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GreenRoofNet: Integrating High-Resolution Aerial Imagery with Deep Learning for Efficient Green Roof Monitoring

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Background: Urban environments are increasingly recognized as both significant contributors to and primary victims of climate change. Buildings in urban settings are responsible for approximately 33% of global greenhouse gas emissions, while cities themselves are often situated on fertile land with high carbon sequestration potential. To mitigate these impacts on climate, adopting nature-based sustainable technologies is essential for developing climate-smart cities. Among these, green roofs have emerged as a critical solution for climate change mitigation.

Significance of Green Roofs: Originally designed for stormwater management, green roofs have demonstrated effectiveness in various environmental aspects. They mitigate urban heat island effects, reduce sound and air pollution, lower building energy consumption, enhance biodiversity, and have the potential for carbon sequestration. Recognizing these benefits, Toronto implemented a by-law in 2009 mandating green roofs on all new large buildings with flat roofs larger than 2,000 m², complemented by incentives for the private sector. Despite the increase in green roof installations, there is a lack of efficient monitoring, leading to concerns about maintenance and compliance.

Challenges in Monitoring: The absence of an efficient green-roof monitoring system is a widespread problem. Traditional monitoring techniques face limitations, including on-site inspections and satellite imagery analysis. High-resolution satellite data are costly, while freely available images (e.g., from Landsat) lack the necessary resolution for small-scale green roof analysis. This gap highlights the need for an efficient, automated, and accurate green roof monitoring system.

Methods: To address this need, we developed an automated, deep-learning-based toolbox (*GreenRoofNet*) for monitoring green roofs using high-resolution (8 cm) orthoimages collected by the City of Toronto for other purposes. We segmented these images into 299x299 pixel tiles with a 20% overlap to ensure comprehensive coverage, particularly of smaller green roofs. Using 500 labeled images for training and validation, and the remainder for testing, we employed the Inception v4 architecture in TensorFlow. This deep convolutional network model was selected for its ability to extract detailed features crucial for accurate green roof detection. The model training involved a cross-entropy loss function, an Adam optimizer, and a dynamic learning rate, with a 50-epoch limit and early stopping to prevent overfitting. Post-processing of tiles was conducted using maximum confidence scores to amalgamate overlapping detections.

Results and Implications: The model has successfully identified green roofs with approximately 95% accuracy and detected their boundaries with about 90% precision. Preliminary analysis reveals that a segment of Toronto's green roofs is undergoing degradation, whereas a substantial proportion remains in good condition, with a smaller segment being currently undetectable or missing. Further testing is underway, with plans to package the results of this project in a web application featuring an open-source map. This tool will play a pivotal role in assessing the effectiveness of the green roof by-law, aiding in the verification of subsidies, guiding the maintenance of green roofs, and facilitating the estimation of their environmental benefits.