Industrial ecology for leverage to let loose less cadmium

Jesse H. Ausubel*

Program for the Human Environment
The Rockefeller University
Box 234, 1230 York Ave
New York, NY 10021–6399, USA
Fax: (212) 327–7519
E-mail: ausubel@rockefeller.edu
*Corresponding author

Iddo K. Wernick and Anthony M. Barrett

Program for the Human Environment
The Rockefeller University
Box 234, 1230 York Ave
New York, NY 10021–6399, USA
E-mail: iddo99@yahoo.com
E-mail: ambarret@andrew.cmu.edu

Paul E. Waggoner

The Connecticut Agricultural Experiment Station
123 Huntington, Box 1106
New Haven, CT 06504–1106, USA
E-mail: agwagg@comcast.net

Abstract: Comprehending how humans let toxic cadmium (Cd) loose in their environment demands analysing zinc (Zn) production, the source of most mined Cd. Analysis of unaccounted Cd with the ImPACT identity as a product of population, affluence, intensity of Zn use, and the used fraction of Cd in Zn ore shows that the used fraction exerted the most leverage. A simulation of emission from Zn mining and processing, refinement of Cd and manufacture of its products, and their use, discard, and recycling quantifies opportunities for less unaccounted Cd. Although acting indirectly, recycling Zn has considerable leverage for loosing less Cd into our environment. Making more Cd products last longer and containing exhausted products also helps. Although cutting Cd use and raising recycling lower emission, they increase the unaccounted Cd. This application of industrial ecology supports encompassing a spectrum of impacts lest concentrating on one merely displace harm to another impact.

Keywords: cadmium; Cd; zinc; Zn; industrial ecology; materials flow analysis; ImPACT identity.

Reference to this paper should be made as follows: Ausubel, J.H., Wernick, I.K., Barrett, A.M. and Waggoner, P.E. (2006) 'Industrial ecology for leverage to let loose less cadmium', *Progress in Industrial Ecology – An International Journal*, Vol. 3, No. 6, pp.522–537.

Biographical notes: Jesse Ausubel's work seeks to elaborate the technical vision of a large, prosperous economy that emits little or nothing harmful and spares land for nature.

Iddo Wernick has worked for 15 years to measure and characterise materials flows at the national level.

Anthony Barrett, who is a graduate student in Engineering and Public Policy at Carnegie-Mellon University as well as a Research Assistant at The Rockefeller University, focuses on risk assessment of environmental and other hazards.

Paul Waggoner has worked on simulation models in agronomy and analytic tools for industrial ecology.

1 Introduction

Among the heavy metals in groups IIA through VIA of the periodic table, some like copper and zinc have a physiological role that redeems their toxicity. Because others such as lead and cadmium do not, campaigns to keep them out of the environment prevail. Influenced by these campaigns, the use of Cd has declined despite its practical uses. Between its peak year 1969 and 2004, US Cd consumption dropped 93%. Although world production peaked later and fell less, Cd consumption nevertheless fell enough to drop the 2004 Cd price to 6% of its 1998 peak in an apparent victory for environmental care.

This seeming victory and the flow of a metal invite industrial ecology. Analogous to ecologists who study networks in nature, industrial ecologists delve into the network of industrial processes as they interact with each other and live off each other, especially in the sense of direct use of each other's material and energy wastes and products. Industrial ecology seeks joint economic and environmental optimisation of the use of materials from cradle to rebirth, from virgin to finished material, including components, products, so-called waste and ultimate disposal. Industrial ecology offers frameworks for improving knowledge and thus sparing resources, using materials, and curtailing waste and pollution.

Industrial ecologists have recommended studying the forces changing the use of individual elements. They have recommended investigating the flows and balances of elements to learn the structure and webs of economic and material relations among actors in industry (Ayres and Ayres, 2002). If leverage is an advantage of effectiveness and practicality for lifting the burden of pollution, then the goal of industrial ecology's recommended studies is finding the most powerful levers. Specifically, where is the leverage to let loose less Cd around us?

Worldwide, the annual production of most toxic heavy metals, including cadmium, lead, mercury, arsenic, zinc, and copper has risen during the past one to three centuries by two or three orders of magnitude (Pacyna, 1986). Notwithstanding impressive gains containing them, significant emissions still let Cd loose around us, creating chances for unintentional ingestion and parallel opportunities for improvement (Ayres, 1996).

Several characteristics make Cd an absorbing illustration of the analytic potential of industrial ecology:

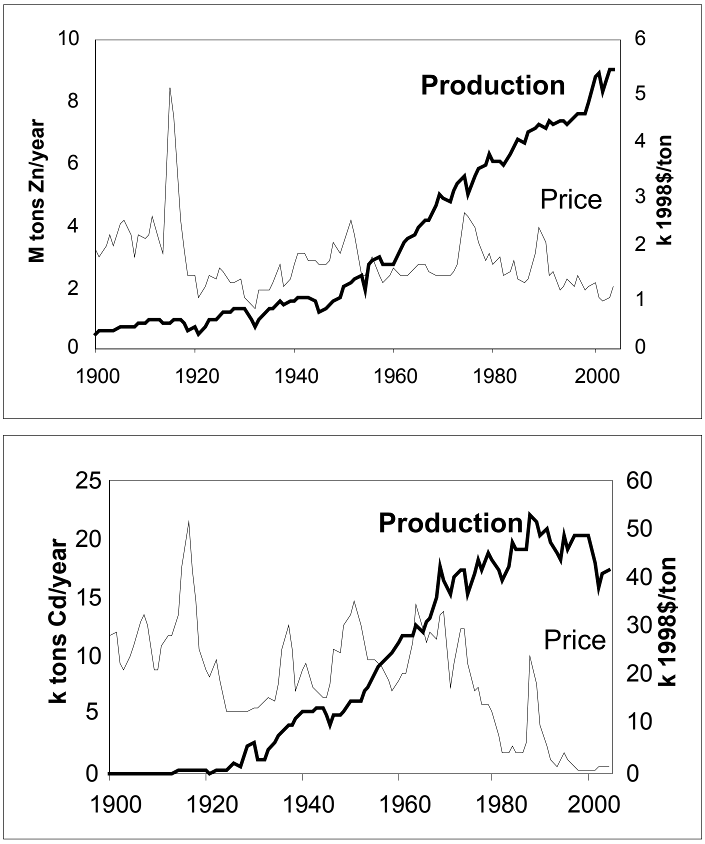
- Cd accumulates in a person's body and may affect behaviour or cause cancer, so avoiding exposure to even a little Cd is wise (Jarup, 2003). Breathing or swallowing much Cd can kill (ATSDR, 1999). While growing species of 'bio-accumulator' plants in Cd-contaminated areas and then disposing them as toxic waste or the extreme measure of soil removal may reverse Cd contamination in some locales, these options are slow or costly at best. Cd is thus a good candidate for *zero emissions*, watchwords of industrial ecology.
- Although some of Cd's uses have declined, its advantages persist for such batteries as those that power portable tools. By 2000, the fraction of Cd use in batteries had grown to three-quarters of all Cd use. Because the fraction of Cd use in batteries is large, the proposed European Union ban on them would affect Cd use profoundly. (Plachy, 2005).
- As an element, Cd cannot be created or eliminated like polychlorinated biphenyls (PCBs) or organic pesticides. Instead, people mine it and concentrate it and cannot simply destroy it, as by incineration, at the end of its use. Its flow chart must balance.
- Because Cd is captured as a virtual by-product of mining and processing other metals, notably Zn, even primary production of Cd represents a recovery of a waste – and a toxic one at that. At least 80% of worldwide Cd metal output is a by-product of primary Zn production, with about 3 kg by-product Cd per ton of Zn produced (Llewellyn, 1994).

Here, we focus on the course of Cd use and its parallel in Zn production, especially the global courses that are not complicated by international trade. Focusing on flow, we diagram the flow of Cd in the 1990s. On that foundation, we then investigate the forces that drive Cd production and search in a simulation for the leverage that could let less Cd loose into the human environment.

2 Courses of Cd and Zn in the 20th century

As customary of industrial ecology, Figure 1 shows the global course of Cd and Zn production. With correction for change in stocks, these global quantities indicate use as well as production. Correction for stocks is slight because Morrow (1998) estimated stocks were only about 20% of production and their change much less than their total. The courses of Cd and Zn differed markedly. While the production of Cd nearly levelled in the 1960s and its price fell from more than $10,000 per ton to almost worthless in the 1990s, the price of Zn stayed around $1,000, while Zn production climbed relentlessly. Although the use of Cd in pigments, stabilisers, coatings, and alloy declined and its use in batteries did not make up the lost quantity, the use of Zn, notably for galvanising, continued undiminished. Remembering that about 3 kg of Cd accompanies each ton of Zn produced and that 80% of Cd metal is a by-product of Zn production makes the diverging courses arresting.

Figure 1 World productions and prices in 1998 dollars of Zn and Cd during 1900 to 2004. Data from US Geological Survey publications, generally online at http://minerals.usgs.gov/minerals/pubs/commodity/

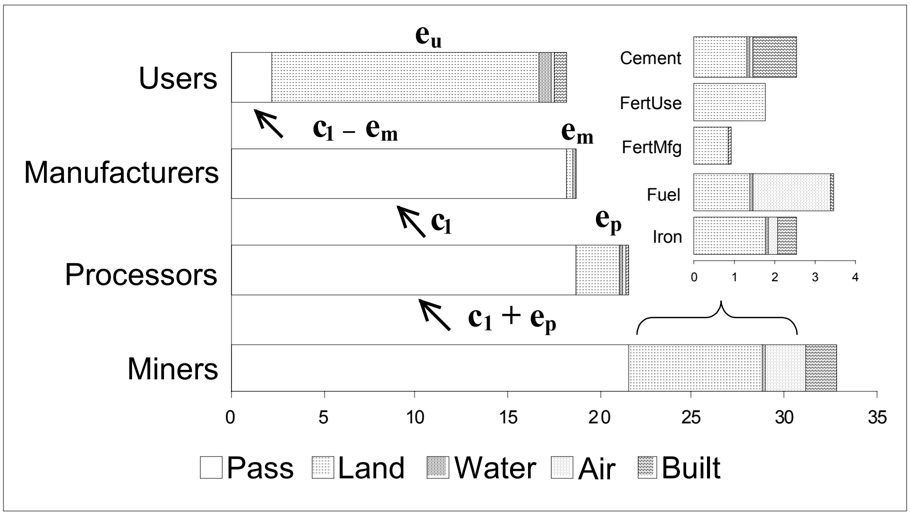


3 Material flow in the 1990s

For clues to the leverage or opportunity for loosing less Cd, we chart the flow of tons of Cd that people propel, intentionally or not. Although people do not make Cd, they take it from Earth's crust, concentrate it and move it about, and let it loose into their environment. In parts per billion, its abundance of 98 in Earth's upper continental crust can be understood by comparison with 35 000 000 for iron, 71 000 for zinc, 25 000 for copper, 20 000 for lead and 1.8 for gold (Nierenberg, 1992*)*. Cd's peculiar association with other non-ferrous metals inevitably makes it either a waste or by-product of mining for zinc, lead and copper. Although some virgin cadmium is recovered during the beneficiation and refining of lead and copper-zinc ores, most is recovered as a by-product of zinc refining. The production and use of cement, fuel, and phosphate fertiliser also remove Cd from Earth's crust. Unsurprisingly, the Cd content of herbage has doubled since 1860, and the content of present human bones is many fold that of prehistoric ones (Ericson *et al*., 1991; Jones, *et al*., 1992).

Jackson and MacGillivray's (1995) chart of 1991 global Cd flow enabled us to draw the global flow in Figure 2. They called losses whether to air, water, or dumping on land *emissions*, and we follow their custom. Plachy (2003b) charted Cd flow in the USA in 2000, but Figure 2 requires global estimates.) The bars representing tons of Cd carry the names of actors who might reduce the tons. The long *Miners* bar at the bottom of the chart represents 33 thousand tons (k tons) per year of Cd taken from Earth's crust during mining. The 33 come from mining for non-ferrous metal, mostly Zn, plus extracting fuel and raw materials for cement, fertiliser, and iron. Because Jackson and MacGillivray did not consider unaccounted Cd, we omitted it from Figure 1, where it would have added to the 33 in the Miner's bar and require a corresponding emission of unaccounted, a matter we shall expand upon below. Of the 33 k tons/year, 22 were passed to processors for Cd production, while 11 were taken unintentionally during mining for fuel, and other raw materials.

Figure 2 The global flows of mined or primary Cd in 1991 expressed as k tons per year. The portion of Cd in tons on the left of the Miners bar is passed upward for Cd metal; the portion on the right passes into the lesser fates of cement, fertilizer and manufacturing, fuel, and iron as shown in the upper right of the figure. Arrows show the Cd for metal passing from one level of actor to another. The hatching shows the Cd emitted to land, water, and air or built into structures by actors from Miners to Users. Unaccounted c_n and recycled c_2 do not appear in the chart. The flow chart rests on estimates by Jackson and MacGillivray (1995).



Before discussing our primary subject of the 22 k tons/year for Cd production, we summarise the emission of the 11 k tons/year shown by the right segments of the lower bar for emission to land, water, air, and the built environment. The same 11 k tons/year is shown in the bars in the upper right where it is allocated to emission from fuel, *etc*. The Cd in fuel, basically coal, dispersed about half on the land and half in the air. About one third of the Cd in phosphate rock taken for fertiliser was lost to land during manufacture and two-thirds passed into the fertiliser itself and so on to farmland. Although considerable Cd in iron ore and raw material for cement became part of the built environment, most ended on land.

Our primary concern, the 22 k tons/year for Cd production, is depicted by the long, left segment of the *Miners* bar. Mostly extracted to acquire Zn but also Pb and Cu in 1991, the 22 passed on to processing as the Cd flow ($c_1 + e_p$). The processors of the three metals emitted the e_p shown by the rectangles at the right end of the *Processors* bar. Processors passed the flow of primary Cd labelled c_1 to manufacturers. With rather small emissions e_m, manufacturers incorporated Cd in products and passed ($c_1 - e_m$) on to users in batteries, plating, and pigments. The right-hand segments of the *Users* bar picture Cd mostly emitted to land as e_u, while the residual 2.1 k tons/year remained with users.

Recycling or secondary production is absent because Figure 2 deals with mined Cd, but it must be considered. To incorporate recycling, a stream of secondary production c_2 would have to be shown flowing into the *Manufacturers* bar. Van der Voet *et al*. (2000) thought Cd recycling was so prevalent in 1999 in the Netherlands that it could scarcely be increased. Morrow (1998) estimated that worldwide recycling was more than 10% and perhaps as high as 20%, and Plachy (2003b) estimated US recycling efficiency was 15%. Accordingly 2.1 k tons/year or 11% of 1991 consumption in the left segment of the User bar could be rationally assumed equal to Cd recycled or accumulated by Users.

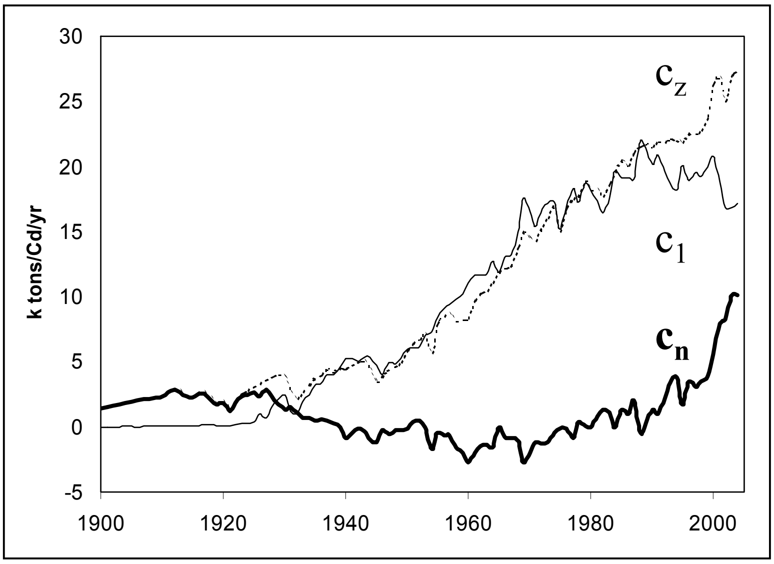
Coupling Cd flow to Zn production requires two more parameters not shown on Figure 2: c_z and c_n. For 1991, Figure 1 shows a Zn production of 7300 k tons/year. At the ratio of 3 kg Cd per ton Zn, this Zn production would be accompanied by about 22 k tons/year of Cd production, which we call c_z. Jackson and MacGillivray, however, reported only 18.7 k tons/year produced by processors and passed to manufacturers in 1991, which leaves roughly 3 k tons/year of Cd unaccounted for and, we presume, accumulating somewhere. Let the difference ($c_z - c_1$) be this unaccounted c_n. To incorporate the new parameters in Figure 2, the flow from miners to processors would become ($c_z + e_p$) rather than ($c_1 + e_p$), and a flow of unaccounted c_n would be added to the flows already leaving processors.

As they mined metals and minerals in 1991, humans shifted 33 k tons of Cd into their close proximity. These tons/year integrated over decades inevitably raise a question for industrial societies: Where to sequester the Cd? Figure 2 dramatises the 22 k tons/year recovery of Cd from processing ore for other metals and a couple of k tons held or recycled by users as the successes. It leaves both recycled Cd c_2 and unaccounted Cd c_n to be investigated.

4 Leverage to leave less Cd unaccounted for in the human environment

In 1900, practically all Cd mined with Zn was unaccounted for. "Before cadmium production started in the United States, about 85% of the cadmium content of the zinc concentrates was lost in roasting the concentrate and fractional distillation of zinc metal" (Llewellyn, 1994). That is, the primary production c_1 of Cd began the 20th century near zero in Figure 3, leaving unaccounted Cd c_n roughly equal to the c_z in Zn. By 1929, the primary Cd production rate c_1 had risen to about half of the Zn by-product Cd flow c_z. By 1950, they were roughly equal, leaving no Cd unaccounted for. During the 1980s, however, Cd production levelled while Zn production climbed, which left unaccounted Cd equal to a quarter of the total Cd by-product from Zn.

Figure 3 From 1900 to 2004, the Cd in world Zn production reckoned at 3 kg Cd per ton Zn (c_z), Cd production (c_1), and the unaccounted Cd (c_n)



Source: Data from US Geological Survey publications, generally online at http://minerals.usgs.gov/minerals/pubs/

Six selected years from 1900 to 2004 reflect the global course of unaccounted Cd, which Table 1 shows in its impact column. Population *P* climbed steeply from 1.6 to 6.4 billion. Affluence *A* climbed even more sharply, more than quadrupling. The *C* column in the table shows the consumption *C* of Zn per economic activity rose for the first half of the century. As for many materials whose use has matured, Zn's intensity of use then declined by a third. The cause might be simplified as the replacement of galvanised pails by plastic buckets or the economy outdistancing the growth of a single, material object, an instance of dematerialisation.

Table 1 The forces defined by the ImPACT identity that drove the impact c_n of unaccounted Cd: Global population *P*, gross world product per person *A*, intensity of Zn use *C*, and the ratio T_2 of unaccounted Cd c_n to the Cd in Zn c_z. The constant T_1 of 3 kg Cd per ton of primary Zn production was omitted from the table.

	Impact c_n	*P*	*A*	*C*	*T_2*
Year	*k tons*	*k capita*	*k \$/capita*	*mg Zn/\$*	*c_n/c_z (%)*
1900	1.4	1,565	1.3	242	99
1929	1.8	2,047	1.8	357	45
1950	–0.1	2,512	2.1	367	–2
1980	–0.1	4,430	4.7	290	–0
2000	5.6	6,071	5.7	253	21
2004	10.1	6.379	5.8	244	37

Sources: US Census Bureau (2004), US Bureau of Economic Analysis (2006) and US Geological Survey (2007).

The rise and fall of an environmental index like *C* as affluence *A* increases has been viewed as a victory. It is called an Environmental Kuznets Curve (Cleveland and Ruth, 1998). Unfortunately our concern, unaccounted Cd in the impact column of Table 2, followed the opposite of a Kuznets curve. It fell but then rose as affluence continued upward. The ImPACT identity, which ties a society's environmental impact (in this case, related to Cd emissions) to its population, income, consumption, and technology, can help reveal what went wrong (Waggoner and Ausubel, 2002). It can help understand why the impact identified as unaccounted Cd did not decline in a Kuznets curve but rather increased during the concluding decades of the century. We focus ImPACT on unaccounted Cd by equating it with impact *I*.

I (c_n, the amount of Cd unaccounted for [tons]) ≡

P (Population [capita]) ×

A (Affluence [gross world product/capita]) ×

C (Consumption or intensity of use of Zn in the economy measured as all Zn production ($z_1 + z_2$) per gross world product [tons/gross world product]) ×

T_1 (Technology measured as $c_z/(z_1 + z_2)$, Cd produced per Zn produced [tons/ton]) ×

T_2 (Technology measured as c_n/c_z, unaccounted Cd per Cd in Zn production [tons/ton])

Reduced to symbols, ImPACT is simply, $I \equiv P \times A \times C \times T_1 \times T_2$.

Table 2 The standard values of the parameters of the simulator. The standard values produce flows represented by the top bar in Figure 5. The realism of these simulated flows for the standard values was established by their resemblance to the 1991 flows estimated by Jackson and MacGillivray and summarised in Figure 2 above.

Parameters	*Standard*
$z_1 + z_2$ Primary and secondary Zn production (k tons/year)	7.31
$T_1 = c_z/z_1$ Ratio of Cd to primary Zn production (ton Cd/ton Zn)	0.003
$r_{z2} = z_1/(z_1 + z_2)$ Ratio of recycled to all Zn production	0.15
r_{ep} Processors' emissions as ratio of e_p to c_z	0.15
$c_1 + c_2$ Primary and secondary Cd production (k tons/year)	18.7
r_{em} Manufacturers' emissions as ratio of e_m to $c_1 + c_2$	0.03
t_U Characteristic lifetime of Cd products (years)	5
t_{c2} Characteristic time for recycling Cd (years)	16
t_X Characteristic time of stock *X* emission (years)	4

The identity adds the actors parents and consumers of Zn to those introduced in Figure 2. Parents are the actors who control population *P*, and workers control affluence *A*.

Intensity of use or consumption *C* is a preeminent parameter of industrial ecology and shows the portion of all the activity encompassed in gross world product that is devoted to a material. Here the material is Zn, whose consumption causes Cd to be unearthed.

Although Figure 2 begins at bottom with the actors called *Miners*, ImPACT is being used to search for leverage to lessen unaccounted Cd. So, ImPACT identifies Zn consumers as the actors determining the intensity of Zn use.

T_1 calculates how much Cd accompanies Zn production. When price encouraged Cd recovery from Zn, processors demonstrated that 3 kg of Cd could be produced per ton of Zn, Figure 3. Hence, T_1 = 3 kg Cd/ton Zn has a secure foundation in history. Recycling Zn and hence digging less Cd-laden ore for the primary plus secondary production could lower the ratio. Also, producing Zn from ore containing less than 3 kg of Cd produced per ton of Zn would lower T_1. On the other hand, the environmentally beneficial task of salvaging Cd from metalworking dust would raise T_1, the ratio of Cd to Zn production. The actors called processors are responsible for T_1, which we set at 3, the value processors demonstrated in mid-century.

Manufacturers can lessen T_2, the amount of unaccounted Cd per ton of Cd in Zn. If consumers of Cd inspire manufacturers to incorporate more Cd into products, this ratio falls and less Cd is left unaccounted for.

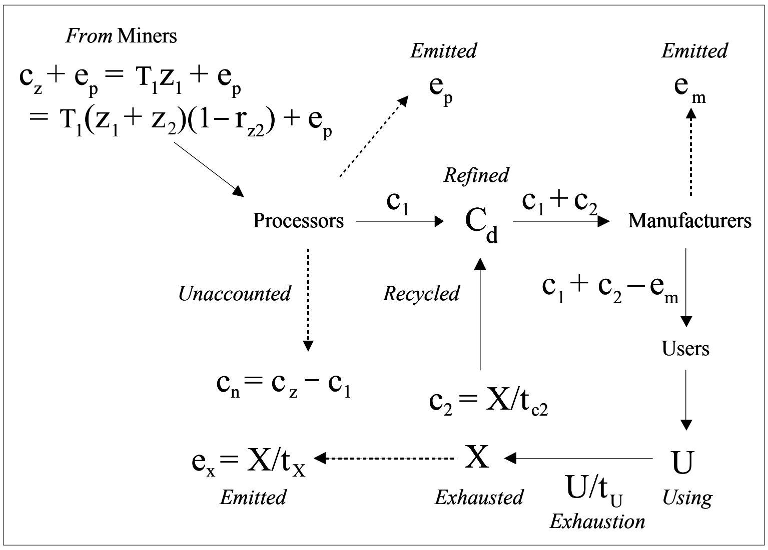
The bad actor to be located or problem to be solved is why the impact of unaccounted Cd traced the opposite of an environmental Kuznets curve. The ImPACT identity and Table 1 identify the culprit as T_2, the ratio of unaccounted Cd to total by-product Cd from Zn production. In terms of the actors we have named, manufacturers failed to incorporate as much Cd in products as Zn production recently offered. Beginning the century at 99%, T_2 fell near to zero and then rose back to 37%. In the language of economics, the negative income elasticity of Zn use intensity shows consumers of Zn can moderate the upward pressure of population and affluence. The early years demonstrated that the income elasticity of T_2 could also be negative and lower unaccounted Cd as income rises. Thus, given demand for Cd, manufacturers should be able to capture Cd and lower the recent 37% of unaccounted Cd in Zn. The unaccounted equals 10 k tons/year, a tonnage of Cd well worth accounting for.

5 Simulation to find leverage

To unaccounted Cd, the simulator depicted in Figure 4 now adds emissions and also recycling of both Zn and Cd. The simulator unifies the global flows and emissions of Figure 2 with the technology parameters of ImPACT to reason quantitatively where the leverage lies for cutting emissions from the processing and use of metal as well as cutting unaccounted Cd. The simulator in Figure 4 is simpler and broader than those that van der Voet *et al*. (2000) composed for The Netherlands and several metals. Their simulators are more complex and at the same time narrower in scope than the scheme of Figure 4. For example, the Dutch simulators encompass the complexities of substitutions among materials and human exposure, but their focus on The Netherlands is narrower than Figure 4's global span. The resemblance of Figure 4 to Jackson and MacGillivary's 1991 global flows in Figure 2 establishes its realism, while its simplicity fosters understanding.

Figure 4 begins with processors receiving a Cd flow ($c_z + e_p$) during primary Zn production and emitting e_p, which is a ratio r_{ep} times c_z. The preceding section attributes Zn production to the actors such as parents, workers, and Zn consumers who through population, income, and Zn use drive global Zn production. The c_z from Zn equals T_1 times primary production, which in turn equals all Zn production ($z_1 + z_2$) adjusted for the recycled fraction r_{z2}. If manufacturers take all the Cd from processors, then c_1 equals c_z, leaving no c_n unaccounted for. On the other hand, a primary Cd production c_1 smaller than the c_z from Zn production leaves some c_n unaccounted for.

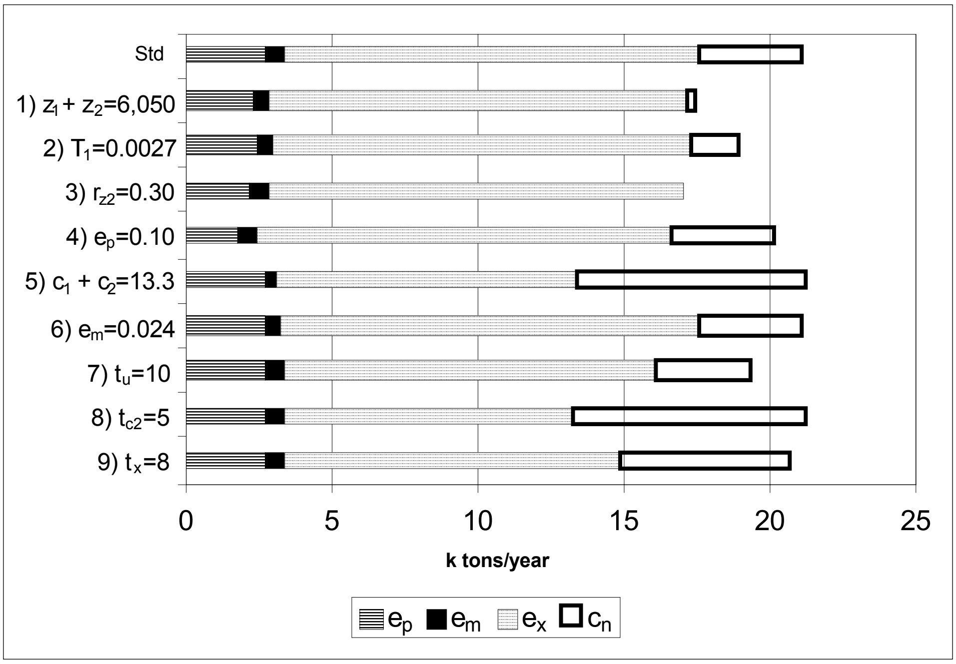
Figure 4 A simulator of Cd flow from Zn processing and Cd recovery through the manufacturing, use, and exhaustion of Cd products. Total Zn production $(z_1 + z_2)$ decreased to primary production z_1 by the recycling fraction r_{z2} provides a flow of $(c_z + e_p)$ tons of Cd per year to processors of Cd, who emit e_p and leave c_n unaccounted for. Manufacturers receive a flow of $(c_1 + c_2)$ primary plus secondary or recycled Cd. Manufacturers emit e_m and pass $(c_1 + c_2 - e_m)$ to users' stock *U* in products. Users exhaust products with a characteristic time t_U into stock *X* of exhausted products, from which $e_x = X/t_X$ is emitted and c_2 recycled. Conventions: stocks are indicated by uppercase except the T_1 borrowed from ImPACT. Flows of Zn and Cd, indicated by lower case letters and labelled in italics, either move along solid arrows of utility or escape along dotted arrows. The flows of utility move among actors labelled without italics.



In the refined stock C_d, the secondary or recycled production c_2 joins primary production c_1. An accumulating refined stock and its effect on recycling could be incorporated, but for now the flow in equals the flow out, preventing accumulation. Manufacturers emit a fraction r_{em} of the flow that they receive and pass the rest on to users' stock *U* of products. Users exhaust the products after a characteristic time or life t_U, passing Cd to the exhausted stock *X* at rate (U / t_U). The important recycled, secondary production c_2 comes from *X* exhausted stock of products according to another characteristic time t_{c2}, increasing when the stock of exhausted products is greater and recycling is quicker. If a stock C_d were allowed to accumulate and the accumulation discouraged recycling, that complication could be introduced in the simulation – but we have kept the simulator simple and easily understood. Indeed, we have consciously constructed our model of Cd flows with a level of resolution intended to highlight the actors involved. Finally, the exhausted stock lets loose into the environment an emission X/t_X regulated by the characteristic time t_X. Figure 2 labels users' emissions as e_u. In the simulator of Figure 4, on the other hand, emission e_x from users' stock *U* recognises the roles of product lifetime, recycling and containment. Although models such as those constructed by van der Voet *et al*. (2000) are more detailed, the model of Figure 4 clearly fixes responsibility. What actors have leverage to loose less Cd into the environment and leave less unaccounted for?

To set a standard of comparison we first specified the parameters in column *Standard* of Table 2 and calculated the approximately steady state after 25 years. The standard parameters produce the outcome depicted in the top bar labelled *Standard* in Figure 5. It resembles the 1991 flows estimated by Jackson and MacGillivray in Figure 2.

Figure 5 Simulated Cd flows per year. The Standard bar shows three annual emissions e_p, e_m, and e_x, and unaccounted c_n k tons simulated from the Standard parameters and values tabulated in Table 2. The numbered bars show the outcomes of changing single parameters to the values shown in their labels.



Next, we searched for leverage by making one realistic change in each of the nine parameters. The outcomes of the changed parameters stabilise to approximately steady state after 25 years. The first three parameters pertain to Zn production.

1 Cut all Zn use

Lowering all annual Zn production 17% from the 7310 k tons of 1991 to the 6050 k tons of 1980 cut unaccounted Cd from an accumulation over 3 to only 0.3 k tons/year. At the 6050 rate of 1980, the simulated primary Cd production nearly balanced or salvaged all that mined with Zn.

2 Process Zn-ore with less Cd

Producing Zn from ore with less Cd and reducing the ratio of Cd by-product to Zn production from 3 to 2.7 kg Cd per ton of Zn also left less Cd unaccounted for. Unfortunately, a lower ratio seems unlikely. During 1950–1971, the strong demand and high Cd price encouraged processors to show just how much Cd could be salvaged instead of lost to the environment or stored. In that long period, T_1 was fully 3.2 kg Cd per ton of Zn, above rather than below the Standard 3.0.

3 Recycle more Zn

The third lever for lowering unaccounted Cd is recycling Zn. Graedel *et al*. (2005) reviewed recycling of zinc at multiple levels. The Standard recycling rate r_{z2} of 0.15 was chosen to encompass the known 3% of secondary Zn production and part of the half undifferentiated between primary and secondary in the world in 2003. In the USA alone, however, the recycling rate was reported as 27%, and in The Netherlands, over 80% (Plachy, 2004; van der Voet *et al*., 2000). Therefore, the rate of 30% that balances Cd and Zn production and eliminates the by-production of Cd seems attainable. If the 80% recycling ratio reported for the Netherlands in 1990 were achieved worldwide, the rate of accumulation of unaccounted Cd would become negative, Cd stocks would fall rapidly and the primary production of Cd from Zn ore would soon be forced to fall.

Pulling the three Zn levers changed only the unaccounted c_n left from Zn production because $(c_1 + c_2)$ was specified at the rate of 1991. Hence, manufacturers' small e_m and users' large e_x remained constant because Cd production $(c_1 + c_2)$ was kept constant. Now let us turn to the six Cd levers.

4 Cut processor Cd emission

Representing processors cutting their Cd emissions by a third, the fourth bar shows only a small consequence overall.

5 Cut all Cd use

Next we turn from the Cd related to Zn production to the nature of Cd production and use. Pigments and stabilisers, which contribute disproportionally to emission of Cd, comprised 29% of all uses in 1991 (Jackson and McGillivray, 1995). Accordingly we simulated a 29% cut of total Cd production as if all use of Cd in pigments and stabilisers were eliminated. As hoped, emissions fell by a quarter even though we did not adjust for the somewhat greater emission per ton of pigments and stabilisers than other products. Because Zn production and attendant Cd by-production c_z go on despite slower total Cd production $(c_1 + c_2)$, the resultant increase in unaccounted Cd countered the improvement from lessened Cd production.

6 Cut manufacturer Cd emission

Cutting the small manufacturer's emissions by a fifth had little consequence.

7 Extend Cd product life

The Standard five-year characteristic life t_U of products in use corresponds to the estimated life of sealed batteries, which comprised nearly half of all Cd use in 1991. Almost all other uses had estimated lives of 10 to 25 years (Jackson and MacGillivray, 1995). We therefore simulated a reasonable doubling of t_U to ten years. The longer life cut continuing, annual emissions e_x by 10%. By an indirect route, longer product life also cut unaccounted Cd. The indirect route was longer time in use, less exhausted product, less recycling, greater primary production, and so less Zn-by-product Cd left unaccounted.

8 Recycle more Cd

The 16-year Standard t_{c2} for recycling Cd in the exhausted stock *X* simulates recycling 20% of all Cd production. A 16-year recycling time also simulates a users' emission e_x of 14 k tons of Cd in 1991, close to the users' emission in Figure 2. Shortening recycling time from 16 to 5 years simulates a doubled recycling rate of 40%. The 40% recycling that van der Voet *et al*. (2000) estimated in The Netherlands makes it a realistic goal. This increased recycling lowers emissions about as much as the 29% lessened Cd use simulated above. In 2006, the European Union directed that all waste batteries will have to be collected and recovered separately from household waste (European Union, 2006). Unfortunately, recycling more Cd increases unaccounted Cd because Zn production goes on apace.

9 Contain exhausted Cd products longer

Lengthening the characteristic time t_X of the stock of user's exhausted material *X* leaking into the environment has a somewhat more complex outcome. The Standard characteristic time t_x of four years simulates a 14-kton per year emission e_x, which resembles the emissions from users in Figure 2. Doubling t_x by closer containment of exhausted products is conceivable, and would cut Cd emission from exhausted products by a fifth. The greater supply of more closely contained exhausted products encourages recycling, and thus less primary production of Cd, with of course, the inevitable consequence of leaving more unaccounted Cd.

Searching with a simulator for an attainable way to loose less Cd into our environment, we conclude that recycling Zn has considerable leverage. Extending the life of Cd products and containing exhausted ones have some leverage. Cutting Cd use and recycling have even more leverage, but rising amounts of unaccounted Cd from Zn production may counter the improvement of less emission.

6 Discussion

The multiplication of the forces of population and income by increasing consumption can increase the use of a new material exponentially. Fortunately for the environment, history shows these trends moderate. Income and intensity of use rarely have the independence implied by multiplication but instead are connected by an income elasticity. A new process like galvanising iron can lift per capita use faster than income, demonstrating an income elasticity greater than 1. Then maturity, as when plastic buckets replace galvanised pails, makes the new material a staple, and lowers the income elasticity of intensity of use of an old material such as Zn into negative territory. Zn and Cd uses have matured, but the link of Cd to Zn lifts the amount of unaccounted Cd as Cd use declines.

Warning about an obsession with recycling, van der Voet *et al*. (2000) wrote, "Management measures should therefore focus on the control of [so-called trace flows], rather than on the still further enhancement of recycling". The global 1991 flow diagrammed in Figure 2 does show a third of all Cd flowing as traces into emission or the built environment unrelated to the metal industry. Nevertheless, globally in 1991, users emitted even more. Unlike The Netherlands where much is recycled, the world evidently has a great recycling opportunity of 16 k tons/year, still exceeding the trace-flow of 11. Further, the global flow of unaccounted Cd grew to 10 k tons/year in 2004. Growing at its recent rate, unaccounted Cd could soon exceed trace flows. So without belittling the trace flows, one can still attend to the world's emissions from users and unaccounted Cd, which have leverages imparted by magnitude and practicality. In addition to recycling, practical control also includes a longer life and then containment of exhausted Cd products.

The growth of unaccounted Cd may surprise readers. Where is it, and why is it overlooked? Llewellyn (1994) told us where it was decades ago when about 85% of the cadmium content of the zinc concentrates was lost in roasting the concentrate and in fractional distillation of Zn metal. When Cd was valuable from about 1940 to the late 1980s, processors demonstrated that they can recover Cd. Because processors can recover it, the unaccounted Cd now likely stays near them, either accumulating or needing disposal.

Perhaps the unaccounted Cd has been overlooked because it is the processors' problem in remote places, whereas the discarded products and deposits in soil accumulate near watchful people. Nevertheless in 2002, Plachy (2003a) observed:

> "Because most Cd is produced as a byproduct, mainly of Zn production, restrictions on the use of Cd in batteries could increase the amount of unprocessed Cd that is disposed in landfills by Zn producers. Therefore, an effective collection and recycling system for spent batteries would probably protect the environment more than a ban on Cd in batteries."

Cd accumulation in remote places does expose people less than the same accumulation where population is dense. Globally, however, accumulating unaccounted Cd is a problem that could become a resource, a file of Cd in a 'filing cabinet' of metals for future use (Frosch, 1996).

Simulation – and common sense, of course – point to beginning with the Zn production that puts much Cd in motion. Concentrating on Cd alone while the sorcerer's apprentice of Zn production continues putting Cd in motion causes accumulating unaccounted Cd to counter improvements in emission. Even putting the stream of unaccounted Cd into filing cabinets for future use is only a delay. On the other hand, a joint improvement of both global Zn recycling *and* Cd recycling to the Dutch rates of 80% and 40%, respectively, would cut emission *and* accumulation of unaccounted Cd. In the long run, a declining supply of Zn by-product Cd for primary production would drive down all Cd production and even encourage emptying the filing cabinets filled by unaccounted Cd.

Although acting indirectly, recycling Zn has considerable leverage for letting less Cd loose into our environment. Making more Cd products last longer and containing the exhausted products helps, too. Recycling and using less Cd cut emissions still more, but a clear victory requires also attending to unaccounted Cd from Zn production. This application of industrial ecology supports a recommendation: Encompass a spectrum of impacts lest concentrating on one impact merely displace its harm to another impact.

Acknowledgement

Research assistance was provided by Peter Elias.

References

Agency for Toxic Substances and Disease Registry (ATSDR) (1999) *Priority List of Hazardous Substances and Toxicological Profile Information Sheet for Cadmium*, Atlanta, Georgia, http://atsdr1.atsdr.cdc.gov:8080/clist.html and http://atsdr1.atsdr.cdc.gov:8080/toxprofiles/tp5-c2.pdf (accessed 24 June 2005).

Ayres, R.U. (1996) 'Zinc and cadmium', in R.U. Ayres and L.W. Ayres (Eds.) *Industrial Ecology: Towards Closing the Materials Cycle*, Brookfield, VT: Edward Elgar, pp.81–96.

Ayres, R.U. and Ayres, L.W. (2002) *A Handbook of Industrial Ecology*, Cheltenham, UK: Edward Elgar.

Cleveland, C.J. and Ruth, M. (1998) 'Indicators of dematerialization and the materials intensity of use', *Journal of Industrial Ecology*, Vol. 2, No. 3, pp.15–50.

Ericson, J.E., Smith, D.R. and Flegle, A.R. (1991) 'Skeletal concentrations of lead, cadmium, zinc and silver in ancient North American Pecos Indians', *Environmental Health Perspectives*, Vol. 93, pp.217–223.

European Union (2006) *Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on Batteries and Accumulators and Waste Batteries and Accumulators and Repealing Directive 91/157/EEC*.

Frosch, R.A. (1996) 'Toward the end of waste: reflections on a new ecology of industry', *Daedalus*, Vol. 12, No. 3, pp.199–212.

Graedel, T.E., van Beers, D., Bertram, M., Fuse, K., Gordon, R.B., Gritsinin, A., Harper, E.M., *et al*. (2005) 'The multilevel cycle of anthropogenic zinc', *Journal of Industrial Ecology*, Vol. 9, No. 3, pp.67–90.

Jackson, T. and MacGillivray, A. (1995) *Accounting for Toxic Emissions from the Global Economy: The Case of Cadmium*, Stockholm Environment Institute, Stockholm.

Jarup, L. (2003) 'Hazards of heavy metal contamination', *British Medical Bulletin*, Vol. 68, pp.167–182.

Jones, K.C., Jackson, A. and Johnston, A.E. (1992) 'Evidence for an increase in the cadmium content of herbage since the 1860s', *Environmental Science and Technology*, Vol. 26, pp.834–836.

Llewellyn, T.O. (1994) *Cadmium (Materials Flow)*, Information Circular 9380, Bureau of Mines, US Department of the Interior, Reston, Virginia.

Morrow, H. (1998) 'Cadmium', *Metals and Minerals Annual Review*, pp.88–89.

Nierenberg, W.A. (Ed.) (1992) 'Continental crust', *Encyclopedia of Earth System Science*, San Diego, CA: Academic Press, Vol. 1, pp.584–585.

Pacyna, J. (1986) 'Atmospheric trace elements from natural and anthropogenic sources', in J.O. Nriagu and C.I. Davidson (Eds.) *Toxic Metals in the Atmosphere*, New York: Wiley, pp.33–52.

Plachy, J. (2003a) 'Cadmium', *U.S. Geological Survey Minerals Yearbook*, Reston, Virginia, http://minerals.usgs.gov/minerals/pubs/commodity/cadmium/cadmimyb03.pdf (accessed 15 September 2006).

Plachy, J. (2003b) 'Cadmium recycling in the United States in 2000', *U.S. Geological Survey Circular 1196-O*, Reston, Virginia, http://pubs.usgs.gov/circ/c1196o/ (accessed 15 September 2006).

Plachy, J. (2004) 'Zinc recycling in the United States in 1998', *U.S. Geological Survey Circular 1196 D*, Reston, Virginia, http://pubs.usgs.gov/circ/2004/1196am/c1196a-m.pdf (accessed 15 September 2006).

Plachy, J. (2005) 'Cadmium', *U.S. Geological Survey Mineral Commodity Summaries*, Reston, Virginia, http://minerals.usgs.gov/minerals/pubs/commodity/cadmium/cadmimcs05.pdf (accessed 15 September 2006).

US Bureau of Economic Analysis (2006) *Gross Domestic Product (GDP)*, Washington, DC, http://bea.gov/bea/dn/gdplev.xls (accessed 9 January 2007).

US Census Bureau (2004) *Statistical Abstract of the United States*, Washington, DC, http://www.census.gov/prod/www/statistical-abstract-2001_2005.html (accessed 9 January 2007).

US Geological Survey (2007) 'Historical statistics for mineral and material commodities in the United States', *Data Series 140*, Reston, Virginia, http://minerals.usgs.gov/ds/2005/140/#data (accessed 9 January 2007).

van der Voet, E., Guinee, J.B. and Udo de Haes, H.A. (2000) *Metals in the Environment: A Problem Solved?*, Dordrecht, The Netherlands: Kluwer.

Waggoner, P.E. and Ausubel, J.H. (2002) 'A framework for sustainability science: a renovated IPAT identity', *Proceedings of the National Academy of Sciences, U.S.A.*, Vol. 99, pp.7860–7865.