学 位 論 文 審 査 の 要 旨

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学 位 論 文 題 名

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）

Many countries lack adequate systems to track and report waste disposal statistics—data crucial for policy, resource allocation, carbon emission estimates, and monitoring Sustainable Development Goals. These statistics include landfill tonnage, airspace changes, waste diversion rates, and collection efficiency. Satellite remote sensing has been identified as a potential solution for monitoring landfill dumping at scale, especially in regions with unreliable or missing data. However, previous approaches using repeat-pass SAR interferometry were limited by temporal decorrelation, resulting in large uncertainties and applicability to only a few case-study sites.

The introduction of Tandem-X single-pass SAR interferometry overcomes this limitation by providing globally consistent elevation data unaffected by temporal decorrelation. Yet, the method's scalability depends on the availability of accurate landfill location data—currently unreported at the global level. This study addresses two key gaps: (1) assessing the global availability and quality of landfill location datasets, and (2) proposing a more accurate and scalable method for estimating landfill dumping using bistatic SAR elevation data, offering improved potential for global waste monitoring.

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 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). 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 examination committee acknowledges that this thesis contribution is significant and provide a methodological framework (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 landfills dumping data for currently underreported regions. In addition, Mr. Louw Albertus Stephanus maintained a strong academic record throughout his Ph.D. studies and publications. Based on this evidence, the committee concluded that he is eligible for the degree of Doctor of Philosophy in Environmental Science.