International Exchange and Innovation Conference on Engineering & Sciences
Kyushu University, Fukuoka, Japan

Empowering Sustainability: Innovative Deep Learning and Remote Sensing Solutions for Urban Monitoring and Sustainable Development

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Abstract: *This study advocates for the innovative use of advanced deep learning and remote sensing technologies in monitoring urban dynamics to enhance our understanding of the environmental implications of urbanization and formulate strategies for sustainable land management. Leveraging the potential of these technologies contributes to the realization of sustainable development goals (SDGs), nurturing the growth of sustainable and resilient cities for the future. Focused on mapping land cover and change detection in Greater Cairo, Egypt, the study employs Sentinel-2 imagery and convolutional neural networks (CNNs). The CNN model, trained on the BigEarthNet dataset with transfer learning using a pre-trained U-Net model, reveals significant land cover changes, particularly in Greater Cairo's eastern region due to the construction of the New Administrative Capital. These findings contribute to the advancement of urban monitoring and its applications in fostering sustainable development.*

Keywords: Monitoring; Urban Expansion; Deep Learning; Remote Sensing; Sustainable Development, Cairo

1. INTRODUCTION

With the global population increasingly gravitating toward urban centers, the challenges of sustainable urban development have become more pressing than ever [1]. As UN-Habitat reports indicate, approximately 60% of the world's population now resides in cities, and this percentage is projected to rise further in the coming years [2]. As urban areas sprawl, we face challenges regarding sustainable development, urging us to find innovative solutions that ensure our cities thrive while safeguarding the environment [3, 4]. Remote sensing technologies provide robust tools for monitoring and comprehending the Earth and its environmental systems [5, 6]. They have transformed our capacity to analyze and trace urban dynamics, particularly concerning urban expansion and changes in land use [7]. This study introduces an innovative approach that employs cutting-edge deep learning techniques and remote sensing technologies to tackle the challenges associated with urban dynamics.

Deep learning, a subset of artificial intelligence, utilizes neural networks to acquire knowledge from vast datasets and execute intricate tasks, including classification of land use and land cover, assessment of vegetation health and habitat, and mapping of urban heat islands [8]. Current methods employed to monitor urban dynamics, such as aerial surveys, ground-based observations, and manual data collection, possess limitations in terms of spatial coverage, data frequency, and the ability to capture nuanced details of urban changes [9, 10]. Moreover, these methods often entail significant financial expenditures, encompassing data acquisition, processing, field surveys, and expert analysis [11, 12]. In contrast, our proposed approach capitalizes on the cost-effectiveness and reproducibility offered by advanced deep learning and remote sensing technologies[8].

By combining deep learning algorithms with high-resolution remote sensing data, our solution enables the extraction of complex information from imagery, encompassing urban extents, land use alterations, and habitat fragmentation [13]. The automation facilitated by deep learning algorithms eliminates the need for manual data processing and expert analysis, resulting in cost reduction and increased efficiency in monitoring efforts. Furthermore, the scalability of our approach enables simultaneous monitoring of vast areas encompassing multiple urban regions. With the ever-growing availability of high-resolution satellite imagery and advancements in computing technologies, our solution can be seamlessly applied across diverse geographical scales, ranging from individual cities to regional or national levels [14, 15].

This approach aims to enable the automatic identification of urban expansion and exploration of land use changes using satellite imagery, providing indicators of urban sustainability, such as the rate of urban expansion, encroachment of agriculture, and habitat fragmentation, among others. By automatically detecting urban expansion and monitoring changes in land use from satellite imagery, decision-makers gain real-time insights into urban dynamics, facilitating successful decisions for sustainable development. Moreover, this approach aligns harmoniously with various United Nations Sustainable Development Goals (SDGs), including Goal 11, Sustainable Cities and Communities, Goal 15, Life on Land, and Goal 16, Peace, Justice, and Strong Institutions. By effectively monitoring urban dynamics, our solution contributes to the development of sustainable urban environments, fostering inclusivity and resilience within cities, and ensuring efficient land use and resource management. The integration of deep learning and remote sensing technologies enhances our understanding of the environmental implications of urbanization, facilitating the formulation of appropriate strategies for sustainable land management. Ultimately, this contributes to the realization of sustainable development goals (SDGs) by fostering the development of sustainable and resilient cities for the future. Fig. 1 illustrates the concept of the approach used in this study.

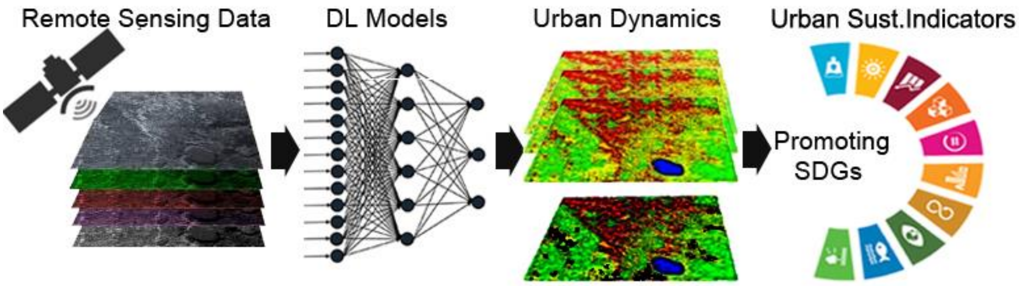

Fig. 1. the concept of the approach used in this study.

This study takes Greater Cairo (GC), Egypt, as a case study and aims to leverage remote sensing data and deep learning techniques to uncover the land cover changes resulting from the recent extensive urban expansion driven by the construction of the New Administrative Capital (NAC) in the eastern region of GC. The study seeks to understand the effects of this urban expansion on the sustainable development of the area.

2. METHODOLOGY

2.1 Case Study

This study takes Greater Cairo (GC) in Egypt as a case study. GC is the biggest and most influential metropolitan city in the Middle East and Africa [10, 16]. GC proper includes Cairo city, Giza city, peri urban areas, and the new cities surrounding the metropolitan areas, 6th of October, Sheikh Zayed, 15th of May, El Obour, El Shorouk, New Cairo, Badr, 10th of Ramadan, and the New Administration Capital [17], as shown in Fig. 2.

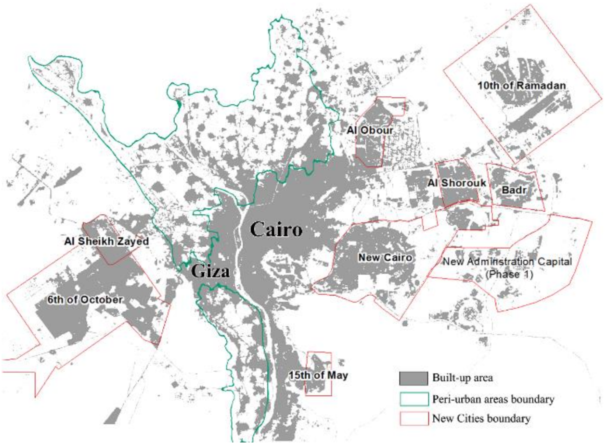

Fig. 2. Greater Cairo and its urban extent in 2021

2.2 Data Acquisition and Preprocessing

For this study, a comprehensive dataset of Sentinel-2 satellite imagery from the European Space Agency (ESA) covering the years 2015 to 2021 was employed. The Sentinel-2 imagery provided high-resolution and multi-spectral data, facilitating accurate land cover mapping and change detection.

To ensure spatial consistency and compatibility, the imagery was projected using the Universal Transverse Mercator (UTM) projection, with the mosaic projection based on the World Geodetic System 1984 (WGS84) reference ellipsoid. This choice of projection enabled seamless integration and analysis of the satellite imagery across different time periods. Furthermore, the data had a cell size of 10 meters, providing a fine-grained level of detail for the study area. Preprocessing steps, including radiometric and atmospheric corrections, were performed to enhance the quality and reliability of the satellite images, minimizing potential distortions and artifacts that could affect the subsequent analysis. The acquisition and preprocessing of the Sentinel-2 satellite imagery formed the foundational steps for the successful implementation of advanced deep learning algorithms and accurate land cover mapping in the Greater Cairo region.

2.3 Deep Learning Model Architecture

In this study, to ensure optimal performance and accuracy in land cover mapping, a customized version of the U-Net architecture with 64 layers was utilized. The U-Net model was trained on the BigEarthNet dataset, which contains multi-temporal Earth observation data acquired through the Sentinel-2 satellites [18]. The U-Net architecture is designed with down sampling in the encoder to capture crucial features from the input data and up sampling in the decoder to reconstruct the spatial information. By combining these two processes, the U-Net effectively merges low-level and high-level features, allowing for precise segmentation based on multiple features.

Furthermore, the U-Net incorporates skip connections that connect the decoder's output with corresponding feature maps from the encoder at the same level. This strategic integration enhances the accuracy of pixel segmentation by preserving and utilizing valuable information throughout the network [19]. The skip connections enable the U-Net to retain intricate details while capturing broad contextual information, ultimately leading to more accurate and detailed segmentation outcomes.

The utilization of the U-Net architecture, with its advanced features and unique design, proved highly beneficial for land cover mapping in Greater Cairo. Fig. 3 visually depicts the architecture of the U-Net model employed in our study, showcasing the efficient and effective mechanism it employs to process and interpret the Sentinel-2 satellite imagery. This deep learning approach, combined with the rich multi-temporal data from the BigEarthNet dataset, contributed significantly to the success of the land cover mapping process, enabling the extraction of valuable indicators for sustainable urban development and environmental conservation.

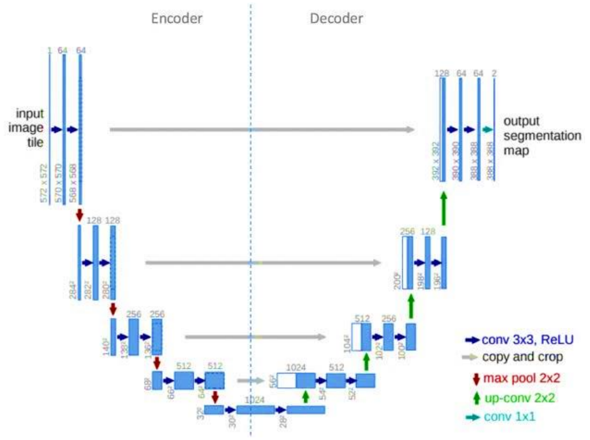

Fig. 3. U-Net Architecture.

2.4 Land Use Change Detection

To detect land use changes, a robust and widely-used supervised maximum likelihood algorithm was employed in the ArcGIS software. The algorithm allowed for precise and accurate classification of land use patterns based on the spectral signatures of different land cover classes. Given the primary focus on urban expansion and changes in the urban class, non-urban land was categorized into three main classes, agricultural, desert, and waterbodies. This categorization process was meticulously performed for each satellite image from the years 2015 to 2021, enabling the identification of temporal variations and trends in land use across the study area. By examining and comparing land use maps over the years, the study was able to capture and analyze significant shifts in land cover patterns, particularly the remarkable urban expansion in Greater Cairo during the study period. The thorough land use change detection process laid the foundation for understanding the dynamics of urban development and its implications for sustainable land management and urban planning.

2.5 Urban Expansion Detection

To precisely identify and visualize urban expansion in Greater Cairo, a dedicated approach for urban expansion detection was employed. Initially, the three non-urban land cover classes, namely agricultural, desert, and waterbodies, were merged into a unified 'nonurban' class. This consolidation allowed for a clear distinction between urban and non-urban areas in the study region. Subsequently, built-up urban areas were designated as black, while all other land cover classes were labeled white. This binary classification scheme effectively highlighted the extent and spatial distribution of urban growth across Greater Cairo. By visually examining the resulting map, the study gained critical insights into the magnitude and patterns of urban expansion over time, particularly focusing on the noteworthy urban growth in the eastern region attributed to the construction of the New Administrative Capital. The urban expansion detection process provided essential data for understanding the dynamics of urbanization and its potential impact on the sustainable development of the region.

2.6 Indicators of Urban Sustainability

The analysis of urban expansion and land use change data yielded several key indicators of urban sustainability. The first indicator is the urban expansion rate, which measures the percentage increase in urban land cover over time, reflecting the pace and scale of urbanization. Another significant indicator is agricultural encroachment, which assesses the intrusion of urban development into agricultural areas, potentially impacting food production and agricultural sustainability.

Habitat fragmentation is another critical indicator derived from the data, indicating the division of natural habitats due to urbanization, which can have adverse effects on biodiversity and ecological balance. Lastly, vegetation loss and green space depletion indicate reductions in vegetated areas within urban environments, highlighting the importance of preserving green spaces for environmental well-being and human health.

The quantification of these indicators involves analyzing changes in land cover over time using the Sentinel-2 satellite imagery and the deep learning model. This process allows policymakers and urban planners to make informed decisions and formulate sustainable land use planning strategies. By understanding the implications of urban expansion on agriculture, biodiversity, and green spaces, authorities can take proactive measures to promote sustainable urban development and ecological conservation, aligning with the objectives of the Empowering Sustainability title. These indicators serve as valuable tools to foster a balance between urban growth and environmental preservation, ensuring the development of resilient and sustainable cities for the future.

3. RESULTS

The study's findings provide compelling evidence of substantial urban expansion in the Greater Cairo (GC) urban area between 2015 and 2021, with a notable increase in the urban area to 227 thousand hectares by 2021, and an average growth rate exceeding 6% during the 2015-2021 period.

The land cover classification using the trained model achieved remarkable accuracy levels, surpassing 90% for all four land cover classes. Particularly striking was the significant expansion of the built area class during the study period, largely driven by the construction of the New Administrative Capital, resulting in extensive urban growth in the eastern region. Fig. 4 visually illustrates the changes in land cover between 2015 and 2021, providing a clear depiction of the transformation.

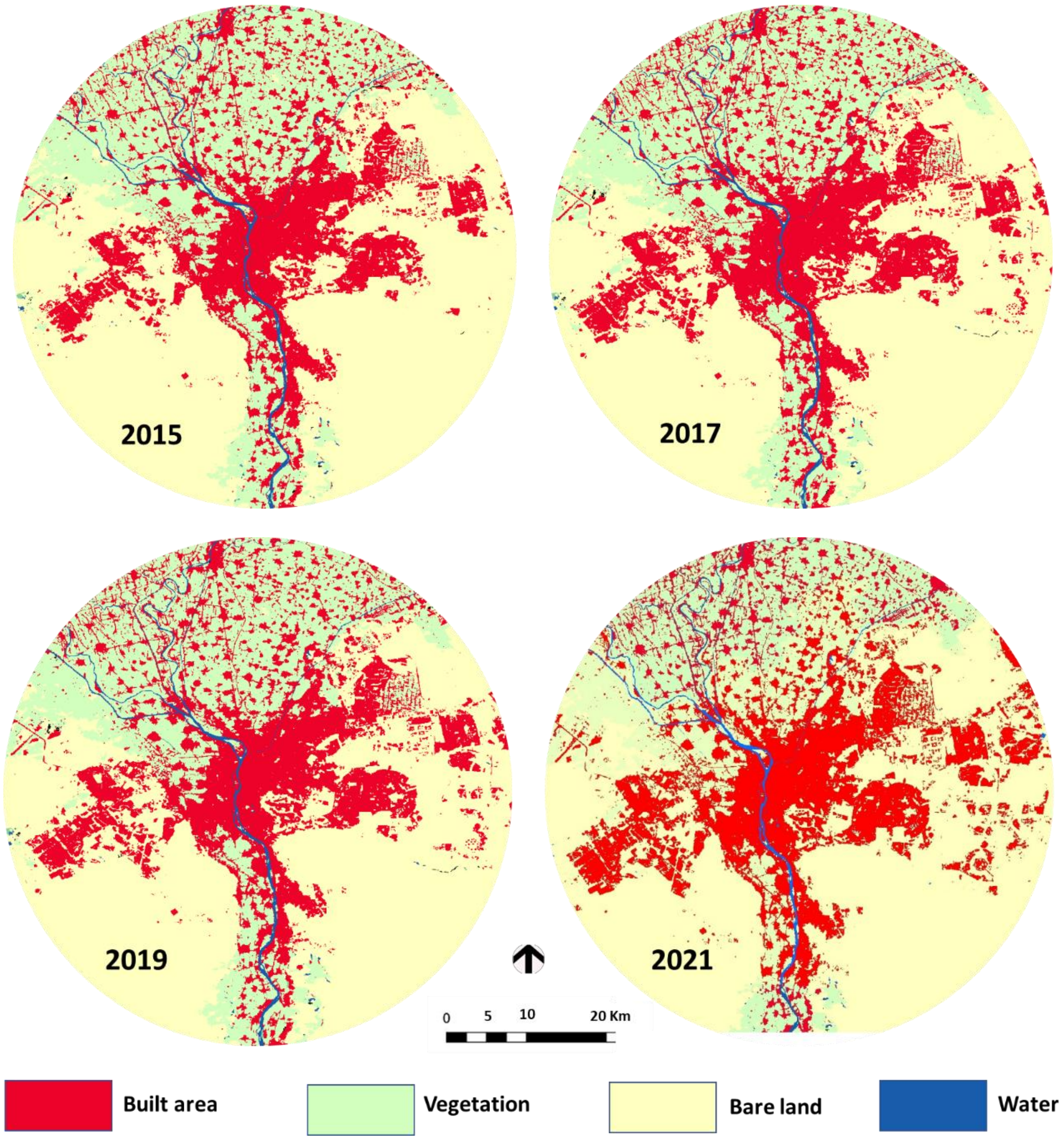

Fig. 4. The change in land cover between 2015-2021.

Based on the study's results, a set of indicators of urban sustainability was successfully extracted, revealing significant trends in the Greater Cairo (GC) urban area. The urban expansion rate demonstrated a continuous increase, rising from 5.6% annually in 2015 to 6.1% annually in 2021, indicating a rapid pace of urban development throughout the study period. Although agricultural encroachment slightly decreased from 1200 hectares annually to 900 hectares annually, it highlighted a significant shift in land use, with urban expansion primarily occurring in desert lands, sparing agricultural areas.

Moreover, the study observed a concerning increase in habitat fragmentation, with the fragmentation index rising from 1.69 in 2015 to 1.74 in 2021. This emphasizes the division and fragmentation of natural habitats due to ongoing urbanization, underscoring the need for sustainable land management practices. Additionally, the study detected vegetation loss and green space depletion within urban environments, signaling a reduction in vegetated areas.

These indicators of urban sustainability provide invaluable insights for decision-makers and urban planners to assess the impact of urbanization, devise strategies for sustainable land management, and prioritize efforts in environmental conservation. The study's findings contribute significantly to the realization of sustainable development goals (SDGs), particularly in fostering sustainable and resilient cities for the future. As Greater Cairo continues to experience urban expansion, these indicators play a crucial role in guiding responsible urban planning and preserving the region's ecological integrity.

4. DISCUSSION

The discussion section provides a comprehensive overview of the study's key findings and their implications. It effectively highlights the advantages of utilizing remote sensing imagery (RS) and deep learning (DL) algorithms, particularly the U-Net architecture, for accurate land cover mapping in the Greater Cairo area. The integration of multi-temporal data from the

BigEarthNet dataset and the application of transfer learning with a pre-trained model significantly contributed to the success of the mapping approach.
By incorporating multi-temporal information, the model could effectively capture temporal variations and changes in land cover, enhancing classification accuracy and facilitating the detection of land cover changes attributed to the New Administrative Capital (NAC) construction.
Transfer learning using a pre-trained model from the ImageNet dataset expedited model convergence and improved training accuracy. The pre-trained model's ability to extract general features from a diverse dataset proved advantageous in the land cover mapping task. Fine-tuning the pre-trained model on the BigEarthNet dataset further refined its feature extraction capabilities, adapting it to the specific characteristics of the study area. The combination of multi-temporal data and transfer learning addressed challenges related to limited labeled training data and spectral similarity between land cover classes. This enabled the model to leverage knowledge acquired during pre-training and apply it effectively to the land cover mapping task in Greater Cairo. As a result, the proposed method achieved high accuracy levels for various land cover classes, including built area, vegetation, and water.
The indicators of urban sustainability extracted from the study provide valuable insights into the patterns and consequences of urban expansion and land use changes in the GC area. These indicators offer a foundation for decision-makers and urban planners to devise strategies that promote sustainable development, biodiversity preservation, and optimized land use and resource management. The findings align harmoniously with the theme of "Empowering Sustainability," contributing to the realization of sustainable development goals (SDGs) by nurturing the growth of sustainable and resilient cities for the future.
For future research, the authors suggest acquiring a larger and more diverse collection of image samples, exploring alternative deep convolutional neural network (CNN) models, and investigating additional land cover classes. These efforts are crucial to advancing land cover mapping and expanding its applications in various fields, including urban planning and environmental conservation. The discussion effectively summarizes the study's significance and paves the way for further advancements in the field, supporting the use of advanced technologies to address urbanization challenges and promote sustainable development in urban areas.

5. CONCLUSION

This study represents a valuable addition to the existing literature on urban monitoring and sustainable development. The study showcases the effectiveness of remote sensing imagery and deep learning algorithms, particularly the U-Net architecture, in achieving accurate and efficient land cover mapping in Greater Cairo, Egypt. By integrating multi-temporal data from the BigEarthNet dataset and implementing transfer learning with a pre-trained model, this research significantly enhances the mapping approach.
The results shed light on a noteworthy urban expansion in the eastern region, attributed to the construction of the New Administrative Capital, underscoring the importance of employing advanced remote sensing and deep learning techniques to monitor and comprehend urban development dynamics. Additionally, the study successfully extracts indicators of urban sustainability, including the urban expansion rate, agricultural encroachment, habitat fragmentation, and vegetation loss, providing valuable insights for decision-makers and urban planners in managing sustainable urban growth and preserving the environment. The findings contribute to the realization of sustainable development goals (SDGs) by nurturing the growth of sustainable and resilient cities for the future. As the study identifies potential areas for future enhancement, such as expanding the dataset and exploring alternative deep convolutional neural network (CNN) models, it holds promising potential to further advance the field of urban planning and contribute to ongoing efforts in environmental conservation. The innovative use of deep learning and remote sensing technologies empowers decision-makers with real-time insights into urban dynamics, enabling them to make informed decisions for sustainable development. Overall, this research exemplifies the potential of cutting-edge technologies in addressing the challenges of urbanization, promoting sustainable development, and fostering resilient cities for a sustainable future.

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