Cadmium, the environment and human health: an overview

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Cadmium is a relatively difficult environmental substance to assess in terms of its ecological effects and its impact on human health. It occurs naturally in the earths' crust, and as a result is found in varying concentrations in virtually all components of freshwater, marine and terrestrial ecosystems. It is also present in the atmosphere as the result of volcanic activity, and the entrainment of vegetative material. In addition, anthropogenic sources are many and varied resulting in substantial numbers of environmental pathways connecting them to humans and ecological species.

Concentrations of cadmium in the atmosphere do not appear to pose a human health problem, unless it is shown that the respired metal is preferentially toxic. In particular, the maximum airborne cadmium concentrations in urban areas and/or in the vicinity of intense point sources (zinc and lead smelters, etc.) are rarely higher than 100 ng/m^3. Assuming that an adult breathes 20 m^3 air per day, the resulting cadmium intake is only 2 µg/day. This compares with estimates of 20–50 µg/day intake via the diet, and 2–4 µg/day for smokers consuming 1 pack of cigarettes per day. Given retention rates of 30% and 8% for inhaled and dietary cadmium, respectively, cadmium retained from inhalation is 0.6 µg as compared to 1.6–4 µg for the ingested metal. Given a much more likely maximum urban-industrial cadmium air concentration of 15 ng/m^3, less than 0.1 µg is retained in the body.

The impact of cadmium on aquatic and terrestrial ecosystems is generally sufficiently subtle that its definition is more a matter of philosophy than of observable, substantial changes in indigenous populations. In general, there is a lack of data with which to define relationships between cadmium concentrations in the environment and ecological damage. This is in part due to the fact that cadmium does not manifest itself ecologically in readily discernible ways. It is also a result of the prodigious amount of data required for this task.

In freshwater ecosystems, little is known about the effects of cadmium on species of the various trophic levels. When introduced to a river or lake in an industrial outfall, the great bulk of the dissolved metal typically precipitates out of solution and resides in bottom sediment. From there it may be taken up by bottom feeding animal species and sediment-rooted flora. It then proceeds up the food chain to fish, with the precise pathways dependent upon the species present. Additionally, the small fraction of cadmium present in water in the disolved form may be ingested directly by fish through the gills and/or skin. Once in the fish, the metal typically is retained in the liver and kidney, with far lower concentrations in the muscle which may find its way into the human food chain. Laboratory experiments on fish species tend generally to suggest higher sensitivities to cadmium, especially with respect to reproductive effects, than are observed in field studies.

The foregoing observations apply equally well to the distribution of cadmium in marine systems. It has been observed that most marine organisms, especially bottom feeders such as molluscs and crustaceans, accumulate the metal to much higher concentrations than are present in their environment. As with the freshwater case, however, the metal tends to be retained in organs and exoskeletal compartments as opposed to muscle tissue which may be consumed by humans. This bioaccumulation pattern is evident both in systems exhibiting natural levels of cadmium, and in those receiving the metal from anthropogenic sources. Impact studies in the vicinity of wastewater outfalls containing high levels of cadmium have, in some cases, shown substantial perturbations of natural marine populations. However, such waste streams usually contain many other organic and inorganic pollutants, thus making the correlation of effects with cadmium extremely difficult.

The behavior of cadmium in terrestrial exosystems is a function of its chemical species. The typical translocation pattern involves the contamination of soil via aerial deposition or agricultural practices. Among the latter are the spreading of municipal sewage sludge or phosphate fertilizers to enhance soil nutrients. Solid waste disposal and subsequent leaching from disposal sites is another mechanism for the spread of cadmium in terrestrial systems. Following soil contamination, cadmium may be taken up by plants which, when foraged by animals or consumed by humans, results in its movement into the human food chain. Ecological effects elucidated from field (as opposed to laboratory) studies are difficult to substantiate due to the fact that cadmium sources intense enough to result in significant ecological alterations also emit other pollutants capable of causing the observed changes. For example, vegetation damage in the vicinity of nonferrous smelters (the most intense sources of cadmium to the atmosphere) appears to be in large part attributable to sulfur dioxide emissions. For this reason, the quantification of the precise role of cadmium, if any, in vegetative blight around smelters is virtually impossible. Laboratory studies involving the growing of plant species in 'pots' or hydroponic solutions suggest that plant physiological effects manifest themselves at levels of cadmium uptake seldom, if ever, encountered in the environment.

Field studies in the United Kingdom at smelter sites which have been inactive since the Middle Ages have uncovered soil cadmium concentrations elevated by factors of hundreds above natural levels. Vegetative biomass in these areas tends to be normal, although there is no way to prove conclusively that plant species diversity has not been affected. Fortunately, the primary mechanisms for cadmium contamination of soils, i.e. aerial deposition, agricultural practices and solid waste disposal, can be readily controlled by modification of these practices and/or controlling point source emissions of cadmium-bearing particulate to the environment.

Cadmium intake by humans is principally effected through inhalation (respiratory exposure) and by the ingestion of food and drink (dietary exposure). Other incidental exposure mechanisms involve such phenomena as 'hand-to-mouth' ingestion in the work place, etc. Episodes of acute cadmium poisoning are extremely rare given the present level of awareness regarding the toxicity of the metal. The primary human health concern is thus related to long term, chronic exposures.

The highest chronic exposures are found in worker populations in facilities where cadmium is either utilized in a production process as a feed material, or is present in by-product streams. The primary mechanism of exposure in the work place is by inhalation with hand-to-mouth also factor where industrial hygiene practices are not stressed. Much of the human toxicity data come from studies on worker populations. Other human toxicity data have been derived from a non-occupational population in Japan subjected to dietary exposure via the contamination of rice paddies by mine run-off. The latter gave rise to the much-heralded Itai-Itai disease which manifested itself in the decalcification of skeletal structure, especially in elderly women. Other studies in Europe suggest lowered kidney function in elderly women residing in highly industrialized urban areas.

The principal target organ vis-a-vis long term human exposure to cadmium appears at present to be the kidney. At sufficient exposure levels, renal tubular dysfunction leading to an excessive discharge of proteins in the urine (proteinuria) has been noted. The clinical significance of the condition is not clear, though it has been implicated in the development of osteomalacia detected in the Japanese Itai-Itai population. Other dieseases in which cadmium has been conjectured to play a role include hypertension, emphysema, and renal and prostate cancer. The bases of these conjectural associations consist generally of animal data, much of which is inconclusive. One is of course faced with the problem of extrapolations to humans even where animal data appear to be consistent.

It was pointed out earlier that the primary mechanism for non-occupational cadmium intake is food consumption. Cigarette smoking may also be an important mechanism for individuals consuming twenty or more per day. The least important source is respiratory exposure via airborne cadmium. Upon entering the body the metal is either excreted in the urine and feces, or retained, primarily in the liver and kidneys. For inhaled cadmium, 10–40% may be retained depending upon the size of the airborne particulate of

Table 1. Estimated cadmium consumption (tons)[5]

	1976	1977	1978	1979	1980	Average	% Total
Metal finishing	2998	2282	2536	2767	1989	2514	51
Pigments	739	573	650	705	507	635	13
Plastic stabilizers	661	507	551	595	429	549	11
Batteries	1300	981	1091	1190	858	1084	22
Miscellaneous*	233	137	143	172	116	160	3
Totals	5931	4480	4971	5429	3899	4942	100

* Alloys, solders, reactor control rods, etc.

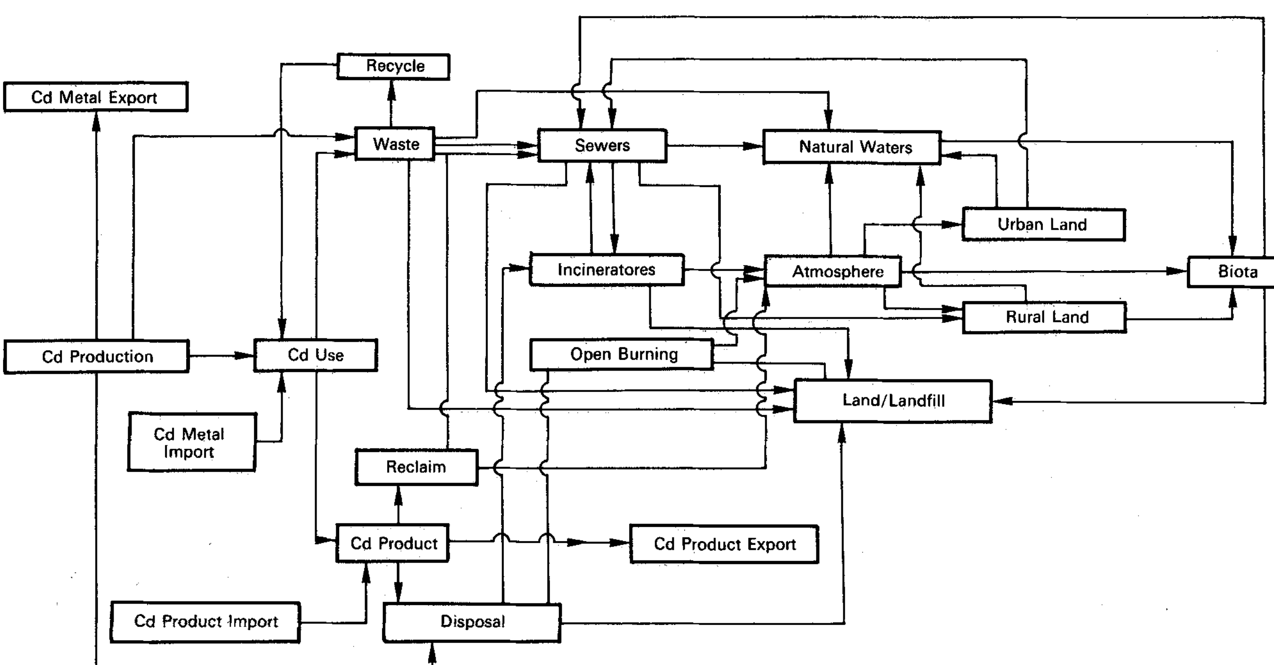

Figure 1. Primary elements of the U.S. cadmium environmental flow system.

Table 2. Fate of cadmium discharged from use-related sources over 10-year simulation period (MT): Current practice*

Source	Receptors Natural waters	Sewage treatment	Municipal incinerators	Atmosphere	Landfill
Electroplating	95.9	839	–	–	20,135
Pigments**	10.0	116	1387	–	6,320
Plastic stabilizers	1.56	12.5	693	–	6,380
Batteries†	–	16.7	2060	145	8,560
Miscellaneous products	3.3	30.4	128	4.5	1,280
Sewage treatment	373	–	–	–	217
Municipal incinerators	72.2	72.2	–	1750	2,200
Sludge incinerators	3.7	3.7	–	21.9	275
Steelmaking	–	14.2	–	342	2,890
Coal-fired power plant	0.07	–	–	203	537
Totals	553	1105	4268	2466	48,794

* Does not include ocean dumping of sludges. † Includes chemical processing and battery production. ** Reclaim treated as 'sink'.

which it is a constituent. Ingested cadmium is retained at a lower rate ranging from 4 to 10%.

Given the inconclusive state of knowledge regarding the health effects of chronic cadmium exposure, it seems prudent to minimize dietary exposure, and to refrain from heavy smoking. Minimizing dietary intake requires a thorough analysis of the environmental flow paths connecting sources to food. It is only on the basis of such an analysis that regulatory policy designed to reduce intake can be realistically undertaken. Such an analysis for the population of the United States has been developed by the author for the U.S. Environmental Protection Agency and a variety of industry trade associations. Details of the study with extensive references are given in a series of papers[1-4].

The objective of the study is to generate estimates of cadmium flow in the environment and (related) human exposures for major cadmium uses and current waste management practices. It is intended to provide a systematic basis for developing regulatory policy decisions.

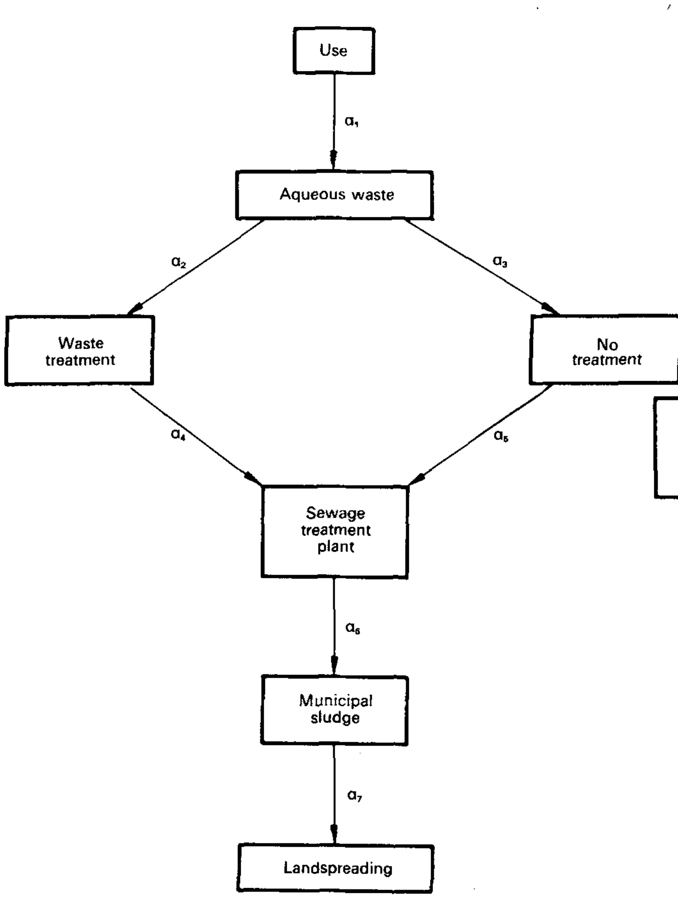

Figure 2. Municipal sludge landspreading-cadmium cropsoil enrichment flow paths for use-related production processes. Coefficient values are given for various uses in table 4.

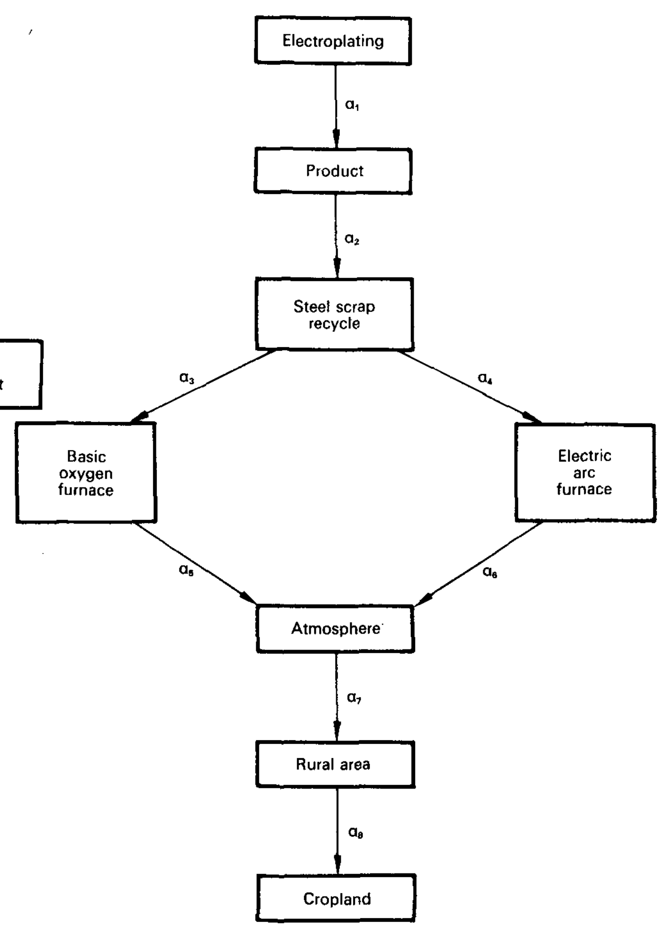

Figure 3. Coupling between electroplating and atmospheric input of cadmium to cropsoils via recycle of plated steel scrap. Coefficient values are given in table 5.

Table 3. Fate of cadmium discharged from use-related sources over 10-year simulation period (MT): Achievable practice*

Source	Receptors Natural waters	Sewage treatment	Municipal incinerators	Atmosphere	Landfill
Electroplating	36.5	262	–	–	20,770
Pigments**	1.88	21.5	1387	–	6,320
Plastic stabilizers	1.56	12.5	693	–	6,380
Batteries†	–	16.7	2060	145	8,560
Miscellaneous products	1.2	9.7	128	4.5	1,300
Sewage treatment	147	–	–	–	85.6
Municipal incinerators	68.9	68.9	–	672	3,330
Sludge incinerators	1.46	1.46	–	8.63	108
Steelmaking	–	14.2	–	342	2,890
Coal-fired power plant	0.07	–	–	203	537
Totals	259	407	4268	1375	50,285

* Does not include ocean dumping of sludges. † Includes chemical processing and battery production. ** Reclaim treated as 'sink'.

Table 4. Use-related pathway coefficients for cadmium aqueous discharge input to cropsoil via municipal sludge landspreading (fig. 2): Current practice

Use	Pathway coefficients for cadmium input to cropsoils α_1	α_2	α_3	α_4	α_5	α_6	α_7	% Consumption to cropsoils
Electroplating	0.1	0.55	0.25	0.08	0.9	0.7	0.25	0.47
Pigments	0.059	1.0	0.0	0.22	0.0	0.7	0.25	0.23
Plastic stabilizers	0.002	0.0	1.0	0.0	0.89	0.7	0.25	0.031
Batteries	0.0018	1.0	0.0	1.0	0.0	0.7	0.25	0.032

Table 5. Use-related pathway coefficients for atmospheric cadmium input to cropsoil via steel scrap recycle and refuse incineration (figs 3 and 4): Current practice

Use	Pathway coefficients for cadmium input to cropsoils α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	% Consumption to cropsoils
Electroplating (steel scrap recycle)	0.9	0.2	0.43	0.57	0.01	0.08	0.55	0.10	0.05
Pigments (refuse incineration)	0.94	0.18	0.44	0.47	0.1	–	–	–	0.35
Plastic stabilizers (refuse incineration)	0.978	0.1	0.44	0.47	0.1	–	–	–	0.2

Table 6. Expressions for estimating use-related fractions of cadmium destinated for cropland

Cadmium input mechanism	P(α): pathway coefficient configuration
Use-sludge landspreading	$\alpha_1(\alpha_2\alpha_4+\alpha_3\alpha_5)\alpha_6\alpha_7$
Electroplating-steel scrap recycle	$\alpha_1\alpha_2(\alpha_3\alpha_5+\alpha_4\alpha_6)\alpha_7\alpha_8$
Cd pigmented/stabilized plastics-incineration	$\alpha_1\alpha_2\alpha_3\alpha_4\alpha_5$

Cadmium release to various environmental compartments is quantified on a national basis for major uses and inadvertent sources. Source-specific biotic and human exposure projections are made with respect to specific sites in cases where the number of U.S. source locations is low. For the more ubiquitous cadmium sources, exposure projections are developed for representative/prototype regions. Cadmium enrichments in environmental media are compared to naturally occurring levels. Two waste management/environmental control strategies are considered. Cadmium consumptions for various uses incorporated in this analysis are given in table 1[5].

1. Current/achievable waste management scenarios

Two waste management/environmental control scenarios are considered in the present analysis. The 'current practice' scenario incorporates waste treatment and management options thought to be representative of current operations among the various processes analyzed. The 'achievable practice' scenario is based on relatively greater utilization, and more efficient operation, of readily available control technology. Specific aspects of the two scenarios are given below.

Electroplating

Current practice: 25% of electroplating waste is discharged untreated, 90% of which goes to sewage treatment plants; chemical destruct waste treatment units are operated with an average Cd removal efficiency of 91%.

Achievable practice: All shops discharging to sewers employ chemical destruct waste treatment units operating at an average 93% removal efficiency.

Pigments

Current practice: Some plants employ settling tanks to recover Cd in wastewater, but have no capability for pH adjustment to precipitate dissolved metal. The resulting industry-wide Cd removal efficiency estimate is only 76%.

Achievable practice: All plants employ pH adjustment, clarification and filtration steps in their waste treatment systems with average Cd removal efficiencies of 97.2%.

Table 7. Sensitivity of use-related cadmium flow to cropland to changes in pathway parameters for municipal sludge landspreading: Current practice

Use	Sensitivity ($\Delta Cd/\Delta\alpha_i$) α_1	α_2	α_3	α_4	α_5	α_6	α_7
Electroplating	0.047	0.0014	0.016	0.0096	0.0044	0.0067	0.019
Pigments	0.039	0.0023	**	0.01	**	0.0032	0.0091
Plastic stabilizers	0.16	**	0.00031	**	0.00035	0.00045	0.0012
Ni-Cd batteries	0.175	0.00032	**	0.00032	**	0.00045	0.0013

Nickel-cadmium batteries

Current practice: 5% of the Cd utilized by chemical processors producing electrode material enters the waste stream, 48% of which is reclaimed. Pocket plate battery Cd production losses are 3%, half of which is reclaimed.
Achievable Practice: Chemical process Cd waste generation is cut to 2%, with 88% being reclaimed. Pocket plate production Cd waste reclaim is increased from 50% to 80%.

Refuse incineration

Current practice: 17% of existing incinerators have no emission control, 23% employ electrostatic precipitators, and 60% have wet scrubbers with an average Cd removal efficiency of 58%.
Achievable practice: The 17% having no control are fitted with electrostatic precipitators; existing scrubbers are upgraded to achieve 75% Cd removal efficiencies on the average.

2. Principal conclusions

Cadmium utilization in the U.S. can continue on an unrestricted basis without harm to human health or the environment given prudent waste management practices. More specific points include:
Respiratory (inhalation) intake of Cd by urban populations is negligible.
A 10-year, 25% municipal sludge landspreading program with 'Achievable practice' waste management results in a negligible (< 1% of the recommended daily intake) per capita dietary Cd increment. Long

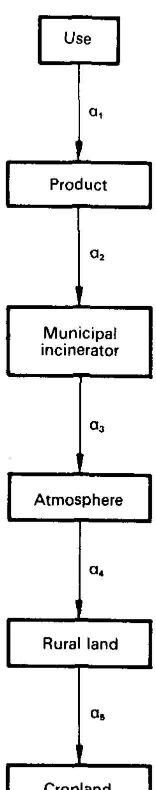

Figure 4. Coupling between a) production of plastics containing cadmium pigments and stabilizers, and b) atmospheric input of cadmium to cropsoils via incineration of municipal refuse. Coefficient values are given in table 5.

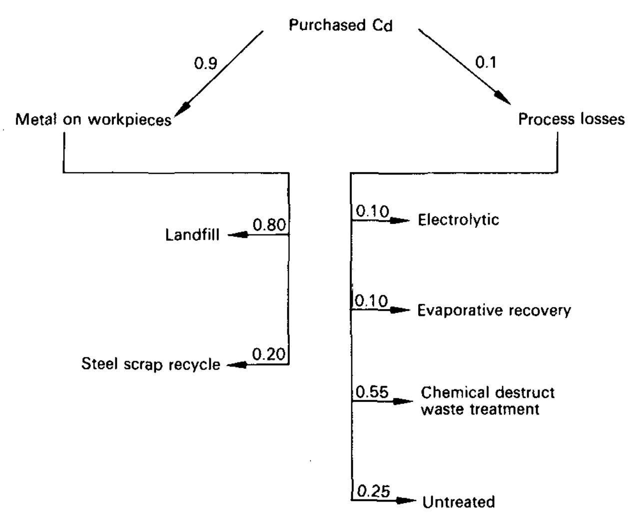

Figure 5. Cd flow in the electroplating process.

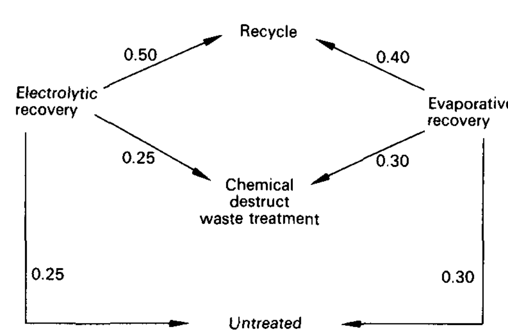

Figure 6. Cd waste management with electrolytic and evaporative recovery options.

term landspreading of sludge from treatment plants receiving uncontrolled Cd discharges may represent a health problem depending upon crop marketing patterns and production levels.
Test results suggest that leaching of Cd from landfilled plastic products does not pose an environmental hazard. Disposal of Cd-rich industrial sludges in nonsecure landfills may result in significant groundwater contamination on a highly localized basis.
A worst case scenario for use-related Cd releases to waterways indicates an average daily Cd intake increment equal to 0.2% of the recommended daily intake by way of shellfish consumption.
Use-related Cd fluxes in U.S. waterways are negligible compared to 'natural' flows associated with background Cd concentrations in river sediments.
Long term (> 50 years) use of high Cd western rock phosphate fertilizers can result in significant increments in the average dietary intake.
The public health impacts of electrolytic refining plants is negligible. Environmental impacts are likewise nimimal given responsible handling (or recycle) of leach residue solid waste.
Tables 2 and 3 summarize the use-related flow and fate of Cd for the 'current practice' and 'achievable practice' scenarios, respectivvely. Figure 1 exhibits the major Cd flow paths encompassed by the analysis.

Dietary exposure sensitivity analysis

It is well known that the primary cadmium exposure route for humans is through the diet. Respiratory intake is likely to be less than 0.5 μg/day, whereas dietary has been estimated at 35–50 μg/day for U.S. adults[6]. For this reason, the elucidation of use-related exposure mechanism is focused on dietary intake. The two principal pathways for cadmium enrichment of the diet are municipal sludge landspreading, and deposition of airborne cadmium on cropland.
Figure 2 portrays pathways coupling cadmium uses to cropland enrichment via municipal sludge landspreading. The pathway coefficients, a_i, denote fractions of the cadmium in the donor nodes (at tail of arrows) moving to receptor nodes (at head of arrows) per unit time. Their dimensions are thus t^{-1}. Coefficient values for the 4 major cadmium uses, with corresponding fractions of metal consumed destined for cropland via sludge landspreading, are given in table 4.
Cadmium flow diagrams relating to cropland enrichment via deposition of airborne particulate are given in figures 3 and 4. Table 5 exhibits pathway coefficient values for the electroplating-steel scrap recycle and pigment-plastic stabilizer municipal incinerator flow systems. Corresponding fractions of cadmium destined for cropland via atmospheric deposition are also given.
A systems analysis typically evolves a variety of interesting by-product information. For example, it is easy to determine the variability of cadmium exposure with respect to pathway coefficients. This process is often called a 'sensitivity analysis', with the resulting variability measures referred to as 'sensitivities'. It requires the construction of algebraic expressions coupling flow system input and output/exposures. For simple, highly aggregated systems of the type discussed here, the expressions are quite simple. Table 6 gives them for the use-sludge landspreading and (two) atmospheric deposition systems. Denoting

Table 8. Weighted sensitivities in order of magnitude for cadmium enrichment of cropland via sludge landspreading: Current practice

Use	Coefficient index	Weighted sensitivity
Electroplating	1	5.5
Electroplating	7	2.2
Electroplating	3	1.9
Electroplating	4	1.1
Electroplating	6	0.79
Ni-Cd batteries	1	0.61
Pigments	1	0.59
Electroplating	5	0.52
Plastic stabilizers	1	0.27
Electroplating	2	0.17
Pigments	4	0.15
Pigments	7	0.14
Pigments	6	0.048
Ni-Cd batteries	7	0.046
Pigments	2	0.035
Plastic stabilizers	7	0.002
Ni-Cd batteries	6	0.0016
Ni-Cd batteries	2	0.0011
Ni-Cd batteries	4	0.0011
Plastic stabilizers	6	7.7×10^{-5}
Plastic stabilizers	5	6.0×10^{-5}
Plastic stabilizers	3	5.3×10^{-5}

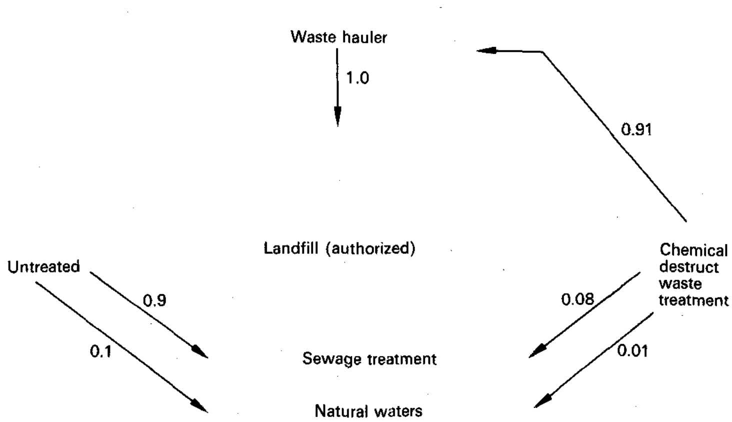

Figure 7. Fate of Cd in electroplating wastewater.

Table 9. Sensitivity of use/waste management practice-related cadmium flow to cropland vs changes in pathway coefficients for atmospheric deposition: Current practice

Use-waste management practice	Sensitivity ($\Delta Cd/\Delta\alpha_i$)							
	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8
Electroplating-steel scrap recycle	0.00055	0.0025	(–)0.0007	0.0007	0.0043	0.0056	0.0009	0.005
Pigments-refuse incineration	0.0037	0.019	0.008	0.0074	0.035	–	–	–
Plastic stabilizers-refuse incineration	0.0021	0.02	0.0046	0.0043	0.02	–	–	–

these expressions as P(a), the sensitivity associated with the ith pathway coefficient is given by:

$$S_i = \frac{\delta P(a)}{\delta a_i}$$

Table 7 gives sensitivities of use-related cadmium destined for cropland via sludge landspreading. The sensitivities are useful for evaluating the relative effectiveness of policies which modify coefficients common to a single use. It is more difficult to compare the impact of policy decisions reflected in coefficient changes where comparisons must be made between measures affecting different uses. To accomplish this, it is useful to weight sensitivities by the product of a) annual cadmium consumption for the pertinent use, and b) the fraction of annual consumption destined for the environmental compartment of interest given baseline/nominal coefficient values (e.g. '% consumption to cropland' column in table 4). Expressing annual average consumption for major uses in hundreds of metric tons (table 1), the weighting factors for electroplating, pigments, plastic stabilizers and Ni-Cd batteries are 118, 15, 1.7, and 3.5, respectively. Table 8 gives a ranking of weighted sensitivities for cadmium input to cropland via municipal sludge landspreading. Note that electroplating pathway coefficients dominate the top of the list. From the policy standpoint, this suggests that regulations designed to reduce cadmium discharges by this industry would be most effective for reducing cadmium input to cropland. To get an idea of how electroplating-related regulations should be formulated, refer to figures 5–7 which portray the flow of cadmium through the plating process. It is seen that the most sensitive coefficient in table 8 (5.5) denotes cadmium lost in the plating process to tank spills and barrel/rack 'dragout'. A possible regulations might involve a requirement for spill containment and counter-current rinses following plating, pickling and acid cleaner baths to reduce dragout. The next most sensitive process-ralated coefficient is a_3 which denotes plating waste discharged without treatment. Figure 5 indicates an estimated 25% of process losses are presently discharged without treatment. An obvious measure would be to require some minimum level of treatment for all plating waste. This can be accomplished indirectly by imposing effluent control guidelines, or directly by writing a technology requirement.

A similar sensitivity analysis for pathway coefficients defining cadmium flow to cropland via atmospheric deposition may be generated by applying the preceding weighting factors to the coefficients in table 5. In this case, of course, the cropsoil-destined fractions of table 5 are factored in with annual major cadmium use consumptions in units of 10^2 MT. Unweighted sensitivities for the cadmium atmospheric deposition path to cropland are given in table 9. Note that, unlike the pathway analysis for sludge landspreading, pigments and plastic stabilizers exhibit larger sensitivities than does electroplating by way of steel scrap recycle. This observation is borne out strongly in the weighted sensitivities ranked in table 10, where the largest plating-scrap recycle sensitivity is 6–10 times smaller than the pigments/plastic stabilizer-refuse incineration maxima. Thus, to reduce the deposition of airborne cadmium on cropland the plastic-incineration flow system should be studied. Major process-related coefficients in the simplified schematic of figure 4 are a_2 and a_3, the fraction of municipal waste incinerated and fraction of cadmium released to the atmosphere from combusted plastics containing pigments/stabilizers, respectively. The latter can be elucidated by considering the cadmium flow pattern for refuse incinerators given in figure 6. It indicates the 17% of U.S. refuse incinerators are uncontrolled, and that electrostatic precipitators are an estimated 7 times more efficient for capturing cadmium-bearing particulate from top gas than are wet scrubbers. Regulations to reduce cadmium input to the atmosphere might include the installation of electrostatic precipitators on uncontrolled incinerators, or perhaps

Table 10. Weighted sensitivities in order of magnitude for cadmium enrichment of cropland via atmospheric deposition: Current practice

Use-waste management practice	Coefficient index	Weighted sensitivity
Pigments-refuse incineration	5	0.078
Pigments-refuse incineration	2	0.042
Plastic stabilizers-refuse incineration	5	0.022
Plastic stabilizers-refuse incineration	2	0.022
Pigments-refuse incineration	3	0.018
Pigments-refuse incineration	4	0.016
Pigments-refuse incineration	1	0.0082
Electroplating-steel scrap recycle	6	0.0071
Electroplating-steel scrap recycle	8	0.0063
Electroplating-steel scrap recycle	5	0.0054
Plastic stabilizers-refuse incineration	3	0.0051
Plastic stabilizers-refuse incineration	4	0.0047
Electroplating-steel scrap recycle	2	0.0032
Plastic stabilizers-refuse incineration	1	0.0023
Electroplating-steel scrap recycle	7	0.0011
Electroplating-steel scrap recycle	3	8.8×10^{-4}
Electroplating-steel scrap recycle	5	8.8×10^{-4}
Electroplating-steel scrap recycle	1	6.9×10^{-4}

the retro-fitting of precipitators on uncontrolled incinerators, or perhaps the installation of electrostatic precipitators on uncontrolled incinerators, or perhaps the retro-fitting of precipitators on units equipped with low pressure/efficiency scrubbers.

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Minireview

Do insects feel pain? – A biological view

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The question of whether insects, or indeed other invertebrates, have a pain sense has received little attention in the literature, despite its obvious biological interest and the ethical implications of the human treatment of insects and other invertebrates. The relevance of this question is that, whilst we could scarcely conceive of a world in which pest insects are not regularly damaged and killed in vast numbers by human design and many others killed incidentally in our daily activities, the experimental biologist still has to face decisions on how to handle his insect material.

Pain, as understood in humans, is a variable, subjective experience involving a class of sensations with which is associated a characteristic 'negative affect and aversive drive'[15]. Its quality and severity may be strongly modified by factors including previous experience, non-nociceptive sensory information, focussing of attention by the subject, and the perceived significance of the experience[15,16]. The unpleasant emotional qualities and strong motivation to remove the source of stimulation appear largely to comprise the experience known generally as 'suffering'. The occurrence of 'suffering' in other animals is usually inferred from physiological and behavioral changes such as flexor reflexes, blood pressure increases, tachypnoea and vocalisation[25], all of which are normally concomitants of severe pain experiences in humans. This inference becomes progressively less defensible as animals phylogenetically more remote from man are considered. The standard reference work on the structure and function of the nervous systems of invertebrates[3] suggests only that pain is inferred if an animal shows behavioral reactions resembling those of a human in pain, the decreasing similarity of reaction in simpler animals being taken to indicate a gradual evolution of a pain sense with the appearance of increasingly complex animals.

Although there is no conclusive proof as to whether an insect can experience something akin to human pain, logical analysis of known examples of insect behavior and physiology may facilitate a rational decision. In the only published examination of the possibility of insect pain known to us, Wigglesworth[24] has, by inference from his observations of insect behavior, concluded that while most of the manipulations to which insects are commonly subjected probably do not cause them pain, certain stimuli, such as high temperature and electric shocks, apparently do so. We here examine the question from three aspects: firstly, the adaptive role of pain in mammals and the relevance of this to insect biology; secondly, the neural basis of nociception and pain perception in mammals and its relation to the insect nervous system; and thirdly, the similarities and contrasts between the behavior of insects and mammals undergoing trauma or noxious stimulation.

Pain may induce a suffering mammal to withdraw from or otherwise neutralize the causative agent and