Use Of Information From Substance Flux Analysis For Human Health Risk Assessment At Regional Scales: Cadmium As A Case Study In Australia

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Abstract: This paper addresses an integration of environmental analytical approaches aimed at providing information to enable sustainable use of materials/substances at a regional level. A major technique in environmental materials accounting, Material/Substance Flux Analysis (MFA/SFA) has been applied in order to provide input information for human health risk assessment framework. MFA/SFA can provide a holistic picture of resource use, and loss through a geographic region at a specific year, allowing us to examine all material/substance inflows, outflows, and stocks through each sub-compartment in the economy. At a regional scale, this aims to provide acceptance criteria related to human health impacts, providing an additional or alternative criterion to geogenic reference points. A heavy metal, cadmium has been selected, and used as an illustrative case study in a system boundary of Australia. Main finding of SFA study shows that most of the cadmium in the environment results directly from human activities such as on-site wastes arising from mining and production facilities, household wastes to landfill, and use of phosphate fertilizers in agricultural soils. The released cadmium outputs/emissions from society activities determined by the SFA study could be a quantified link between economic process outputs, then environmental concentrations, and subsequent ecosystem and human health risks. Environmental fate and transport model that is already incorporated in exposure assessment of risk assessment can be used as a bridge to connect SFA to risk assessment process.

Keywords: *Material/Substance Flux Analysis (MFA/SFA); Cadmium (Cd); human health risk assessment; environmental fate model, Australia*

1. INTRODUCTION

It is essential that a holistic picture of environmental information should be available to enable policymakers to make informed judgements about regional policies and plans, relating to the sustainable use and disposal of material resources. In terms of implementation of environmental management systems for regions, a set of indices relating to the sustainability questions of activities for regions is needed to determine whether the processes and activities in the entire system are sustainable now, and into the future (Moore and Changsirivathanathamrong 1999).

A study of Material Flux Analysis (MFA) or Substance Flow Analysis (SFA) originally developed by Baccini and Brunner (1991) as a tool of environmental material accounting is in focus on this paper. It can provide a holistic picture and model resource use, and loss through a geographic region at a specific year, allowing us to examine all material/substance inflows, outflows, and stocks through each sub-compartment in the economy, starting from mining and extraction, production and manufacturing, consumption and use, and then waste management. It has been later extensively applied and described as a comprehensive approach that has been used as a tool for policy development and analysis (Van der Voet et al., 1994; Brunner and Obernosterer 1997; Lampert and Brunner 1999). In addition, expanding the scope of SFA with environmental fate modelling then linked to risk assessment is possible in order to provide acceptance criteria related to human health impacts, providing an additional or alternative criterion to geogenic reference points. The integrative approach will enable improved management of materials such as cadmium or phosphorus in the economy, to better avoid resource depletion and environmental/human health contamination problems. In this research, a heavy metal, cadmium is of interest and has been used as a case study in the selected system boundary of Australia.

2. APPROACHES AND METHODOLOGY

The focus of the research has been on the following approaches and methods:

- Based on a material balance principle. It has been described that material can be transformed or transported within system (a closed system), going into or leaving the system (an open system), but they cannot be made or destroyed. It would be principally applied for calculation both in economic part and environmental fate modelling.
- The unit flux is in tonnes/year or kg/year through a "regional surface" in km^2.
- A reference year, fiscal year 1998/99 is selected.
- A heavy metal, cadmium, is considered. The reasons for this choice are the availability of information, and its bioaccumulative and toxic properties, leading to potentially adverse effects on humans and ecosystems. With its non-degradability, once it enters the environment it will remain in potentially bio-available form for a long time. In addition, it is evident that high levels of cadmium are often reported in Australian environment and foodstuffs (e.g. sediments, water, vegetables, grains, meat, and seafood).
- The geographic boundary is defined. Australia and appropriate local area have been selected for this particular research.
- All data used in the Substance Flux Analysis method is based on the utilization of existing data sources such as the Australian Bureau of Statistics (ABS), the National Pollutant Inventory (NPI), websites, relevant Australian Product Associations, and working papers.
- The sinks in the environment for cadmium released from the economy are required so that the next step of transfer to human s (mostly via food products) and calculation of human health risk can be completed. An environmental fate model, with associated software is required to predict environmental concentrations (PECs) of Cd in waters, air, soil, and sediments.
- A conceptual framework of multi-exposure pathways to cadmium in risk assessment needs to be established to analyse health risk.

3. SUBSTANCE FLUX ANALYSIS OF CADMIUM IN AUSTRALIA

3.1 Estimation of Cadmium Emission

The estimation is based on the National Pollutant Inventory (NPI), Australia's national public database of pollutant emissions. This only covers industrial sectors of the economy; cadmium in phosphate fertilizers applied in agriculture is not included in this section. Fiscal year 1998-99 is the first year report for NPI. As such, the NPI is still a growing, evolving program, and users of this database can expect to see further development and improvements in the database, internet site and CD ROM in future years (Environment Australia 2000).

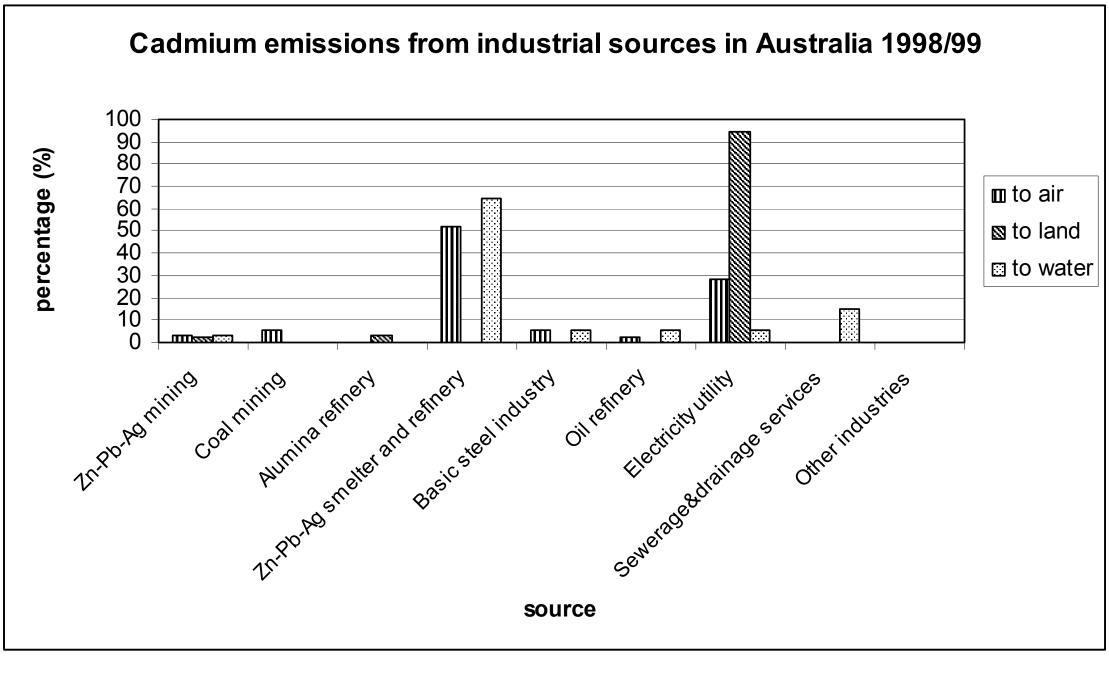


Figure 1. Industrial production emission of cadmium in Australia 1998/99

The emission is calculated on a spreadsheet using available production statistics for the relevant sectors/facilities generating the emissions, and then extrapolated to derive total cadmium emission for the whole nation. The result is shown in Figure 1. Regarding to atmospheric emission, production of non-ferrous metals Zn-Pb and electricity utilities by fossil fuel combustion are the prominent sources of emissions, accounting for 52% and 28% of total Cd emission to air in 1998/99. The basic steel industry, coal mining, Zn-Pb mining, and oil refining contribute 6%, 5.5%, 3% and 3% of total Cd emission respectively. For aqueous emission, production of non-ferrous metals Zn-Pb accounts for 65% of total Cd emission, 15% for sewage & drainage services. The remaining water emissions are from electricity utility (6%), oil refining (5%), basic steel industry (5%), and Zn-Pb mining (3%). For emission to land, electricity utility releases approximately 95% of total emission. Overall, non-ferrous metals production and electricity utilities are major industrial sources for the emission of cadmium to Australian environment in 1998/99. Apart from the weakness of the database stated above, it has been observed that there has been much less reporting of Cd emissions data for water and especially for land to the NPI in 1998/99 than in following years.

3.2 Cadmium Flows in Australian economy

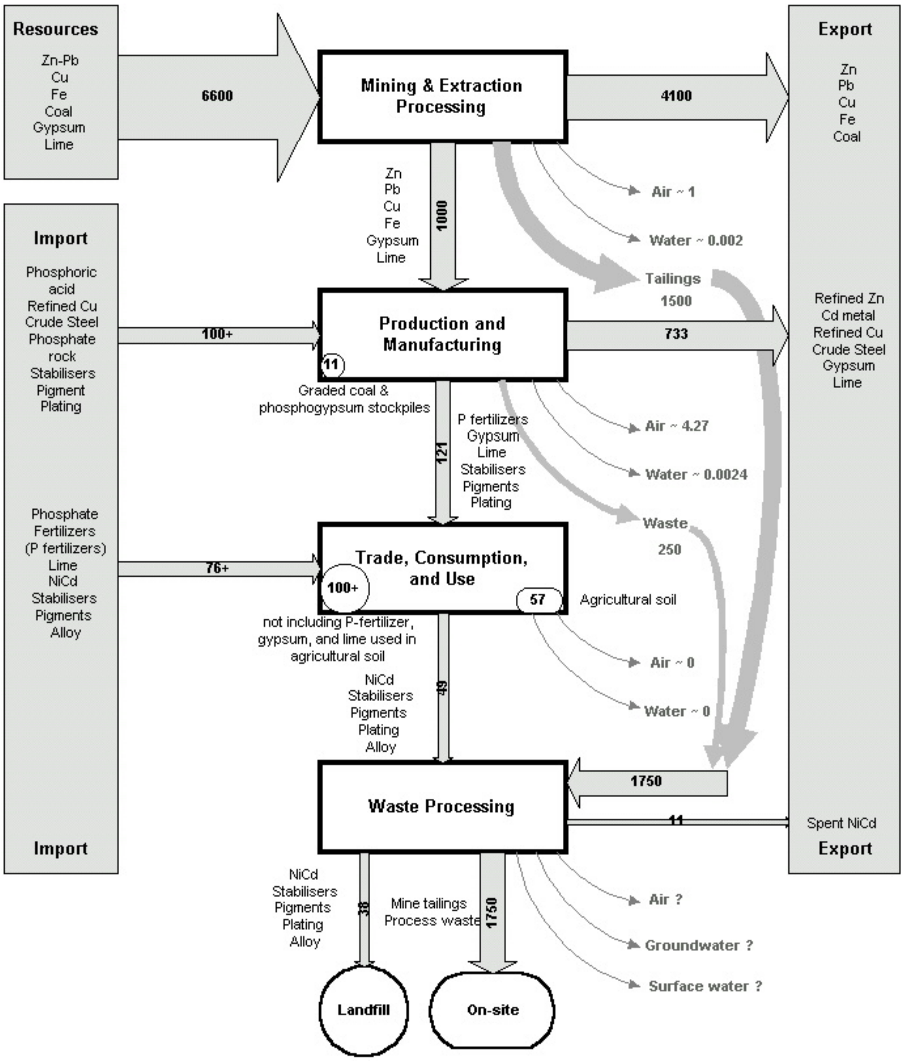
A case study of cadmium in Australia identifies products containing cadmium and their pathways through the Australian economy. A summary of the cadmium flow analysis using SFA method for the Australian economy based on fiscal year 1998/99 is given in Figure 2. Data from a great many sources have been used to complete this picture. The whole economy has been modelled into four main sub-compartments - mining and extraction, production and manufacturing, consumption and use, and waste management. Import and export processes are also included in the diagram as important systems.

The study has primarily considered mining and production of ores relating to cadmium content in Zn, Pb, Cu and Fe. In particular, the main source of cadmium is associated with Zn-Pb ores. The cadmium contained in Zn-Pb ores is generally of sufficiently high concentration that separating and refining it as a by-product of zinc refining is economically feasible. In Australia, refined cadmium is produced at three base metal smelters and refineries, all owned and operated by Pasminco Metals: the Risdon zinc refinery at Risdon, Tasmania; the Cockle Creek zinc refinery and lead smelter at Cockle Creek, New South Wales; and the Port Pirie lead smelter/refinery at Port Pirie, South Australia. Most of ores, in form of concentrates (Zn, Pb, Cu) are exported, and all refined cadmium metals are exported overseas, mainly to Japan for use in further production (Pasminco Metals-Sulphide Pty Ltd 1998).

In addition, goods containing cadmium included in this study can be categorised into two main groups:

Intentional uses include NiCd batteries, stabiliser, pigment, plating, and alloy. All NiCd batteries both sealed and vented types used for household, commercial, and industrial purposes are imported from overseas. Several cadmium compounds such as metallic Cd, cadmium oxide, cadmium fluoride etc. used as raw materials to produce stabiliser, pigment, alloy, or to plate some metals are also mostly imported from overseas. Furthermore, some finished goods such as plastics; especially PVC, plated metals and alloys that contain minor cadmium contamination are imported for trade and consumption in the economy.

Unintentional uses include contamination in phosphate fertilizers, coal, lime, gypsum, and phosphogypsum (by-product). Australia imports phosphate rock and phosphoric acid to manufacture phosphate fertilizer such as single superphosphate and di-superphosphate for agricultural application. Phosphogypsum is a major by-product of phosphoric acid production; approximately 3.7 tonnes of gypsum per 1 tonne of phosphoric acid produced (Department of Secondary Industry 1973). Although phosphoric acid production ceased in early 1990 there are two remaining by-product gypsum stockpiles in eastern Australia, and these are being used to remedy sodic soil. Coal used for combustion for electricity, lime and natural gypsum used for agricultural soil and for construction materials (i.e. plasterboard, cement) also contain minor amounts of cadmium.



Legend: ☐ = sub-compartment ◯ or ▭ = accumulation ⇨ = inflow or outflow

Figure 2. Aggregated cadmium flow in Australian economy, 1998/99 [tonne(s) per year]

The following is a summary of key findings of Substance Flux Analysis of cadmium in Australian economy.

- Cadmium resources in Australia has been linked to zinc, lead, copper, iron, lime, and gypsum, especially to zinc and lead.
- Majority of cadmium has been exported as impurities in Zn, Pb, Cu concentrates, and iron ores
- On-site waste from industrial facilities is a major Cd flow in waste management process (e.g. tailing wastes, slag, coal washery waste, coal flyash etc.)
- Intentional uses of cadmium in certain goods (e.g. batteries, plastic, plating materials) have been discarded to normal household waste landfill. Small amount of Cd in spent NiCd batteries has been sent out for recycling plant in oversea.
- Prominent sources of cadmium emission
  - non-ferrous metals Zn-Pb production
  - electricity utilities by fossil fuel - coal
  - sewage and drainage services
- Construction materials have been found as another important interim sink of Cd in the economy.

3.3 Cadmium Inputs to Agricultural Soils

Agricultural soil is being defined as a part of the economy, and a range of cadmium-contaminated materials have been identified and evaluated for the agricultural application in Australia. Inflows and outflows of cadmium through the agricultural soils have been attempted on an excel spreadsheet. The loadings and accumulation in such soil are extensive, and the cadmium content can be extremely contaminated at some certain areas such as agricultural areas or home gardens nearby Zn-Pb smelter in New South Wales (Cockle Creek), South Australia (Port Pirie), or Tasmania (Risdon). Foodstuff and crops grown on such soils would be concerned as high cadmium-contaminated vegetations. Most human cadmium exposure comes from ingestion of food, and most of that arises from the uptake of cadmium by plants from fertilizers, sewage sludge, manure and atmospheric deposition (WHO 1992). Specifically, this study estimated that the relative importance of various cadmium sources to human exposure via foodstuffs grown on agricultural soil is as follow:

Atmospheric deposition	60%
Phosphate fertilizers	36%
Phosphogypsum (by-product)	1.4%
Lime	1.2%
Sewage sludge	0.8%
Manure	0.3%
Natural gypsum	0.3%

4. USE OF SFA INFORMATION FOR EXPOSURE ASSESSMENT

Exposure assessment is an integral part of health risk assessment process. It evaluates movement of a chemical from its source to a potential human receptor by identifying potential exposure pathways. In moving from its source to a receptor organism, a chemical concentration generally decreases by processes of dilution, dispersion, and degradation and, as a result, a receptor typically receives less than a concentration of a chemical in an environmental medium. The goal is to use the best availability information and knowledge to estimate health risks for the subject population, important subgroups within the population (e.g. children, pregnant women, and the elderly), and individuals at the center and "high end" of the exposure distribution (Graham et al., 1992; Sexton et al., 1992). Using an environmental fate model is one of the approaches to quantify exposure. The most widely recognized and used multi-media mass balance models are those of Mackay (1991; 2001), who introduced the concept of fugacity as a convenient method of describing and quantifying the fate of chemicals in air, water, soil, and sediments.

The results of SFA can feed directly into the exposure assessment. In other words, emissions estimation from SFA study can be used as input parameters for the fate model. Balance differences between input and output of 10% are common and are usually not decisive for the conclusions (pers. comm. Brunner/Moore, via email Feb 2003). To illustrate simulation in the model, the emission rate was nominally given as 1000 kg Cd per year into each media (air, water, and soil) over the region of Australia. The result from the model for understanding of cadmium behaviour in the environment is shown in Figure3.

Cadmium does not degrade at all. Atmospheric deposition to soil leads to a large build-up of cadmium in the soil (approximately 99%), from where it eventually leaches to groundwater and/or surface water to the ultimate sink of sediment, accounting for about 0.5%. It can be seen that output/data generated from the fate model can be used to obtain a qualitative understanding of the fate of cadmium. To obtain quantitative predictions of environmental concentrations (PECs), the next stage of the research will analyse the Cd emission from processes in the Lake Macquarie region, using well-specified point and diffusive emission sources. The ChemCAN model will then be used to predict the concentration of Cd in soil, water, air, and sediment in this region at specific locations. These concentrations will be compared with acceptable concentration of Cd in soil, sediment, and water from Australian and New Zealand Guidelines for Freshwater and Marine Water Quality, and Guidelines for the Assessment and Management of Contaminated Sites to give an indication of whether emissions, over time may exceed these levels. Because of the coarseness of the ChemCan model, lack of detail on area extent and concentration (contours) around emission sources may not give clear conclusions; but indications may be sufficient to identify the need to provide early greater levels of control. Transfer of Cd from these environmental sinks to humans will then be attempted by human health risk assessment.

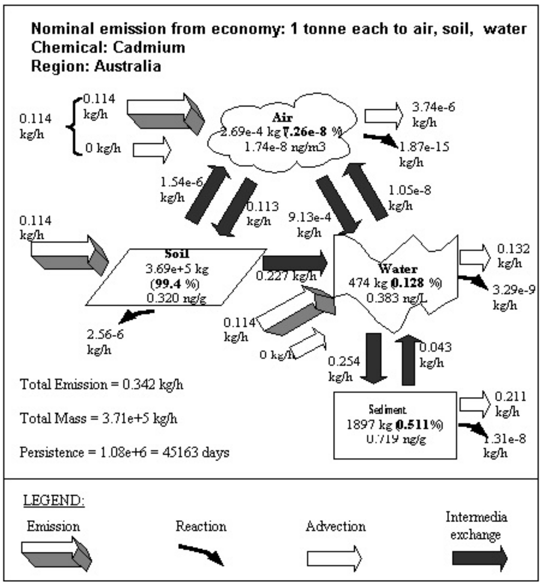


Figure 3. Fate of cadmium in the environment, for an illustrative emission of 1 tonne from the economy to each environmental compartment of air, soil, water.

5. CONCLUSIONS

The current study allows the following conclusions to be drawn:

- In relation to a SFA study, we can understand how cadmium is being used in regional economics, and how it is being dissipated into the regional environment. This covers both intentional and unintentional uses of cadmium
- Besides awareness of cadmium emissions from industrial facilities released into the environment the SFA result shows that most of cadmium in the environment resulting directly from human activities comes from on-site wastes arising from mining and production facilities, use of phosphate fertilizers in agricultural soils and household wastes disposed of to landfill.
- Each separate approach (SFA, Environmental fate model, and human health risk assessment) developed for an environmental management system can supply information for each other in order to gain a holistic view. The final composite of information can provide a more comprehensive understanding on how to achieve sustainability via implementation of environmental management systems at facility and regional scales.

6. ACKNOWLEDGEMENT

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