In-Use Stock of Copper Analysis Using Satellite Nighttime Light Observation Data*1

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We have developed a novel methodology for analyzing the worldwide copper stock-in-use by using nighttime light images. Radiance calibrated nighttime light imaged data (RCD) for the entire world has been assembled from the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) by the National Geophysical Data Center. It has been recognized that the intensity of nighttime light is strongly associated with such aspects of human settlement as population density and energy consumption. We assumed that the presence of light implies the use of electrical conducting material, namely copper. The stock-in-use data for copper in Japan, North America, Australia and China were obtained from previous material flow analysis studies. We analyzed the relationship between light accumulation and the size of the copper stock in those countries. A significant correlation was found and the feasibility of this method was confirmed. We employed this method to analyze the stock-in-use in other Asian countries. The in-use stock of copper was correlated with the gross domestic product (GDP).

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Keywords: resource recycling, copper stock, defense meteorological satellite program/operational linescan system, satellite, remote sensing, nighttime light image

1. Introduction

An understanding of material flow is needed if we are to build the most appropriate collection system and then accelerate the recycling of resources. Material flow analysis (MFA) and substance flow analysis (SFA) have been used to analyze the social material flow. The world-scale material flows with respect to copper,1–3) silver,4) chromium5) and iron6,7) have already been reported as MFA/SFA case studies. Recently, the dynamic MFA/SFA model has been attracting attention because information about past stock and flow are important in terms of resource conservation. Therefore, there have been various reports related to the dynamic flow analysis of materials and substances including lead,8) iron9,10) nickel,11) copper,12,13) aluminum,14,15) and stainless steel.16) The reports provide a dynamic depiction of a material cycle system. The amount of waste and its collection were estimated, and the emissions into environment were visualized. The lead stock in the Netherlands,8) the steel stocks in Japan10) and the USA,17) and the copper stocks in the USA18) and northern America18) were quantified because the material stock-in-use constitutes the second resource. Moreover Gordon et al. discussed the sustainability of metal consumption based on a metal stock analysis.19)

In MFA/SFA, stock-in-use estimation methods can be classified roughly into top-down and bottom-up approaches. The top-down method consists of estimating the material stock-in-use in society, based on production figures and/or input-output tables for each material and the lifetime distribution of the end products. Most previously reported material flow analyses have been undertaken using this top-down method. By contrast, the bottom-up method involves estimating the material amounts included in products by multiplying the number of end products and their compositions. For example, G. Xueyi reported a case study related to Chinese copper that employed this bottom-up method.20)

However, in developing countries where public data tend to be scattered, stock-in-use estimation is difficult with both the top-down and bottom-up methods.

This study considers the close relationship between the light at night and human activity. The obtained nighttime light images were processed at National Ocean and Atmosphere Administration (NOAA)’s National Geophysical Data Center using Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) data collected by the US Air Force Weather Agency. Recently, nighttime light images have attracted considerable attention, and they are reportedly related to energy consumption and such economic activity indicators as Gross Domestic Product (GDP).21,22) The copper stock-in-use appears to correlate closely with the strength of nighttime light. Artificial light requires electricity and copper is used in electric cable. However, the relationship between light accumulation and the copper stock-in-use has not been reported. The nighttime light image data covers the entire world. Therefore, the copper stock-in-use can be estimated even for countries for which there are no published data. A novel method for estimating copper stock-in-use by using nighttime light has been developed and is reported here.

2. Method

2.1 Estimation of copper stock

The nighttime light images were divided into those for countries and those for areas. Light intensity distribution

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maps were drawn by using histogram analysis. The accumulation of light (Illuminated Urban Area (IUA) dome volume) defined by eq. (1) was estimated.

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\text{Light accumulation} = \sum (\text{light intensity} \times \text{number of pixels}) \quad (1)
\]

An example analysis is shown in Fig. 1. The copper stock data were gathered from existing studies. The relationship between the accumulations of light and the copper stock was plotted.

2.2 Used data

2.2.1 Nighttime light image data

The radiance calibrated nighttime lights image data (RCD) produced by C. D. Elvidge in March 1996 and in January and February 1997 were used, and they were based on the DMSP/OLS data. In the RCD, nighttime light images with different gains overlapped and the influence of sensor gain fluctuation was eliminated. The accumulation of light was estimated without luminance saturation. The information regarding the amount of light is correlated with geographic data thus making it possible to analyze a country and/or an area. For example the light accumulation was estimated using RCD data, and a positive correlation with population and electricity consumption was reported. The RCD data can be used as an indicator for estimating economic activity across the globe.

2.2.2 Copper stock-in-use

D. van Beers et al. estimated the copper stock of Australia and Australian provinces by multiplying the concentration of copper by the product volume. S. Spatari et al. estimated the North American copper stock by using a substance flow analysis based on the dynamic modeling method. I. Daigo et al. estimated the Japanese copper stock by using a population balance model. G. Xueyi estimated the material flow of copper in China and we estimated the Chinese copper stock using their results. The copper stock-in-use of the world, Switzerland and Sweden were estimated based on the stock/capita values reported by D. van Beer et al. Table 1 shows the in-use stock of copper, year and reference. An average value was used when there were multiple data sources. The year of publication is shown when the year the data were collected is unknown.

### Table 1 In-use stock of copper.

<table>
<thead>
<tr>
<th>Region</th>
<th>Copper stock, $S/Gg$</th>
<th>Year</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>284000*</td>
<td>2001**</td>
<td>D. van Beers23)</td>
</tr>
<tr>
<td>North America</td>
<td>70000</td>
<td>1999</td>
<td>S. Spatari18)</td>
</tr>
<tr>
<td>USA</td>
<td>77605*</td>
<td>1999**</td>
<td>D. van Beers23)</td>
</tr>
<tr>
<td>Japan</td>
<td>19000</td>
<td>2000</td>
<td>I. Daigo20)</td>
</tr>
<tr>
<td>China</td>
<td>11000</td>
<td>2000</td>
<td>G. Xueyi20)</td>
</tr>
<tr>
<td>Australia</td>
<td>4300</td>
<td>2000</td>
<td>D. van Beers23)</td>
</tr>
<tr>
<td>Switzerland</td>
<td>1600</td>
<td>2003**</td>
<td>D. van Beers23)</td>
</tr>
</tbody>
</table>

*Average value
**Publication date

3. Relationship between Light Accumulation and Copper Stock-in-Use

3.1 Relationship between light accumulation and copper stock-in-use at country level

Figure 2 shows the relationship between the accumulation of light and copper stock-in-use for Japan, North America, China, Switzerland, Sweden, the USA and Australia. The strong correlation ($R^2$ was 0.99) between the accumulation of light and the in-use stock of copper suggests that this estimation method can be used at the country level.
3.2 Relationship between light accumulation and copper stock-in-use for Australia

To verify the copper stock-in-use estimation from the accumulation of light for a small area, the relationship between the light accumulation and the copper stock-in-use for each Australian province\textsuperscript{25} was analyzed. Figure 3 reveals that there was a strong relationship (R\textsuperscript{2} = 0.97), and the feasibility of this method was thus confirmed.

3.3 Application of method to Asian countries

Next we estimated the copper stock-in-use of Asian countries whose stocks are unknown and where few data have been published. The approximation formula shown in section 3.1 was used to estimate the copper stock-in-use. Table 2 shows the results.

Binder \textit{et al.} analyzed the flow of copper in 1994 for 50 countries and revealed the strong relationship between the copper stock and the gross domestic product (GDP) per capita (purchasing power parity, PPP).\textsuperscript{25} The relationship between the estimated copper stock-in-use and the GDP (on the basis of PPP) per capita was analyzed and is shown in Fig. 4. A linear relationship (R\textsuperscript{2} is 0.58) was obtained. Binder analyzed the flow for one year and we analyzed the stock-in-use. Nevertheless, we both obtained the same positive relationship between the stock and the GDP (PPP) per capita.

4. Conclusions

It has been revealed that the nighttime light observed by satellites and the in-use stock of copper are closely correlated. A new bottom-up estimation method has been developed. This method can be used to estimate the in-use stock both at the country and province level. This method was used to estimate the copper stock-in-use of Asian countries, and the estimated value exhibited a strong relationship with GDP per capita. This shows the same tendency as a study that reported a close correlation between copper flow and GDP per capita. As the next step, the estimated stock-in-use of copper will be verified using another method, and the applicability of this new method to other materials will be investigated. Furthermore the feasibility of applying this method to other materials stock will be investigated.

Acknowledgement

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REFERENCES

24) http://www.ngdc.noaa.gov/dmsp/download_rad_cal_96-97.html