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Material stock's overburden: Automatic spatial detection and estimation of domestic extraction and hidden material flows

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ABSTRACT

Anthropogenic material stocks are expanding at ever-increasing rates across the world, and their environmental and economic impacts draw more and more attention from academia, policy makers, and economic and environmental bodies. As the knowledge base regarding anthropogenic material stocks expands, it is important to not only comprehend the societal side of material stock growth but also its counterpart to the material balance—the natural environment from which the materials used for stocks come from. However, due to difficulties of data procurement, and muted interest in materials which are considered low-value high volume, the environmental burdens related to construction minerals have received less attention so far despite the huge amounts involved. In this study, we employ geographic information systems (GIS) with digital elevation model (DEM) datasets, to form an automated method of detection and measurement of the anthropogenic disturbance of soil and earth at excavation and mining sites, which accounts not only for the material extracted for usage in the anthroposphere, but also its related unused extraction. This geographically explicit method allows to directly pinpoint the location and volume of anthropogenic disturbance. Using Japan as a case study, the results suggest that the ratio of unused extraction to used extraction may exceed 1:1 for construction minerals in Japan. We also find that the environmental effects of anthropogenic activity are bigger than natural soil disturbance by several orders of magnitude, highlighting the need to reduce raw material extraction and increase the efficient use of the existing material stock.

1. Introduction

Research into societal in-use material stocks has been on the rise in recent years. There is an ever-increasing base of knowledge regarding the dynamics of stock growth and related flows (Müller, 2006; Fishman et al., 2014, 2016; Wang et al., 2015), the material composition of stocks (Hu et al., 2010; Marcellus-Zamora et al., 2015; Ortlepp et al., 2015), the spatial distribution of stocks (Tanikawa and Hashimoto, 2009; Hsu et al., 2013; Rauch, 2009; Reyna and Chester, 2014; Tanikawa et al., 2015), the relations of material stocks with economics, energy, and CO2 emissions (Allwood et al., 2012; Fishman et al., 2015; Müller et al., 2013; Pauliuk et al., 2015; Pauliuk and Müller, 2014), and the life cycles of stocked materials (Ciacci et al., 2015; Daigo et al., 2015; Kapur et al., 2008; Liu and Müller, 2013; Pauliuk et al., 2013). Studies of the material flows of nations uncover that in terms of mass large shares – in many cases more than 50% – of the materials consumed yearly by human society are materials that become part of the anthropogenic material stock (Adriaanse et al., 1997; Schandl and Schulz, 2002; Weisz et al., 2006; Schandl and West, 2010, 2012; West and Schandl, 2013; Singh et al., 2012; Krausmann et al., 2009, 2014, 2016; Gierlinger and Krausmann, 2012), including metals, timber, and plastics, and most predominantly minerals for construction such as aggregate, sand, bitumen, and cement. In recent years the global amount of construction minerals entering the economy has reached about 35 billion tonnes per year, or around 5 t per person per year, although there are large discrepancies among countries: in China the figure is over 13 t per year per person, while in Africa the per-capita average is only about 1.5 t per year (Miatto et al., 2016, early review).

The material balance principle at the foundation of material flow and stock accounting states that as the anthropogenic in-use material stocks increase, natural stocks decrease at an equivalent amount. However, for every unit of material that enters the economy, there is a certain amount of material which was mined, quarried, excavated, moved, or otherwise disturbed during the pro-

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curement of the wanted material but has no economic function and remains in nature, albeit in an altered state. This material, termed overburden, hidden material flow (HMF) (Adriaanse et al., 1997), or unused extraction (Eurostat, 2001) has long been recognized to be of the same order of magnitude as the used extraction (Matthews et al., 2000). It acts as an indicator of the ecological stresses associated with material extraction, which include alterations to the landscape, changes in land cover and the water system, as well as impacts on biodiversity and animal habitats. Specifically in the case of the construction industry, resource extraction, cut-and-fill for residential development and construction for buildings and social infrastructure generate large scales of geomorphological changes (Tamura, 2012). This rapid anthropogenic disturbance causes destruction of the natural environment, and it is accelerated by technical innovations in industrial fields and ongoing demands for construction materials and mineral resources.

The indicator of total material requirement (TMR) was instituted to account for both used and unused material flows (Bringezu et al., 2004; Eurostat, 2001). Nevertheless, since the focus of recent advancements in the field material stocks, as cited above, have been on the socio-economic angle of material stock balance, the side of the natural environment has been somewhat neglected. This may be due to the ubiquity of construction minerals and their relatively small apparent ratios of used-to-unused materials as compared with materials such as metals and precious minerals, but the main reason for this is probably difficulties related to data procurement. While the materials consumed by society are commonly accounted for economic reasons, and the in-use stocks can be identified and counted through bottom-up, top-down, and other methods (Müller et al., 2014; Tanikawa et al., 2015), there is less data available for the unused material. Often indirect accounting methods are used, such as coefficients (Bringezu and Schuetz, 2001) and ratios of overburden to useful material (e.g. Douglas and Lawson, 2000) calculated from specific case studies, but these have very high variances both spatially and temporally – different locations have different mineral and chemical soil compositions, and mining and quarrying sites get depleted over time increasing their ratios, adding to the uncertainties of such indirect methods. While these issues are common to other material categories such as metals and industrial and precious minerals, the decentralization and ubiquity of the construction mineral excavation industry makes data collection even more difficult.

Although construction minerals are of low economic value and have relatively lower used-to-unused ratios compared to other materials, due to the sheer amounts of construction materials consumed the overall environmental effects are prominent and there is a growing need to accurately account and analyze the anthropogenic disturbance (AD) caused by the societal accumulation of stock of construction minerals. The extraction of materials leaves clear physical alterations of excavation and mining sites. Analysis of these geomorphological changes enables to directly measure the anthropogenic disturbances caused by ongoing demands for societal material stocks. In this study we introduce an automated method to detect anthropogenic disturbances by identifying the unique characteristic geomorphological changes of excavation sites and open-pit mines in contrast to natural disturbances of soil. We employ this novel method on the entirety of Japan in order to gain a direct measurement of the anthropogenic disturbance in the country. Japan makes a good case study for this method, since the contemporary domestic extraction of materials in the country is almost entirely limited to construction minerals from excavation and quarrying. Active underground mines or wells, which would not be detectable through surface change methods, are virtually nonexistent. These anthropogenic disturbances (AD) include both the used extracted material (domestic extraction, DE in MFA parlance) and the unused extraction (HMF). Thus the anthropogenic disturbances detected and mapped with our method can be easily related to the official DE (used extraction) statistics, and the difference between the two can be assumed to account for Japan's hidden material flow. Throughout the study we refer to our estimations as anthropogenic disturbances related to construction and not as the TMR of construction materials in order to differentiate between the methods used to calculate each, and we discuss these differences in the discussion section.

2. Data and methods

2.1. Research approach

Disturbances and impacts to the ground surface are commonly studied using topographic maps, aerial photos and field surveys, and recently the development of remote sensing technology and Geographic information systems (GIS) promoted the use of three dimension models (Ross et al., 2016). GIS and specifically elevation maps, referred to as Digital Elevation Models (DEM), facilitate direct measurements of geomorphological changes by comparisons of changes in elevation and other geomorphological attributes over time. DEMs are made from several data sources such as satellite data, aerial photos, and contour maps. The original data selection depends on the purpose of DEM usage. Aerial photos and contour maps are suitable for reproducing old geomorphology, but their coverage is limited compared to satellite data. For instance, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) Global Digital Elevation Model and ALOS (Advanced Land Observing Satellite) World 3D – 30 m are DEM datasets created from satellite data and their coverage is almost the entire planet. However, their resolution and elevation accuracy is lower than DEM created by aerial photos (Japan Space Systems, 2012; Remote Sensing Technology Center of Japan, 2016).

Table 1 presents recent examples of DEM-based studies of geomorphological changes. DEMs have been used in various fields such as agricultural science, environmental science, geography and geology. Land slide and erosion are known as natural disturbances which cause geomorphological changes. in the field of disaster prevention and environmental science, not only the geomorphological information but also important information of landslides, such as their causes, dynamics and impacts are explored by using DEM (Shimizu et al., 2008; Quan and Lee, 2012; Shahabi and Hashim, 2015). Especially, visual interpretation and the analytic hierarchy process (a theory of measurement through pairwise comparisons in order to assess the relative weight of multiple criteria and to derive priority scales) are commonly used for locating the natural disturbance site and landslide susceptibility site (Satty, 2008; Quan and Lee, 2012). These methods have been employed successfully for identification of natural disturbances such as landslides and erosion in medium to large spatial scales of regions, yet for anthropogenic disturbances studies have been so far limited to measurements of small spatial regions such as single mining or excavation sites due to the time-consuming activity of identifying locations of AD (Tanikawa and Imura, 2001; Kawahara and Tanaka, 2010; Sugimoto et al., 2015; Ross et al., 2016). Worthy of special mention is that the analytic hierarchy process (AHP) which would be a suitable method for locating natural disturbances has not been applied to detect anthropogenic disturbances.

Fundamentally, anthropogenic disturbance is calculated by a comparison between two periods of time of the changes in elevation in a site of mining or excavation, in effect measuring the volume of earth moved at the site. However, this method would also detect natural disturbances of soil. In previous studies (Yoshida et al. under review), a site of anthropogenic disturbance had to be known in advance or manually identified and then its geomorpho-