Available online at www.sciencedirect.com
ScienceDirect
Journal of Cleaner Production 15 (2007) 849–861
Journal of Cleaner Production
www.elsevier.com/locate/jclepro

Spatial characterisation of multi-level in-use copper and zinc stocks in Australia

D. van Beers[1], T.E. Graedel*

Centre for Industrial Ecology, School of Forestry and Environmental Studies, Yale University, 205 Prospect Street, New Haven, CT 06511, USA

Accepted 21 June 2006
Available online 8 September 2006

Abstract

A methodology has been developed to characterise the in-use stocks of copper and zinc at a variety of spatial levels. The approach employs representative concentrations of copper and zinc in their main in-use reservoirs (which account for virtually all the metal put into service) together with geographic information system (GIS) data sets of the spatial locations and densities of these reservoirs. The authors have applied this methodology to Australia at four spatial levels: central city, urban region, states/territories, and country, to produce what is believed to be the first multi-level spatial characterisations of the in-use stocks of technological materials. The results are presented quantitatively and as a series of stock density maps for Inner Sydney, Sydney Metro, all Australian states/territories, and Australia itself. The total stocks in Australia are estimated at about 4.3 Tg Cu (4.3 thousand million kg) and 3.8 Tg Zn (3.8 thousand million kg), or about 240 kg Cu/capita and 205 kg Zn/capita. A statistical analysis of the data shows that the metal stock density at a given spatial level is largely determined by a small number of high-density components at the next lower level. The spatial analysis of the in-use stocks indicates that 50% of all copper and zinc stock resides in just 10% of Australia's local government areas. The largest stocks occur in large urban regions, which can contain copper and zinc densities more than a hundred times higher than rural areas. These regions are expected to be major Australian "metal mines" in the future.

Keywords: Australia; Copper; Zinc; Exploratory spatial data analysis; Geographic information systems (GIS); Resource management; Stocks

1. Introduction

Questions related to pattern and spatial level have become central to discussions in biological ecology that relate to population biology and ecosystems science [1,2]. The inherent challenge is to develop a quantitative understanding of how properties or actions at one spatial level generate the signature properties, patterns, or actions that are perceived at levels higher or lower. It has been historically difficult to address these issues in any detail, because suitable multi-level spatial data sets have been rare. With the advent of geographic information systems (GIS) and the analysis of GIS data by the methods of exploratory spatial data analysis [3,4], however, progress can now be demonstrated for insects [5], seabirds [6], and trees [7], to name a few examples. The approach has also been applied to vector-borne diseases [8], an arena where nature and humans interact. Here the authors applied a similar philosophy to a wholly anthropogenic system: that of in-use copper and zinc stocks in Australia.

Why is it of interest to spatially characterise an anthropogenic system? The basic reason is that there is little understanding about the spatial patterns of the human use of resources. Historically, the material use by our technological society has been largely based on virgin stocks (mineral deposits). For a number of reasons, these stocks may in future become inadequate or unavailable at various times and locations. At present, Australia exports more copper and zinc than it uses domestically [9,10]; it could change that pattern if desired. However, other than virgin reservoirs exist: these

* Corresponding author. Tel.: +1 203 432 9733; fax: +1 203 432 5556.
E-mail addresses: d.vanbeers@curtin.edu.au (D. van Beers), thomas.graedel@yale.edu (T.E. Graedel).
[1] Present address: Centre of Excellence in Cleaner Production, Curtin University of Technology, GPO Box U 1987, Perth, WA 6845, Australia. Tel.: +61 8 9266 3268; fax: +61 8 9266 4811.

0959-6526/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jclepro.2006.06.022

resources are principally contained in products stored or discarded over the years by corporations and individuals. These reservoirs, designated by Jacobs [11] as the ‘‘mines of the future’’, could become important over the next few decades as a result of rapid population growth and increasing per capita resource use. As yet, however, there is rather little quantitative information on their total abundance and distribution [12].

Three pieces of information are required to consider mining a resource from any reservoir, natural or otherwise: how *much* (a) of the resource is present, in what *form* (b), and at which *locations* (c)? Once this quantitative and qualitative information is known, the costs of recovery and processing can be examined. These costs can be compared to the anticipated market price, and a decision on whether or not to proceed can thus be made. In this way, the authors are following the common practice in resource geology of locating and quantifying virgin resources, but applying the approach instead to secondary resources.

One can argue that scrap merchants are already aware of their scrap metal sources in terms of available quantities and locations, and which infrastructure projects are up for renovation or demolition in the future. However, the value of the work presented here lies in the multi-level scale of the study (scrap metal merchants tend to operate at a local level) and the fact that other actors (such as metal processing/recycling facilities and governmental policy makers) are unaware of the resources that are literally stored under their feet and in their direct living environment. Without claiming total accuracy and completeness of the results, it is hoped that the presented case-study results offer knowledge to the recycling, mining and mineral processing sector that was previously not available. Additionally, the study results might assist in assessing the technology requirements and sustainability framework that should be in place to recover future scrap metals from currently stored product in a techno-economic feasible way.

This paper draws on a methodology developed for Cape Town [13] and Sydney Metro [14] to characterise in-use copper and zinc, and is applied at several different spatial levels in Australia. The authors are not aware of another study of in-use stocks of any resource that utilises a combination of GIS and exploratory spatial analysis. Paper II of this series [15] reports on the potential quantities of discarded copper and zinc resulting from the in-use stocks presented in this paper, and the policy options for metal recycling that this information implies.

Table 1
Units conversion

Scientific units (used in this paper)	Engineering units (commonly used by industry)
1 Megagram (Mg)	1 thousand kilograms 1 metric tonne 10^6 grams
1 Gigagram (Gg)	1 million kilograms 1000 metric tonnes 10^9 grams
1 Teragram (Tg)	1000 million kilograms 1 million metric tonnes 10^{12} grams

Copper and zinc were selected as case-study metals because both metals are of interest to both resource economists and environmental scientists. They have been widely used for millennia, and are stored in several different chemical and physical forms. They are also materials that may eventually be supply limited, at least at low contemporary prices [16,17]. If desired, the presented approach can be applied to other metals as well.

Australia was chosen as a geographical area for a detailed assessment of the copper and zinc stocks in Oceania. Australia is the largest country in the Pacific, covers an area of 7.6 million square kilometres, and has a population of 19.2 million [18]. The gross domestic product (GDP) per capita is about 22,000 US$, with a predicted growth rate of approximately 2.5% for the coming years. The economic sectors in Australia are services (71% of GDP), industry (26% of GDP), and agriculture (3% of GDP). Australia is a developed economy with a high standard of living, and thus representative of other developed economies where in-use stocks of metals are likely to be significant; this case-study can therefore produce evidence of usefulness and generalisability in other socio-geographical contexts. The ready availability of the data required to examine the feasibility and usefulness of our approach makes this region particularly attractive.

The scientific units used in this paper are shown in Table 1.

Table 2
Specification of the copper reservoirs

Reservoirs	Copper-containing products	End-use fraction (%)[a]	Estimated residence time (years)
Building and construction	Building wire and copper tube	50	30–50
Infrastructure	Copper cable used by telecom utilities and power utilities	22	30–40
Transportation	Automotive equipment, railway equipment, ship building, aviation	5	20–40
Consumer durables	Appliances and extension cords, consumer electronics, fasteners and closures, household products, ordnance	5	20
Business durables	Business electronics, lighting and wiring	10	25
Industrial durables	Industrial (in-plant) machinery and equipment	8	25

[a] Baume P, Copper Development Centre, Sydney, Australia. Personal communication with D. v. Beers. 2003.