THE INTEGRATION OF REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM (GIS) IN MANAGING URBAN ECOSYSTEMS

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KEYWORDS: Urbanization; Ecosystem; Sustainability; Planning; Spatial dynamics; Satellite images

ABSTRACT

Urban ecosystems face numerous challenges due to rapid urbanization and population growth. Effective management of these ecosystems is crucial to ensure their sustainability and the well-being of urban residents. Remote sensing (RS) and Geographic Information Systems (GIS) have emerged as valuable tools for understanding and managing urban ecosystems. The integration of remote sensing and GIS technologies facilitate the monitoring and assessment of urban biodiversity, aiding in the conservation and restoration of ecological habitats. With this mind, the objective of this study was to investigate the integration of remote sensing and GIS technologies for real-time monitoring and assessment of environmental parameters in urban ecosystems, and their role in supporting sustainable urban ecosystem conservation efforts. Landsat 8 Operational Land Imager (OLI) images were acquired between January 2nd and April 5th 2020 to assess and monitor the dynamics in urban ecosystems in Abidjan, Accra, and Lagos. The Normalized Difference Built-up index was used to detect areas covered with concrete structures and impervious surfaces, while the Normalized Difference Vegetation Index and Normalized Difference Water Index were used to detect areas covered with vegetation and water bodies, respectively. Results of the study show that Abidjan, Accra, and Lagos experienced increased built-up areas at the expense of other land uses such as forests. Remote Sensing and GIS technologies provide valuable insights into the spatial and temporal dynamics of urban environments, supporting evidence-based decision-making and sustainable urban planning and development.

INTRODUCTION

Rapid urbanization is putting a strain on urban infrastructure and resources, and urban managers often lack the resources they need to provide essential services to their citizens and protect the ecosystems. This is particularly so in developing countries where discrepancies in urban planning policies and programs associated with rapid urbanization threaten sensitive urban ecosystems such as urban forests, water resources, and soil (Du et al, 2013). Like many developing metropolitan cities, Abidjan, Accra, and Lagos are faced with several environmental problems due to unplanned urbanization, including urban flooding and urban forest loss (Mensah, 2014; Oppong et al, 2023). The effective management of urban ecosystems is crucial to ensure their sustainability and the well-being of urban residents across time and space.

Urbanization has noticeably increased in recent years across the world due to the associated socioeconomic development. However, poor development plans have created environmental problems for urban ecosystems in many countries. This is particularly the case in developing countries where management of urban ecosystems is weak (Mensah, 2014). Urban ecosystems are complex and dynamic environments that face numerous challenges due to rapid urbanization and population growth (Oppong et al, 2023). These dynamics in the environment affect local biodiversity at different levels (Elmqvist et al., 2013), thereby increasing environmental injustices at local, regional, and national levels. Thus, the negative environmental impacts of rapid urbanization in developing countries cannot be overlooked.

Management of urban ecosystems in these areas require holistic and integrated approaches that encompass stakeholder collaboration, indigenous knowledge and practices, modern technology, public education and awareness programs, as well as public and stakeholder interactions (Gaston et al., 2013). These strategies according to the United Nations Environmental Program (2016) report can help to ensure that urban ecosystems in developing countries are managed in a sustainable way, which can be beneficial to both the people and the environment. However, management of urban ecosystems are not incorporated into mainstream urban planning programs and measures, exposing them to internal development pressures and reducing the services they provide to the local people (McPhearson et al., 2015).

Remote sensing (RS) and Geographic Information Systems (GIS) have emerged as valuable tools for understanding and managing urban ecosystems (Wang and Xie, 2018). Remote Sensing and Geographic Information Science (GIS) are two powerful tools that can be used to collect, store, analyze, and visualize spatial data. RS is the process of obtaining information about an object or area from a distance, without coming into physical contact with it, while GIS is a computer-based system for storing, managing, and analyzing spatial data. Remote sensing can be used to collect data about a wide variety of things, including land cover, vegetation, water bodies, and human settlements (Hu and Xu, 2018). GIS can be used to integrate remote sensing data with other types of data, such as demographic data and economic data, to create a more complete picture of a particular area (Longley et al., 2015). This data can be used to monitor changes over time, assess the impact of human activities, and plan for future development (Wang and Xie, 2018). In so doing, RS and GIS become cost-effective tools for the development of urban planning measures and policies, essential for effective environmental development and protection (Wellmann et al., 2020).

The integration of remote sensing (RS) and geographic information systems (GIS) has become an essential tool for the management of urban ecosystems. RS provides synoptic, high-resolution data on a variety of land cover and environmental variables, while GIS allows for the integration, analysis, and visualization of this data (Du et al, 2013). This integration can be used to address a wide range of urban ecosystem management challenges, such as: map land use and land cover changes, identify areas of potential development, and assess the impacts of development on the environment, identify areas of flooding and drought (Wang and Xie, 2018), identify sources of pollution, identify areas of contamination, and assess the impacts of waste disposal on the environment (Singh, 2019), map the distribution of diseases, identify risk factors for disease, and assess the impacts of environmental factors on human health (Lü et al, 2019).

In this paper, studies from three rapidly urbanizing districts/ cities in West Africa are used to provide information on how Remote Sensing (RS) and Geographic Information System (GIS) tools can be used to monitor and evaluate urban development processes. The objective of this study was thus, to investigate how remote sensing and GIS can be integrated into the management of urban ecosystems and highlight their benefits and applications in urban planning, environmental monitoring, and decision-making processes in Abidjan, Accra, and Lagos. This study demonstrates the advantages of RS and GIS information to urban ecosystem planning and development, especially in cities faced with serious environmental problems and ecological risks from human activities.

METHODOLOGY

Study Areas

Abidjan

With a population of about 5.6million people (World Population Review, 2023), Abidjan is the most populous city in Ivory Coast. It is also the largest urbanization city in the country, and it is considered the economic capital of the country (Angoua et al., 2018). It covers a total land mass of 422 km^2. The city of Abidjan lies on the Ébrié Lagoon, within latitude 5.41667N and Longitude 4.03333W (Fig. 1). With a Tropical Savanna climate, the area records an annual mean temperature between 23.8°C and 29.6°C, and an annual mean rainfall of 1,847.6mm (Soumahoro et al., 2021). The city of Abidjan in this study covers the main Abidjan city, Ile Boulay, Vridi, and Paa. Abidjan is both an industrial and agricultural hub, providing food (Vanié et al., 2022) and other economic benefits to the people and the country at large. The rapid rate of urbanization in the city has led to poor environmental conditions and living standards (Angoua et al., 2018).

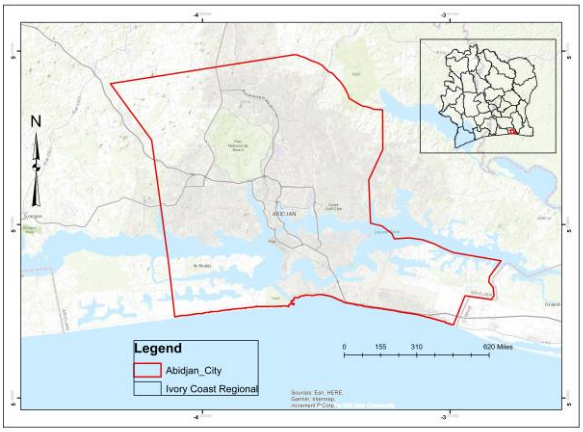

Figure 1. A map showing the location of Abidjan, Ivory Coast

Accra

Accra is the capital of Ghana, which is located within the dry equatorial climatic and coastal savannah ecological zones (Fig. 2). The total land mass of the area under study is about 200km^2 which lies along the southern coast of the Gulf of Guinea. The major vegetation types found within Accra are coastal lands (dunes and wetlands), grasslands and shrublands. The area records an average annual rainfall of about 730 mm and annual average temperature of 25^{o}C. The monthly mean temperature usually ranges from 22^{o}C to 33^{o}C (Wemegah et al., 2020). For the purpose of this study, Accra extends from the Accra Metropolitan area to Ga East, Ga West, Ga South and Ga Central. The Ghana Statistical Service (2021), recognizes Accra as the most populous city in the country with a total population of 5,223,027. Until the onset of the 3rd millennium, majority of the indigenous people in Accra were engaged in fishing and farming. Owing to the geometric population increase of residents living in Accra which has necessitated rapid changes in the physical and socio-economic characteristics of the area there is high demand for land to create employment centres, provide housing and other financial and social infrastructure (Oduro et al., 2015).

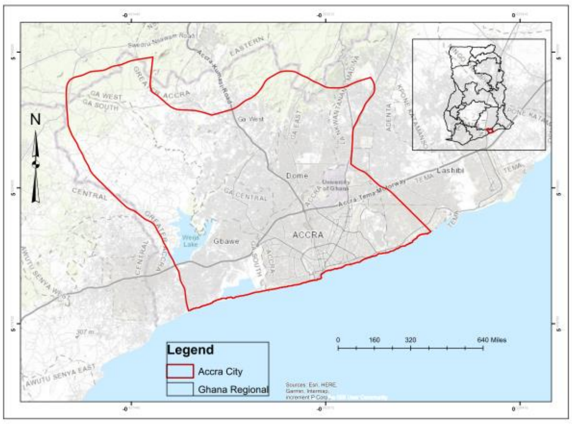

Figure 2. A map showing the location of Accra, Ghana

Lagos

The city of Lagos is the most urbanized and populous city in Nigeria. Located in the Southwestern part of the country along the Gulf of Guinea (Fig. 3), the city is home to about 17.5million people (Igwenagu, 2023), and covers a total area of 316 km^2. Major economic activities in the area include farming, fishing, entertainment, as well as formal and informal commercialization. The area according to Lawanson and Oduwaye (2014) contributes more than half of the country's economic development, though it faces several environmental problems due to improper planning from rapid urbanization and increased migration into the city. It has an annual mean temperature between 22.8°C and 30.8°C, and an annual mean rainfall of 1,506.6mm. For this study, the city of Lagos encompasses the Lagos mainland, Lagos Island, and immediate surrounding areas.

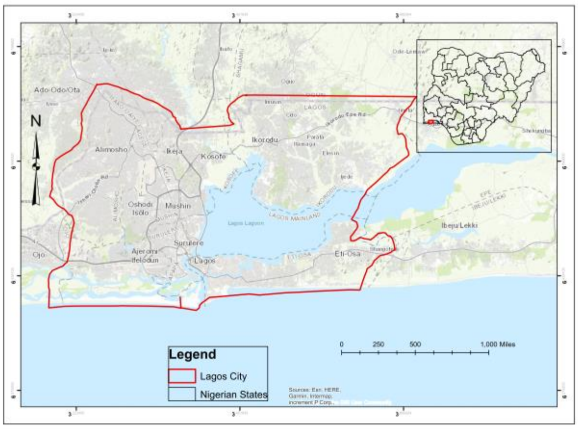

Figure 3. A locational map of Lagos, Nigeria

Image Acquisition and processing

Landsat 8OLI data was acquired from the Google Earth Engine (GEE) image cloud and USGS Earthexplorer for the three study areas. The images were all acquired within the same period (January 2nd and April 5th 2020) to ensure consistency and accuracy in the analysis. Image selection was based on less cloud coverage (0-10%) and fit with the city boundaries. The images acquired did not require any atmospheric corrections since they were preprocessed before being made available for public download. The stacked and composited images were clipped using a shapefile of each city, and two image tiles acquired for Abidjan were mosaic into a single tile for further analysis.

Image Analysis

The Built-up Index (BU) helped in understanding land surfaces in each city covered by impervious surfaces and other infrastructure. BU according to Kshetri (2018) and Karanam and Neela (2017) is derived from the Normalized Difference Built-up and Normalized Difference Vegetation Indices (NDBI and NDVI). The BU values range from -1 to 1, with lower values indicating water bodies and higher values indicating highly built-up areas. NDBI and NDVI were derived from the near infrared (NIR- band5), shortwave infrared (SWIR- band 3) and red bands (band4) of landsat data (Kshetri, 2018; Karanam and Neela, 2017). The BU index is expressed as,

$$BU = NDBI - NDVI \approx \frac{(SWIR-NIR)}{(SWIR+NIR} - \frac{(NIR-Red)}{(NIR+Red)} \quad (1)$$

The Normalized Difference Vegetation Index (NDVI) was performed to assess vegetation vigor in the three study areas. This was to help understand how the local ecology influences vegetation growth and development. Using the raster calculator tool in ArcMap, the NDVI for each city over the study period were created with red (band4) and near infrared (NIR-band5) bands of the acquired Landsat images (Robinson eta l., 2017). Lower (negative) values indicate areas of little of no vegetation cover, and higher (positive) values indicate areas of high vegetation cover. The NDVI formula used is expressed as,

$$NDVI = \frac{NIR- Red}{NIR+ Red} \quad (2)$$

The Normalized Difference Water Index (NDWI) was used to identify and assess water resources within each city. The associated values indicate presence of water (positive values) and non-water covered areas (negative values). The NDWI was performed to assess the impacts of urbanization on water resources, especially as the study areas are coastal cities. It was performed with the green (band3) and shortwave infrared (SWIR- band6) bands of the Landsat images acquired for the study (Kshetri, 2018) with the raster calculator tool in ArcMap. The NDWI function is expressed as,

$$NDWI = \frac{Green-SWIR}{Green+SWIR} \quad (3)$$

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-M-3-2023-169-2023 |

RESULTS AND DISCUSSION

Associated with urbanization are population growth, increased social and economic activities, and land use and land cover changes. The resulting maps from the Normalized Difference Built-up Index for Abidjan, Accra, and Lagos are shown in figures 4-6 respectively. These maps are color-coded to show the magnitude of built-up areas (red) and other ecosystems (green-forest, orange-water) within each city. The spread of built-up areas in these cities shows the potential impacts of development and increased human activities associated with rapid urbanization on vulnerable ecosystems such as urban forests, water and soil. As Aburas et al. (2018) reported, integrating Remote Sensing (RS) and Geographic Information Systems (GIS) into the management of urban ecosystems would help urban managers/ planners to monitor urban development processes constantly and efficiently.

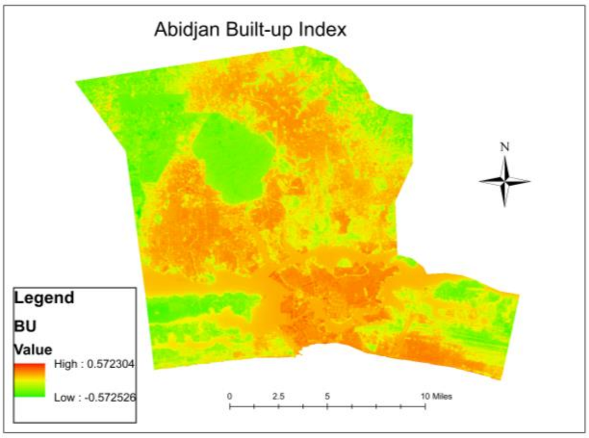

Figure 4. Built-up index for Abidjan, Ivory Coast (2020)

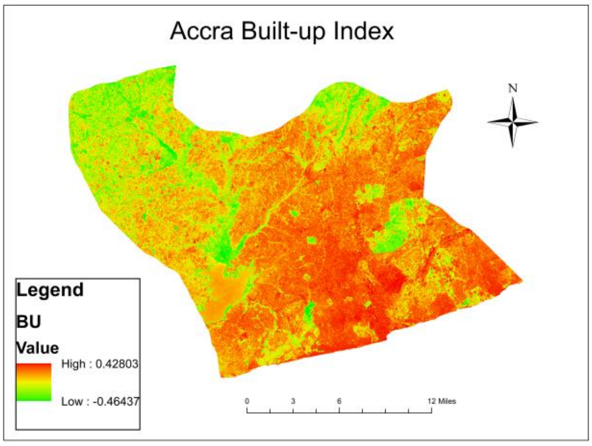

Figure 5. Built-up index for Accra, Ghana (2020)

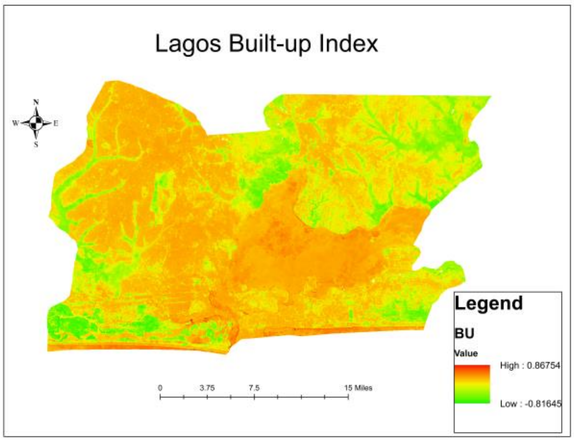

Figure 6. 2020 Built-up index for Lagos, Nigeria

Urban forests provide several ecosystem services beneficial to both humans and the environment. However, rapid urbanization and increasing population growth in the study areas threatens the sustainable management of these resources (Oppong et al., 2023). As shown in figures 7-9 below, Abidjan, Accra, and Lagos each has sufficient urban forest cover (green). The uneven distribution of the forest cover in these cities exposes residents in non-forest covered areas (orange colored) to severe environmental conditions such as Urban Heat Island (UHI) effect, poor air quality from pollution, and increased surface runoff. The Normalized Difference Vegetation Index (NDVI) maps below illustrate how RS data and GIS visualization tools can also help in planning for service provisions, to cater for the needs and wants of the people, while at the same time protecting the environment. Effective urban forest management would help increase the human-environment relationship, and also enforce natural resource preservation and protection efforts within these cities.

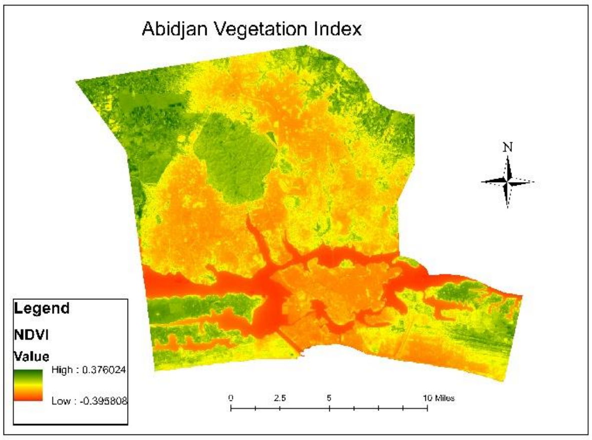

Figure 7. 2020 Vegetation index for Abidjan, Ivory Coast

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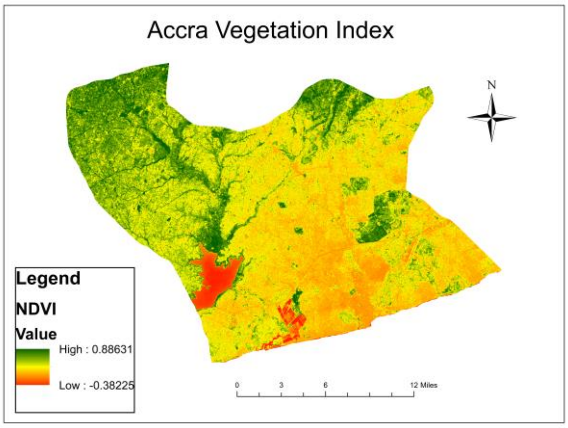

Figure 8. Vegetation index for Accra, Ghana (2020)

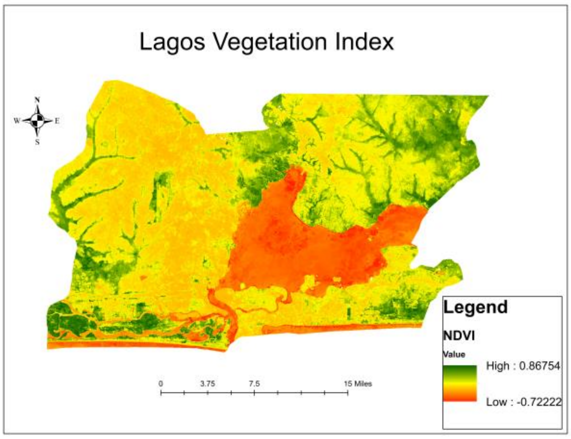

Figure 9. 2020 Vegetation index for Lagos, Nigeria

Lastly, with RS and GIS tools, urban managers can collect and manage information necessary for informed decisions to promote proper urban planning and development. Water resource scarcity is a major problem across many parts of the world. The increasing rate of urbanization and population growth in urban areas poses further challenges to urban dwellers (Liu et al., 2023). The Normalized Difference Water Index (NDWI) used in this study helped to identify areas covered by water bodies in the study areas. Figures 10-12 show the NDWI maps for each city, color coded to differentiate waterbodies (blue) from other land cover types. As physical development in the study areas expands, demand for water may exceed supply, affecting water utilization. Also, the associated negative impacts of urbanization in these cities expose the available water sources to conditions such as pollution and dry-out from human activities and Urban Heat Island effects (Cai et al., 2021).

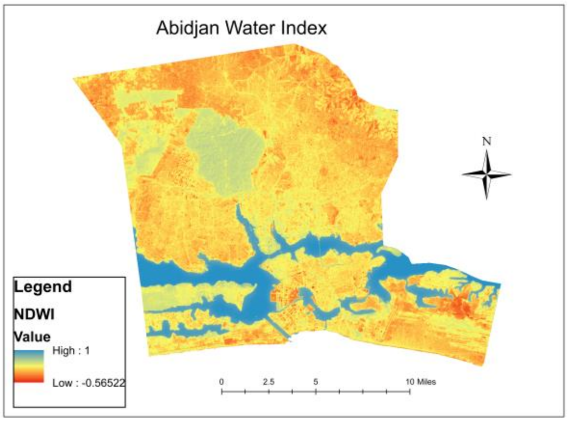

Figure 10. Water index for Abidjan, Ivory Coast (2020)

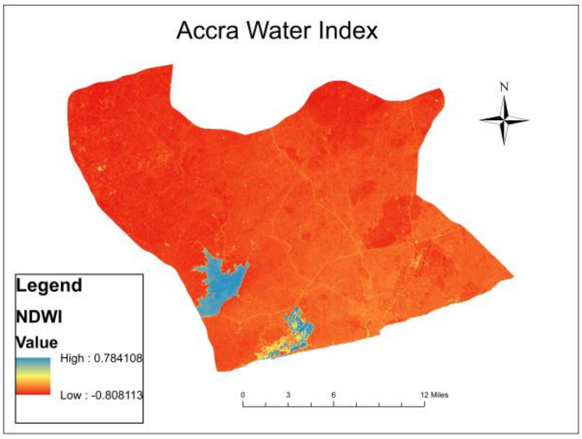

Figure 11. 2020 Water index for Accra, Ghana

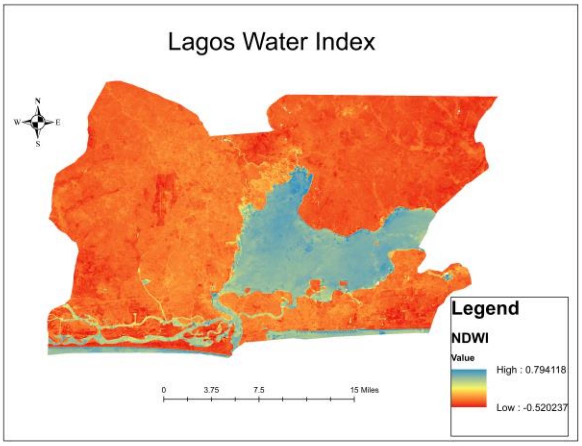

Figure 12. Water index for Lagos, Nigeria (2020)

CONCLUSION

With the current rapid urbanization across the world, ecosystem management in developing countries is essential to ensure their sustainability and increase the services they provide. This study illustrates how Remote Sensing (RS), and Geographical Information System (GIS) tools can be utilized to enhance management of urban ecosystems in three rapidly urbanizing cities in West Africa. These technological tools enable the understanding of spatial patterns and dynamics, support evidence-based decision-making in urban planning, and facilitate environmental monitoring and conservation efforts. The results show the vulnerability of sensitive urban ecosystems such as urban forests and water bodies to harsh environmental conditions associated with urbanization. The integration of remote sensing and GIS could contribute to the development of sustainable urban ecosystems by providing insights into the impacts of urbanization and guiding the design of resilient urban infrastructure. As cities continue to grow, the use of remote sensing and GIS will become increasingly vital in ensuring the sustainability and livability of urban areas. However, it should be noted that data availability and technological know-how affects the effectiveness of remote sensing and GIS in urban ecosystem management.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the American Society for Photogrammetry and Remote Sensing (ASPRS) Foundation for the Student grant award to present this paper at the Summer 2023 ASPRS International Technical Virtual Symposium. We would also like to acknowledge the USDA National Institute of Food and Agriculture (NIFA) McIntire Stennis Forestry Research Program (project award number NI22MSCFRXXXG077, and Project title: Enhancing Graduate Education and Research Productivity in Urban Forestry and Natural Resource Management.) for the Student Graduate Assistantships.

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