学 位 論 文 内 容 の 要 旨/Dissertation Abstract

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学 位 論 文 題 名/Title of Dissertation

Region-wide estimation of landfill volume changes due to waste disposal, using global digital elevation change maps and landfill location datasets

（地域広域における埋立容量の変化推定：全球版標高差図と埋立地データセットの活用）

Often countries don't have adequate systems in place to measure and centrally report waste disposal statistics, yet such data are necessary to inform waste policy and government resource allocation, estimate waste-sector carbon emissions, and are used in some indicators for the Sustainable Development Goals. Waste disposal statistics here refers measures such as the tonnages of waste disposed in landfills, change in available landfill airspace, the proportion of waste diverted from landfills, the proportion of total waste generated that is collected and managed, etc. Satellite remote sensing has been flagged as a potential approach to help address waste sector data shortages, for example by remotely measuring the amount of waste dumped in landfills. The appeal of such a tool would lie in the ability to remotely and centrally collect waste dumping statistics for entire regions of interest where reported data are missing or unreliable – which could be feasible considering the often global coverage of satellite data products. However, previous studies that investigated the measurement of waste dumping by satellite remote sensing data reported large measurement uncertainties, and were only applied to a small number of case-study landfills (e.g., two or three). Past studies generally used synthetic aperture radar data, coupled with repeat-pass radar interferometry to generate elevation models of target landfill sites at different time points, and then calculated landfill volume changes between those time points. However, due to quick surface changes in landfill sites caused by daily waste disposal and redistribution by compactor vehicles, interferometric processing was strongly affected by a phenomenon known as 'temporal decorrelation', leading to low coherence and large elevation uncertainties in produced elevation maps. However, since the completion of prior studies, missions such as the Tandem-X satellite pair have made bistatic synthetic aperture radar data publicly available, which is not affected by temporal decorrelation during interferometric processing, and also has global coverage. This thus represents an opportunity to revisit the landfill-dumping measurement problem and address issues identified in earlier work. However, even if a measurement technique could successfully be presented, the extent to which it could be scaled up and used as a tool to collect dumping data over large regions depends entirely on the availability of corresponding landfill location datasets, since landfill locations and perimeter needs to be known before volume changes in the landfill can be measured by remote sensing. Yet, the current availability of landfill location across the world, and the characteristics of the data is still unreported, deeming it difficult, at the outset, to even gauge the possible scope of such a method's usability. Therefore, to promote more complete collection of global waste disposal statistics, this study had two primary research aims: firstly, to evaluate the global availability and quality of landfill location data, since landfill locations need to be known before volume changes can be estimated by remote sensing; and secondly to propose and evaluate a new remote sensing approach for estimating dumping in landfills that has potential to be applied globally, and that has higher accuracy than previous work – achieved by using bistastic synthetic aperture radar derived elevation data.

To address the first aim, a global inventory of publicly available landfill location datasets was compiled and assessed in terms of their data formats, facility types included, number of facilities, etc. The compiled datasets and their attributes are presented, along

with maps showing their global spatial footprint. Government compiled datasets were available for 64 countries, and some sub-national jurisdictions, yet these were mostly in the "Global North", while many developing countries had no landfill location data, especially in Africa, the Middle east and Southeast Asia. OpenStreetMap has the largest landfill location dataset (exceeding 51,000 landfills), but global coverage was nevertheless low, with 49% of 11,541 cities not having any reported landfills in a 30 km vicinity. And, by comparing OpenStreetMap to reference landfill location datasets from around the world (7,132 reference landfills in total) it was found that overall, only 37% of reference landfills were represented in the OpenStreetMap data – indicating low data completeness. Further, 50.7% of OpenStreetMap sites don't have any descriptive information – such as the type of facility or its name – making it difficult to use this data in other analyses.

To address the second aim, a landfill volume change measurement method was proposed that relies on elevation change data from the TanDEM-X satellite mission. In short, measured elevation changes are translated to volume change by multiplication with pixel area size, and the time stamp of the elevation data are used to calculate the rate at which volume changes occur. Waste mass disposed in the landfill is then estimated by multiplying volume changes with an estimate of the density of waste in the landfill. The remotely estimated volume changes had high agreement with in-situ measured data from selected case study landfills in Columbia (97% agreement) and Hong Kong (93% agreement[1]). However, scaling the analysis to 100 landfills around the world showed that temporal coverage of the data product varies between regions, and for 24% of considered sites only a single change measurement could be estimated using the proposed approach. Further, it was observed that the length of time between consecutive elevation measurements is inversely proportional to the error in the volume change estimate. This means that if an application requires higher landfill volume change measurement frequency, there will be a more stringent requirement on the vertical accuracy of input elevation data to achieve the same final volume change accuracy. A code module was developed to enable batch processing and calculation of landfill volume change for many landfill sites simultaneously.

A further case study was used to demonstrate how this proposed technique for estimating waste dumping could supplement existing waste reporting infrastructure, and to assess limitations of the method in an operational setting. The proposed method was applied to all the landfills in South Africa's metropolitan municipalities, and municipality level waste disposal to landfill was estimated and compared to government reported statistics. Measured volume changes had $r = 0.86$ correlation with reported waste mass in 7 reference landfills, and estimated annual waste mass going to landfills at the municipality level had high correlation ($r = 0.92$) with government reported statistics.

The thesis's overall contributions were (1) to show that landfill location data is currently unavailable for many regions, restricting the application of remote sensing based landfill monitoring in those areas; and thus indicating that relevant authorities need to prioritise landfill location data collection and promote public sharing in interoperable data formats. (2) A new approach to measuring landfill volume changes by remote sensing was successfully proposed, which can assist collection of landfill dumping data for currently underreported regions. Further, the method's limitations and possible solutions are clearly presented, to guide further work.

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[1] Assuming the same waste density as reported for the Columbia landfill, since the Hong Kong landfill statistics report tonnages, and the relation between tonnage and volume change is not mentioned in the official statistics.