same absorption capacity will not be available later. The benefit obtained from depositing Cd is that control costs can be avoided. The demand curve for Cd deposition is hence the cost curve of controlling Cd deposition onto soil.

The Demand Curve for Cd Absorption Capacity

One faces a number of challenges in determining the cost of avoiding the deposition of a pollutant onto a specific plot of land:

- the cost curve depends on what sources contribute to polluting a specific plot of land and is therefore specific for each location;
- a single atmospheric source contributes to the pollution in many regions;
- the fraction of deposited material that actually stays in the soil may be unknown or dependent on soil properties (Shimada and Jaffe, 1996)
- pollution control equipment may result in multiple benefits, i.e.; dust removed from power plants and smelters reduces the emissions of a range of heavy metals, improves visibility etc. What fraction should be attributed to Cd?
- data on the cost of reducing pollution is inherently uncertain, especially if a technology is site specific or not yet widely employed. The removal of Cd from P-fertilizer depends on Cd concentration and other fertilizer properties. Smelters may find cheaper ways to reduce pollution, i.e., through housekeeping measures or the speedy employment of an emergent technology;
- costs of emissions reduction are not constant across time.

No attempt will be made here to resolve the issue of spatial distribution of absorption capacity which would result in different optimal expenditures for pollution prevention at each emission point. Instead, soil is treated as uniform, receiving uniform deposition. The average of the deposition in the Rhine basin is used for constructing a demand curve.

The assumption of uniform mixing is often used in environmental science and forms the basis for "unit world" (Mackay-type) fate and transport models (Mackay & Patterson, 1981) that are now applied for the regulation of chemicals (Jager and Visser, 1994), the setting of clean-up goals (McKone, 1993) and life-cycle assessment (Guinée and Heijungs, 1993).

For the purpose of this exercise it is assumed that all the deposited Cd stays in the soil, except for that removed through erosion, plant uptake and leaching in exercise 2. Adjustment for a lower retention factor could easily be made by adjusting the demand curve accordingly.

I assume that pollution control serves only to avoid Cd deposition, which is true for removing Cd from P-fertilizer, but not for atmospheric controls. The resulting estimates will hence be conservative; over-estimating future costs of Cd-control, especially in exercise 1. The elasticity of the demand curve will be higher, leading to a greater sensitivity of the starting price with respect to the discount rate. The cost of Cd control of atmospheric emissions present an upper limit.

Table 1 shows the calculation of the demand curves. For P-fertilizer it was assumed that the control costs vary linearly between 60 DM/kg and 400 DM/kg. Data on the deposition in the Rhine basin was taken from Stigliani and Anderberg (1994), data on Cd removal costs is based on Klepper et al., (1995). Klepper asserts that the costs of Cd control cannot be adequately assessed; his data for end-of-pipe measures hence provide an upper limit and do not include additional benefits. The efficiency of Cd removal was estimated based on control efficiencies and capture probabilities of the various technologies.

The cost curve for Katowice was obtained using the 1987 data on the input of Cd from atmospheric and agricultural sources and scaling the Rhine basin cost functions for atmospheric and agricultural sources to this distribution of input. It was assumed that atmospheric Cd pollution stems from the same mix of industries. A comparison of Figures 1 and 2 shows that most of the input in the Rhine valley came from agriculture, whereas in Katowice atmospheric deposition dominates. A higher fraction of arable land accounts for lower control costs of atmospheric deposition in Katowice. The cost curve for Katowice was constructed only to illustrate the effect of a higher demand for Cd absorption capacity on the calculations. Lack of data on atmospheric sources and future development as well as a higher importance of sources from outside the region make the curve very unreliable.

Figures 1 and 2 also present fits of linear, constant elasticity and exponential functions to the cost curves of Table 1. The parameters of the constant-elasticity and the exponential fits are listed in Table 2, which also contains the linear fit. The Figures display linear fits for the demand above 2.4 g/ha/a, as used in exercise 2. The parameters of the linear curves displayed in the Figures are listed in Table 3.

A comparison of the cost curves shows that a constant-elasticity cost curve provides the best fit to the data on the Rhine basin, whereas a linear curve provides the best fit to the Katowice data. Due to the bad fit of the constant elasticity cost curve to Katowice data, this data will not be used in exercise 1.

Calculations

Exercise 1 -- Absorption capacity as a purely exhaustible resource

To illustrate the Hotelling model in its classical form I present a treatment of Cd absorption capacity as a purely exhaustible resource. The reader familiar with this model may skip this section and go to exercise 2, which is more applicable to the environmental management problem at hand.

Equation 1 displays the constant elasticity demand function, equation 2 the Hotelling criteria and equation 3 the limited stock S of resource available. Q_t is the "consumption" per year (g/ha/a), P_t the corresponding price per unit (DM/kg), and r is the discount rate . An evaluation of the integral in equation (3) will give the initial price P_0 , as presented in equation (4). The (optimal) consumption of the resource asymptotically approaches zero at a rate of r/α.

$$P_t = \left({Q_t}/{Q_k} \right)^{-\alpha} \tag{1}$$

$$P_t = P_0 \cdot \exp(r \cdot t) \tag{2}$$

$$S_0 = \int_0^{\infty} Q_t \cdot dt \tag{3}$$

$$P_0 = \left(\frac{r \cdot S_0}{\alpha \cdot Q_K} \right)^{-\alpha} \tag{4}$$

$$Q_t = \frac{r \cdot S_0}{\alpha} \cdot \exp\left(-\frac{r \cdot t}{\alpha} \right) \tag{5}$$

The stock of absorption capacity was determined using the Dutch "signal value" of 0.8 mg/kg of Cd in soil and a background concentration of 0.3 mg/kg; the conversion to g/ha is based on the assumption of a 20 cm relevant (plow) depth and a density of 1.5. The maximum allowable concentration actually varies between 0.5 and 1 mg/kg depending on soil type. This variation was investigated using a sensitivity analysis.

Equation (4) makes clear that the result will depend on the interest rate r and the elasticity α. Figure 3 displays the optimal consumption rates at different discount rates and Figure 4 presents the corresponding price paths. The shadow price of using up to 1kg of absorption capacity is 600 DM at r=1%, 2 DM at 3%, and 0.1 DM at 5%. Cline (1992) argues that a social discount rate of 1.5% is appropriate for global warming and other large scale environmental problems. In the case of Cd, with decreasing demand and some replenishment of the "resource", a slightly higher discount rate may be justified.

The sensitivity of the initial price P_0 with respect to the resource stock S_0 and the elasticity of demand is presented in Figure 5. The constant-elasticity demand functions were adjusted so that they would have the same price at 2.5 g/ha/a. The curve shows that there is a significant dependency of the price both on the elasticity and on the initial stock. For a stock of 1500 g/ha, the initial price is 2.10^{-5} DM/kg for $\alpha = 1$, 80 DM/kg for $\alpha = 5$, and 2.10^{10} DM/kg for $\alpha = 9$. For a constant elasticity of 5, the initial price varies between 2 DM/kg at S = 3000 g/ha and 200,000 DM/kg at S = 300 g/ha. The price sensitivity with respect to the elasticity increases as the quantity at which the prices are equal is decreased.

Exercise 2 - a partial replenlishment of the resource

In reality, environmental absorption capacities are at least partially renewable. Heavy metals are removed by erosion, leaching to deeper layer and eventually the groundwater, and uptake by plants. New soil is formed by weathering and the addition of litter. In this section, I take the "renewal" into account and treat the absorption capacity in excess of the renewal rate as the resource that needs to be efficiently allocated. For this purpose, a simple model of Cd in soil is used and the effects of the replenishment on the size of the resource and allocation pattern are considered.

It is assumed that the stock of Cd in the soil is governed by equation (6). The initial stock S_i is smaller than S_{max}. From this, the maximum allowed steady state input of Cd to the soil, Q_{ss}, can be calculated as $m \cdot S_{max}$.

$$\frac{dS_t}{dt} = Q_t - m \cdot S_t \tag{6}$$

Until S_{max} is reached, more Cd can be deposited. At t=0, the stock of the absorption capacity in excess of Q_{ss} is $S_0 = S_{max} - S_i$; if Q_{ss} is deposited, this stock decreases at the rate m. The stock of our resource S is hence not constant, it decreases with time. This effect adds to the time preference of consumption represented by the discount rate.

For this exercise I use a linear demand function, because I am interested only in the demand in excess of Q_{ss}. This requires the solution of the following set of equations:

$$P_t = P_T - k \cdot (Q_t - Q_{SS}) \tag{7}$$

$$P_t = P_0 \cdot \exp((m + r) \cdot t) \tag{8}$$

$$P_T = P_0 \cdot \exp((m + r) \cdot T) \tag{9}$$

$$S_0 = \int_0^T (Q_t - Q_{SS}) \cdot \exp(-m \cdot t) \cdot dt \tag{10}$$

This system cannot be solved analytically. The goal seek function in Excel™ was used to obtain a solution for P_0 that would satisfy this system of equations.

Stigliani and Anderberg (1994) give a removal of 8 t/a from the agricultural soils of the Rhine basin, compared to a stock of 7000 t. This corresponds to a residence time of 1000 years ($m = 0.001\ a^{-1}$). Hutton (1982) assumes residence times between 175 and 360 years and Prieler et al. (1996) quote removal rates of 5-6 g/ha/a, corresponding to a residence time of around 200 years. I only consider the upper limit here, because at lower residence times Q_{ss} is larger than the current average input and no accumulation above S_{max} could be achieved. If $m=0.001\ a^{-1}$, $Q_{ss} = 24$ t/a or 2.4 g/ha/a. A reduction of present deposition from an average of 5 g/ha/a to 2.4 g/ha/a in the Rhine basin can be achieved by just removing Cd from P-fertilizer, the least expensive option. The parameters of the demand curves are given in Table 3.

The results of this exercise are displayed in Figures 6 to 9. Figures 6 and 7 show the "optimal" deposition rates in tons of Cd per year. The shape is characteristic for a linear demand curve. The curves labeled *constant resource* would results if there was a linear demand curve and the maximum allowable deposition of 2.4 g/ha/a was removed from the soil even before the maximum allowable concentration has been reached. This case is similar to the pure Hotelling case with a linear demand curve. The "decreasing resource" curves give the "optimal" deposition rates if there is a replenishment of absorption capacity following a donor-controlled outflow, the assumption in this exercise. For more than 400 years, Cd deposition is in excess of the critical load in the Rhine basin. The curves are not very sensitive to the discount rate, especially in the initial 200 years. The stock of Cd in the soil, displayed in Figure 8, shows even less sensitivity to the discount rate. Under optimal allocation of the absorption capacity, the stock increases significantly faster than if only deposition at the critical load Q_{ss} is allowed. Figure 9 displays how the optimal expenditure on mitigation of Cd deposition approaches 400 DM/kg in the Rhine basin. In the case of a 1% discount rate, the price P_0 starts at 2 DM/kg, otherwise it is negligible. This result indicates that the assumption of a smooth demand curve is somewhat unrealistic, since it is hard to imagine that any amount of deposition reduction could be purchased for just 2 DM/kg.

Figure 9 illustrates the basic differences between Katowice & the Rhine valley; a higher demand for absorption capacity results in a more than twice as fast consumption of this resource and drastically higher initial as well as final control costs. The figure suggests that, based on considerations of absorption capacity alone, no immediate action is needed in the Rhine basin, but at least the removal of Cd from fertilizer is required in Katowice. This is reflected in the deposition rates in Figure 7; the deposition for a discount rate of 1% starts out at a significantly lower level than the current deposition, suggesting that deposition should be reduced by almost 1 g/ha/a. The calculations for Katowice are based on the initial stock of cadmium in the soil of the Rhine valley and have not been adjusted for the higher level of cadmium in many of the soils in Katowice. Higher initial Cd levels would require a faster reduction of Cd deposition.

The Problem of Local Differentiation

The “Unit World” approach is very appealing not only for environmental science but also for the economic aspects of this model. A unit of emissions reduction leads to a uniform 0.4 units of deposition reduction in our problem, or a 1% emission reduction leads to a 1% deposition reduction on all the agricultural soils. In this way , we can treat every emitter equal and do not have to worry about highly impacted areas.

A consideration of the granularity and geographical nature of the issue at hand introduces a number of problems and generally tends to increase the shadow price of absorption capacity. Following problems have to be considered:

1. In the unit world model we started with the assumption that a degradation of agricultural land--all agricultural land--would not be allowed. Now we have the option to only degrade some land and keep the rest for food production. A conservation goal needs to be specified, e.g., that no degradation is allowed, 5% degradation is allowed, or degradation is allowed only until food prices would rise by a certain fraction.
2. A source of atmospheric emissions may impact both a contaminated and a fairly clean site, or one with high deposition rates and another with low deposition rates. The value of avoiding deposition at the contaminated site or the site receiving high deposition rates will be higher than that at the lower site. The value of avoiding emissions is a composite of the two. The difficulty is that the value of avoiding deposition at all sites is needed to calculate the cost curve for avoiding deposition at any specific site and the cost curve is needed to determine the present value of a unit absorption capacity. An iterative approach may help to resolve this circularity.
3. The Hotelling model requires a knowledge of the time path of the demand (or here: cost) curve and is most easily solved with a curve constant in time. The problem at hand, however, has a time dimension in that the absolute difference in the values of avoiding deposition in different regions changes with time. This time dynamics is difficult to treat mathematically.

The value question (1) is not addressed here, although ethical considerations suggest that permanent degradation of agricultural land should not be allowed. No final solution can be offered for the other two issues, a sketch of a solution, however, is provided.

Sketch of a Resolution of the Cost Allocation Problem

Following iterative approach may be able to provide a solution to the cost allocation problem:

1. Cost curves are constructed for each location, starting with the most polluted (highest deposition, smallest “stock”). The most polluted location carries the total control costs of all source of significant deposition (to be appropriately defined).
2. A shadow price for the absorption capacity is determined for each location, using the estimated cost curve.

3. The product of the present shadow price and the fraction of the emissions that are deposited in a region is used to allocate the control costs to a specific region.
4. Using the control costs for each source as determined in the previous step, new cost curves of deposition control at each location are constructed.

Steps 2, 3 and 4 are repeated until the solution converges. The procedure is based on a static situation; the cost allocation in step (3) gets around the time dimension by canceling out the factor of exp $(r \cdot t)$ in the shadow prices. The solution breaks down as soon as a time dependency is introduced, e.g., through technical progress lowering control costs at rates that differ among facilities, or as soon as some facilities relocate to take advantage of lower pollution control costs somewhere else. These difficulties arise because the cost of consuming environmental absorption capacity consists of foregoing the opportunity to consume the capacity later and the problem discussed here is one of pollution control cost allocation across time.

The problem of spatial granularity does not exist in the application of the Hotelling model to fossil or mineral resources because zero transportation costs and free trade are assumed; the questionable assumptions of perfect information about stock and quality of the resource and future demand are further aggravated by the need to know current and future exploitation costs. Simplifying assumptions employed in resource economics, such as a uniform or analytically well described resource quality and corresponding constant or uniformly increasing marginal costs of resource exploitation are similar to those made here.

Conclusion

I investigated the usefulness of the Hotelling model for assessing the exhaustion of environmental absorption capacity. Following tenuous assumptions are required and limit the applicability of the results:

- The model has to rely on average deposition rates and absorption capacities and therefore does not reflect geographical variability. If emissions follow the recommendations of the model, local hot spots will receive too much cadmium, and therefore have to be taken out of production.
- There are difficulties in attributing the benefits of emissions reduction to specific sites and, if more than one pollutant is reduced, e.g., by reducing particle emissions, to specific pollutants.
- The calculations assume that industrial structure and technology do not change and that hence the demand for cadmium emissions will remain constant.
- The results are very sensitive to the shape of the demand curve, which cannot be determined exactly.

The current exercise provides a number of interesting insights in spite of these weaknesses. The opportunity costs of using up environmental absorption capacity arise in addition to the current damage costs. Traditionally, environmental economics assesses only the latter; the former provide additional motivation for reducing emissions. The comparison between the Rhine valley and the Katowice district illustrated significant differences in the demand for pollution control. In Katowice, the same absorption capacity is used up much faster and higher investments in emissions control are therefore justified, as illustrated by Figure 9.

This research was guided by the concern that cadmium accumulation in agricultural soils might represent a "chemical time bomb." The results indicate, however, that accumulation of cadmium poses no immediate problem, and that the rates of emissions reduction required are fairly low.

Tables and Figures

Table 1: Cost curve of the reduction of Cd deposition onto agricultural soil in the Rhine valley and an estimate of the same for the Katowice voyvodship.

Source	**Rhine Valley**		**Katowice District**		**Reduction Efficiency**
	Reduction [g/ha/a]	**Cost** [DM/kg]	**Reduction** [g/ha/a]	**Cost** [DM/kg]	
P-fertilizer	2.87	230	2.0	200	80%
Zn refining	0.23	5,000	0.7	3,300	90%
PB refining	0.02	5,000	0.3	3,300	90%
Cu industry	0.05	10,000	0.6	6,700	90%
Coal-fired power plants	0.17	12,500	2.1	8,300	90%
Waste incineration	0.19	25,000	0.3	17,000	90%
Oil-fired power plants	0.11	37,500	1.3	25,000	90%
Sewage sludge	0.10	40,000	1.0	30,000	100%
Private coal combustion	0.05	50,000	0.6	33,000	90%
Iron&steel industry	0.16	50,000	2.0	33,000	90%
Cement production	0.03	50,000	0.4	42,000	90%
Private oil combustion	0.03	100,000	0.3	67,000	90%
Battery manufacturing	0.11	100,000	0.5	67,000	90%
Motor traffic	0.05	100,000	0.2	67,000	90%

Table 2: Fits of constant elasticity, linear, and exponential functions to the demand functions presented in Table 1 and the corresponding correlation coefficients. The units are in DM/kg for the price and g/ha/a for deposition (Q).

Constant elasticity			Linear			Exponential		
$P_t = \left(\frac{Q_t}{Q_k}\right)^{-\alpha}$			$P_t = P_T - k \cdot Q_t$			$P_t = P_F \cdot \exp(-b \cdot Q_t)$		
	Rhine	Katowice		Rhine	Katowice		Rhine	Katowice
Q_k	107	83	P_T	7,300	65,000	P_F	390,000	210,000
α	5.0	3.3	k	1,900	5,700	b	1.9	0.46
r	0.91	0.60	r	0.74	0.965	r	0.97	0.93

Table 3: Linear demand function used for exercise 2 and correlation to the constructed demand functions above $Q_{SS} = 2.4$ g/ha/a.

Linear demand function		
$P_t = P_T - k \cdot (Q_t - Q_{SS})$		
	Rhine	Katowice
P_T	400	51,000
k	130	5,700
r	1	0.988

Figure 1: Demand function for Cd absorption capacity in the Rhine basin.

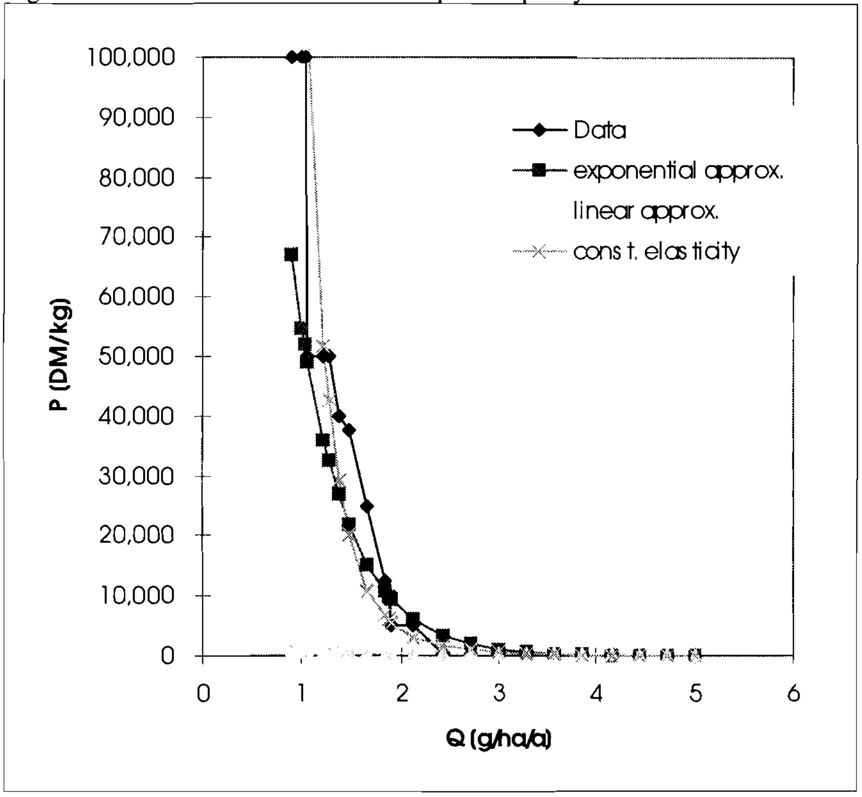


Figure 2: Demand function for Cd absorption capacity scaled to the Cd inputs to soils in the Katowice region.

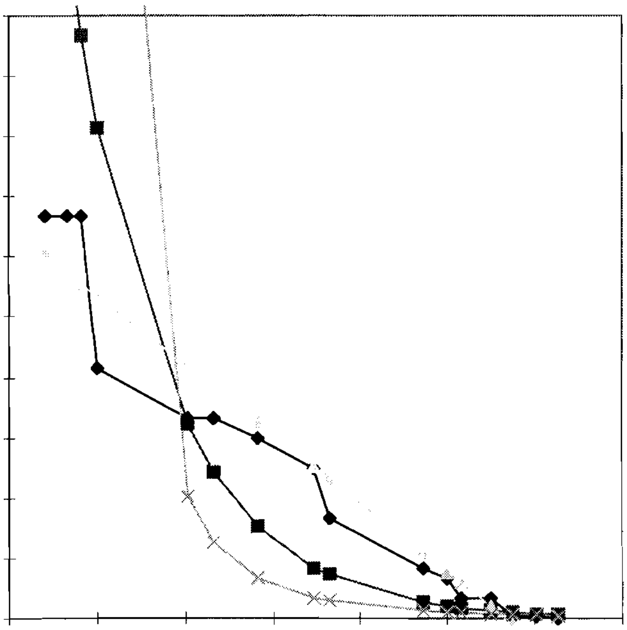


Figure 3: "Optimal" Cd deposition paths in the rhine basin, determined at different discount rates.

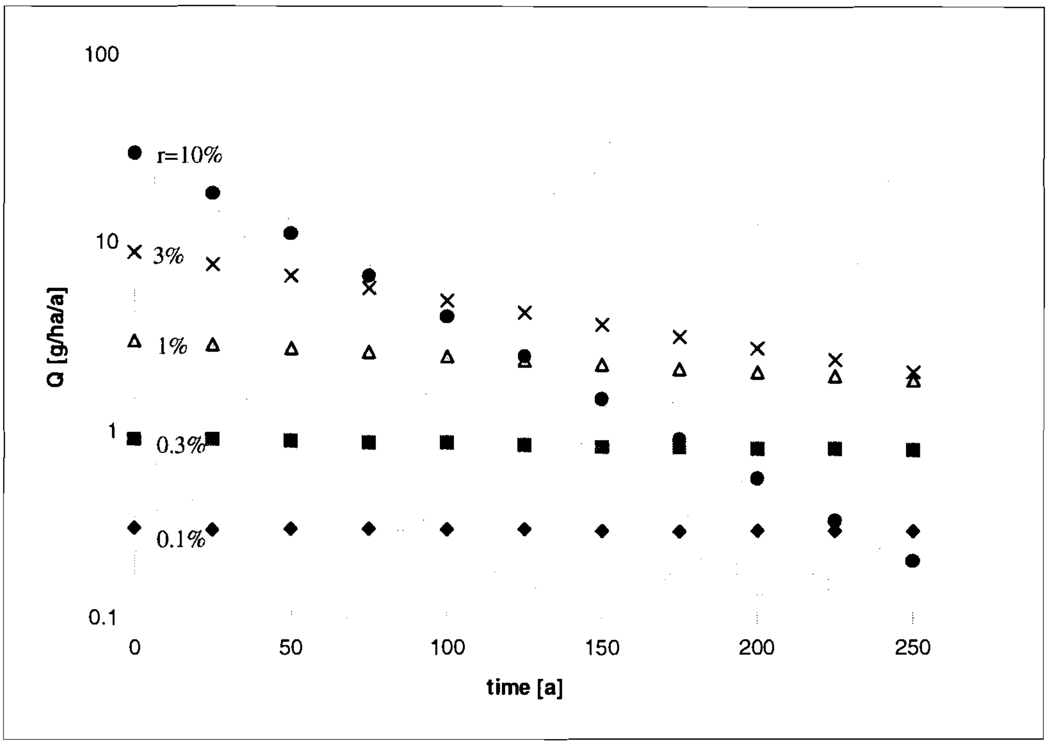


Figure 4: "Optimal" price paths for exercise 1

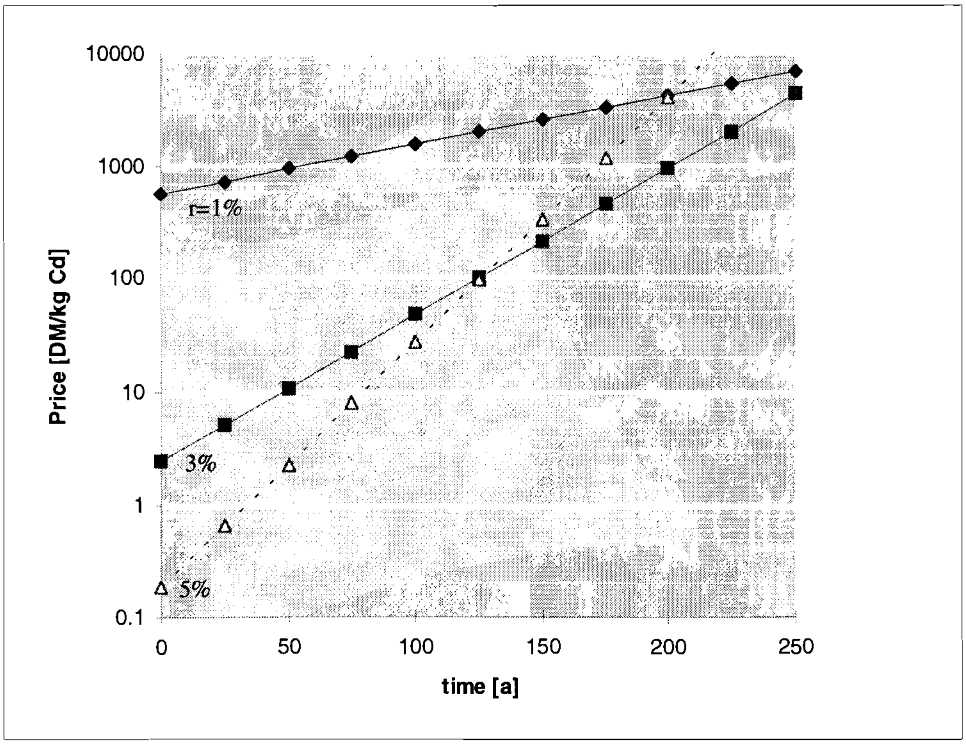


Figure 5: Sensitivity analysis of the initial price with respect to the price elasticity of demand alpha and the initial stock. The five constant elasticity demand functions tested in this txercise intersect at 2.5 g/ha/a. The discount rate was 1.5%.

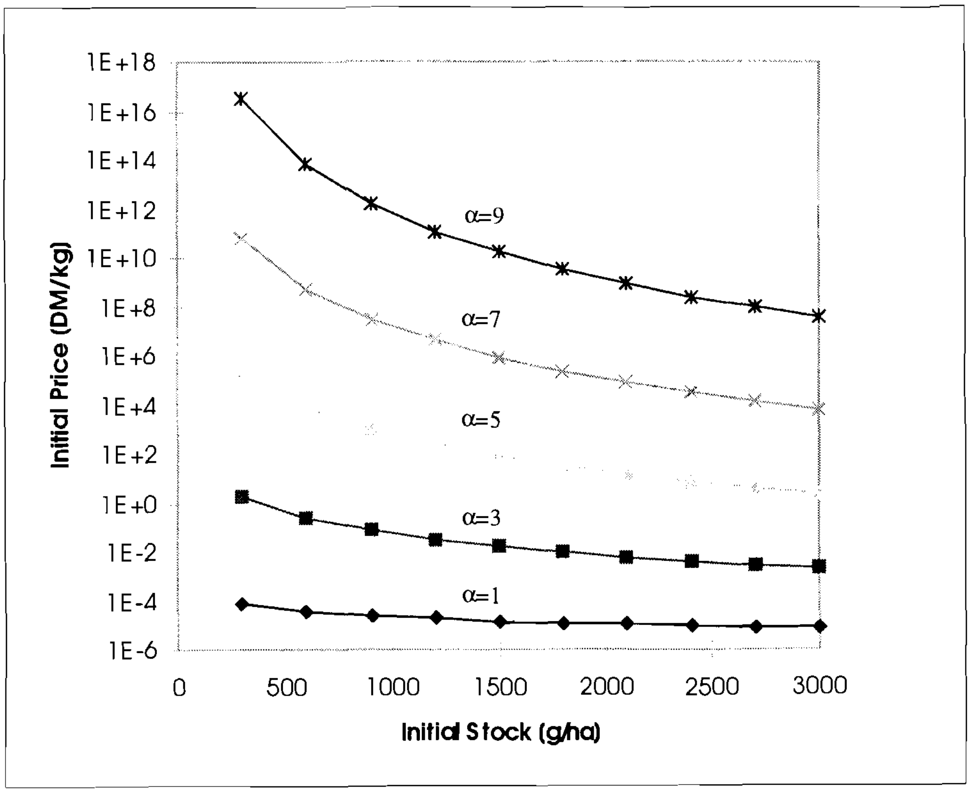


Figure 6: "Optimal" deposition rate of cadmium onto soils in the rhine basin under the assumptions of exercise 2. When cadmium leaching is proportional to the cadmium concentration in the soil, the curves labeled "decreasing resource" apply. The curves labeled "constant resource" reflect the allocation of the demand for absorption capacity above 2.4 g/ha/a under the ideal Hottelling case.

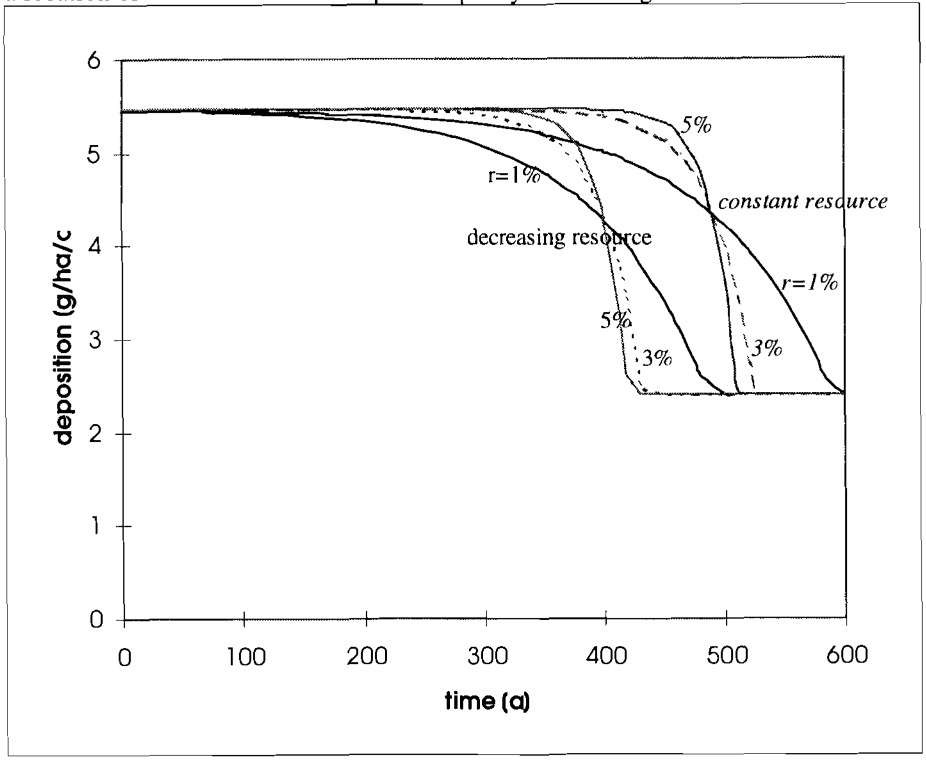


Figure 7: "Optimal" deposition rate in the Katowice region, as determined by exercise 2.

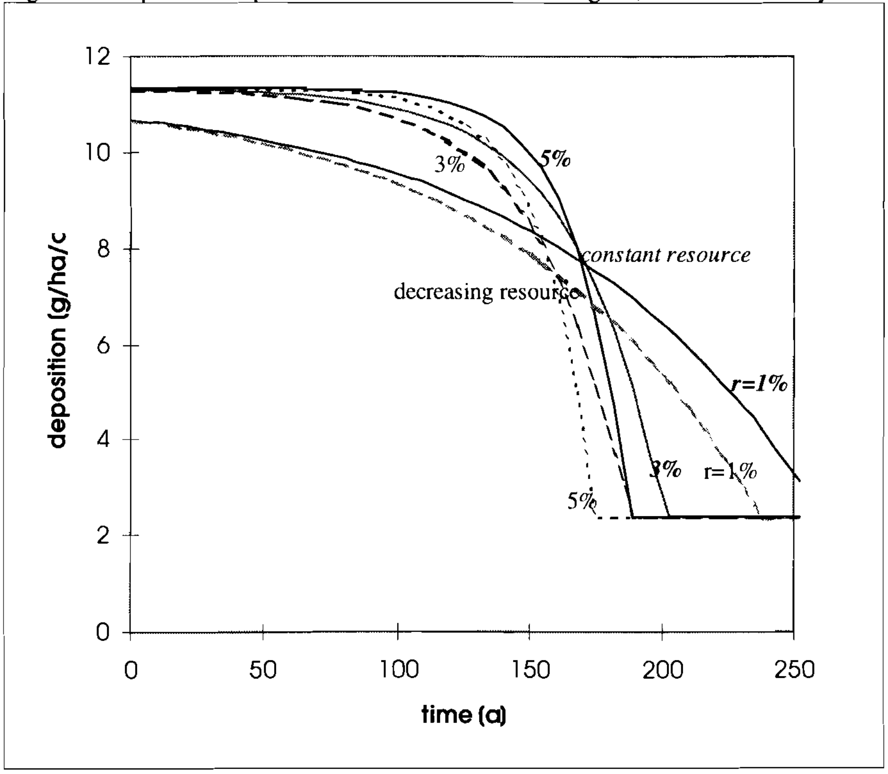


Figure 8: Stock of Cd in agricultural soils in the Rhien basin and the Katowice district (exercise 2). The stocks are compared with the stock that would result from a continuous deposition of the critial load.

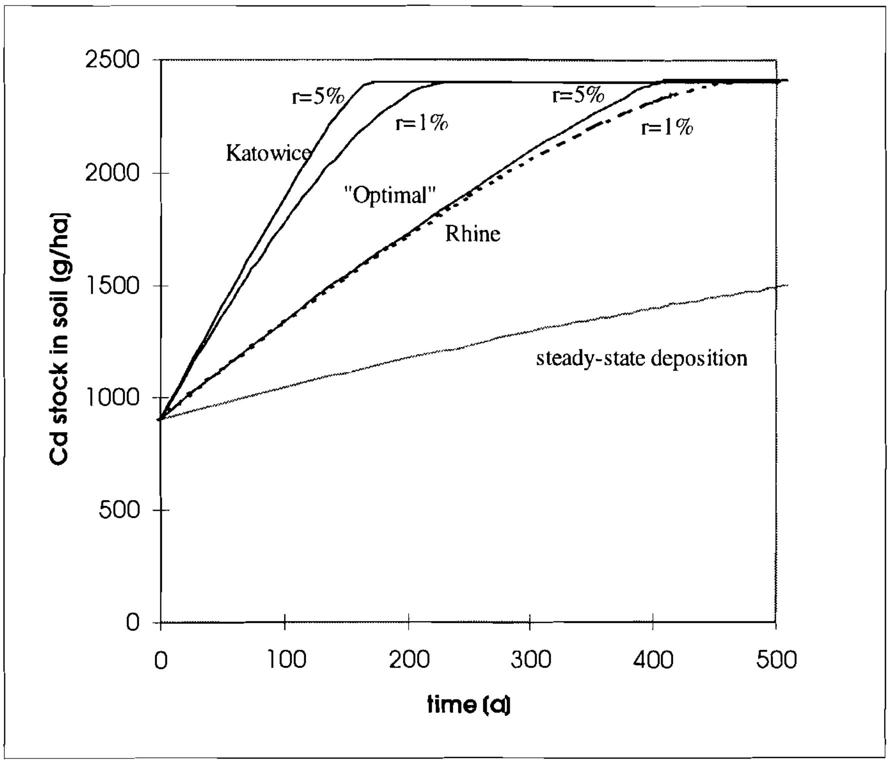
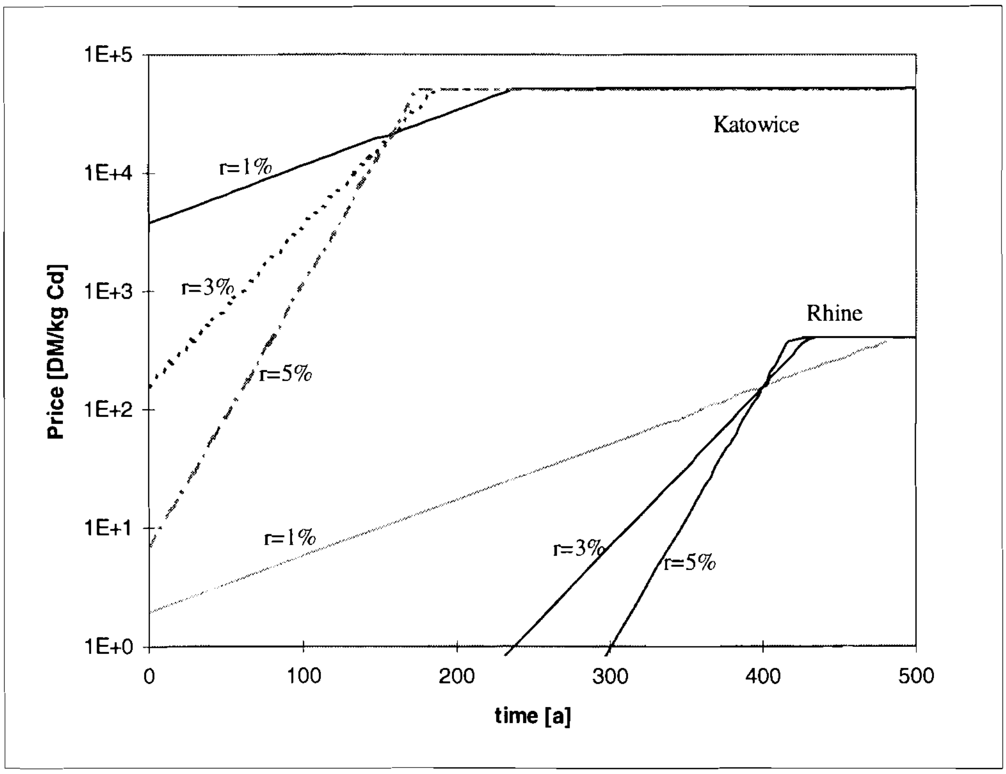


Figure 9: Price path of Cd absorption capcity for the Rhine basin.



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