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DIGITAL TRANSFORMATION OF TREE INVENTORY THROUGH GIS: OPTIMIZING FORESTRY PROCESSES VIA SPATIAL DATA COLLECTION, INTEGRATION AND ANALYSIS

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Abstract

The digital transformation of tree inventory through Geographic Information Systems (GIS) is reshaping contemporary forestry practices by enabling higher accuracy, enhanced data integration, and increased operational efficiency. GIS technologies revolutionize forest inventory workflows by facilitating precise spatial data collection and supporting advanced analytical processes. The integration of spatial datasets with modern analytical tools allows for dynamic monitoring of forest resources and provides a robust foundation for informed and sustainable management decisions. The aim of this article is to demonstrate how GIS-based digital methodologies improve the efficiency, standardization, and analytical depth of forest inventory processes, while highlighting their role in supporting modern forestry management. To achieve this, a dedicated field data collection form was developed using Survey123, specifically designed for tree inventory and analysis. This standardized form ensures consistent data acquisition and seamless integration into GIS platforms for subsequent spatial processing and interpretation. Overall, the proposed workflow illustrates the transformative potential of GIS technologies in optimizing forestry operations and advancing sustainable forest resource management.

Key words*: Digital Tree Inventory, Forestry Management, GIS, Survey123.*

INTRODUCTION

Sustainable forest management has become one of the major challenges of the 21st century, driven by climate change, biodiversity loss, increasing anthropogenic pressures, and the growing demand for forest resources. In this context, reliable and up-to-date information on forest ecosystems is fundamental for supporting informed management decisions. White et al. (2013) emphasize hat the development and continuous maintenance of forest inventories are essential not only for assessing current forest conditions but also for projecting future forest development and supporting long-term sustainable management strategies (White et al., 2013). Similarly, Aulló-Maestro et al. (2021) describe forest inventories as the primary source of information for assessing forest structure and monitoring forest dynamics (Aulló-Maestro et al., 2021). For decades, forest inventories have relied on conventional field-based methods involving paper forms, manual measurements, and subsequent office-based data processing. Although these approaches have provided valuable information for forest management, they are characterized by several limitations, including high labour requirements, long processing times, difficulties in data updating, and increased susceptibility to transcription and positioning errors. According to Keskes et al. (2025), many forest inventory variables are still measured manually in the field, making the inventory process both time-consuming and costly, particularly across large and heterogeneous forest landscapes.

The rapid development of digital technologies has fundamentally transformed the way forest inventories are planned, conducted, and managed. Rather than representing a simple transition from paper forms to digital devices, digital transformation involves the integration of advanced technologies into a comprehensive information management system. This

transformation combines field data acquisition, Global Navigation Satellite System (GNSS) positioning, Geographic Information Systems (GIS), remote sensing, laser scanning, cloud-based databases, and spatial modelling within a unified digital workflow. As highlighted by White et al. (2013), modern forest inventories increasingly rely on multi-source information to provide more accurate, timely, and spatially explicit estimates of forest resources (White et al., 2013).

Among these technologies, Geographic Information Systems (GIS) plays a central role by integrating, storing, visualizing, and analysing geospatial information collected from multiple sources. Aulló-Maestro et al. (2021) state that GIS and remote sensing technologies have transformed the use of forest inventory data by enabling wall-to-wall estimation of forest variables based on field measurements and spatial modelling (Aulló-Maestro et al., 2021). The capability of GIS to combine field observations with remotely sensed information allows forest managers to evaluate forest resources more efficiently and consistently than conventional inventory approaches. Recent advances in remote sensing have further accelerated this digital transformation. According to Fassnacht et al. (2024), remote sensing has become an omnipresent technology in forestry and is increasingly applied in operational forest inventory and monitoring (Fassnacht et al., 2024). Airborne LiDAR, terrestrial laser scanning (TLS), mobile laser scanning (MLS), unmanned aerial vehicles (UAVs), and multispectral satellite imagery now provide detailed information on tree position, canopy architecture, stand density, biomass, and forest health. Liang et al. (2018) demonstrated that terrestrial laser scanning significantly improves the accuracy of tree-level measurements, while Hyyppä et al. (2020) showed that laser scanning technologies enable highly precise three-dimensional characterization of forest structure. The integration of these diverse datasets within GIS environments provides substantial advantages for forest management. Spatial databases facilitate efficient data organization, improve interoperability among information sources, reduce redundancy, and support rapid updating of inventory records. Furthermore, spatial analysis techniques enable the assessment of stand structure, species distribution, growth dynamics, regeneration processes, accessibility, harvesting operations, and environmental risks. These capabilities contribute to more informed planning and more effective allocation of forest resources. Digital transformation is also closely associated with the emergence of Precision Forestry, a management paradigm based on high-resolution spatial information and data-driven decision-making. As discussed by Uusitalo (2010), modern forestry increasingly depends on accurate digital information systems that support operational planning and resource optimization (Uusitalo, 2010).

More recently, Damaševičius et al. (2024) highlighted that digital technologies improve the sustainability, efficiency, transparency, and resilience of forest management by facilitating evidence-based decisions and strengthening the integration of ecological, economic, and operational information. Another important aspect of digital forestry is the continuous updating of forest information. Traditional inventories often require several years between successive measurements, whereas digital workflows supported by GIS and remote sensing allow near real-time monitoring of forest conditions. This capability is particularly valuable for detecting disturbances caused by storms, pests, diseases, wildfires, and illegal logging, enabling forest managers to respond more rapidly and effectively.

In addition to improving operational efficiency, GIS-based inventories enhance the quality and consistency of forest information. Spatial databases reduce the likelihood of transcription errors, facilitate data sharing among institutions, and provide standardized datasets that can support national forest inventories, ecosystem monitoring programmes, and scientific research. The integration of field observations with remote sensing products also enables advanced spatial analyses and predictive modelling of forest growth, regeneration, biomass accumulation, and future stand development under different management scenarios.

Against this background, the present study investigates the digital transformation of tree inventory through Geographic Information Systems by analysing the complete workflow of spatial data collection, integration, management, and analysis. The research explores how

rigorous field measurements combined with GIS technologies can optimize forest inventory processes, improve the quality of spatial information, support sustainable forest management, and facilitate evidence-based decision-making. Ultimately, this integrated digital approach contributes to more accurate forest resource assessments, greater operational efficiency, and enhanced capacity for monitoring and managing forest ecosystems in a rapidly changing environmental context.

MATERIALS AND METHODS

Digital transformation driven by GIS technologies is revolutionizing how forest inventories are conducted, delivering enhanced accuracy and significant operational efficiency. The integration of spatial data with advanced analytical tools enables the dynamic monitoring of forest resources and provides a solid foundation for more informed, sustainable management decisions.

To implement the project on the digital transformation of forest inventorying via GIS, a dedicated field datasheet was developed using Survey123 for tree inventory and analysis. This datasheet ensures the standardized collection of data required for seamless GIS integration and establishes a baseline for subsequent analyses.

In the following paragraphs, we will outline the methodology implemented for data integration and demonstrate how geospatial analysis elevates a standard tree inventory into a strategic asset for smart forestry. Ultimately, our goal was to show that digitalization is no longer an optional technical upgrade, but a fundamental necessity for the efficiency, transparency, and long-term sustainability of modern forestry.

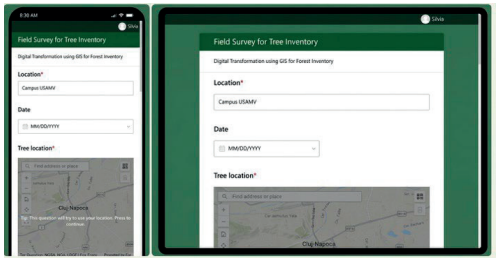


Figure 1. Visualizing the questionnaire and ensuring its accessibility across multiple devices (such as tablets and mobile phones) enhances user accessibility

More precisely, the survey initiates with the record of location-specific details and the date of completion, followed by the acquisition of the precise tree location through the logging of its latitude and longitude coordinates, as shown in Figure 2.

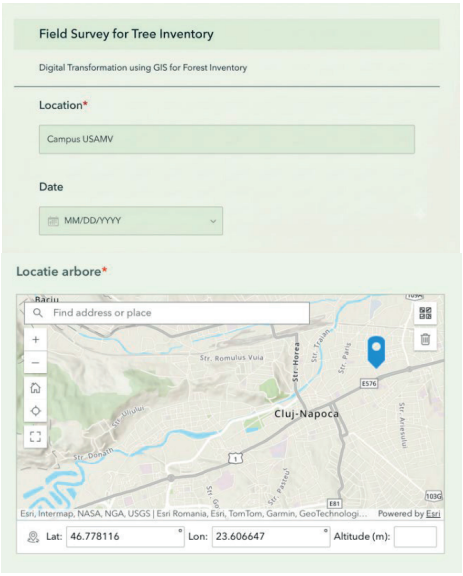


Figure 2. The image shows the initial section of a digital field survey for tree inventory designed to leverage GIS technology, featuring data entry fields for capturing the specific location and the collection date

The image illustrates an interactive map interface within a data collection tool used to precisely capture a tree's geographic coordinates - specifically its latitude and longitude - by placing a marker within the city of Cluj-Napoca. We also present a section marked in Figure 3, dedicated to species identification, featuring mandatory data fields for the common Romanian name, the scientific name, the origin (native or exotic), and the provenance (generative or vegetative) of the tree. In addition, information regarding tree height, clear bole height, and tree diameter was collected (Figure 4).

The questionnaire also includes information regarding the trees' vegetative status, as shown in Figure 5, for example luxuriant, vigorous, normal, sluggish/declining, and dying and health condition (good, satisfactory, poor, or others), along with dedicated sections for field observations and photographs.

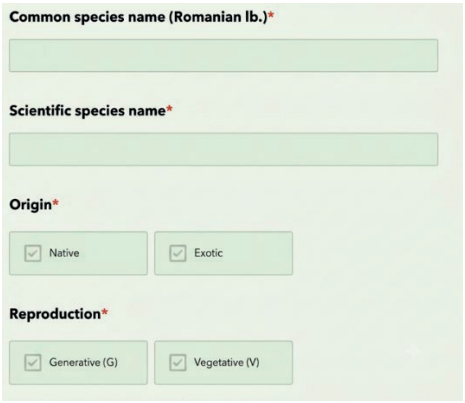


Figure 3. Methodological approaches to dendrometric data collection and species identification

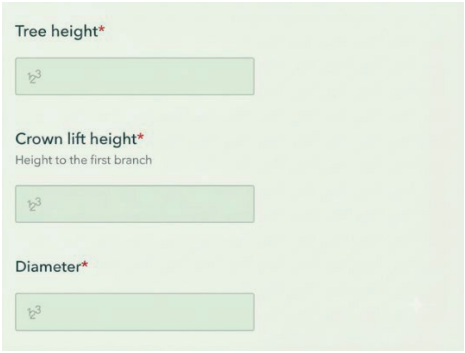


Figure 4. Methodological approaches to dendrometric data collection

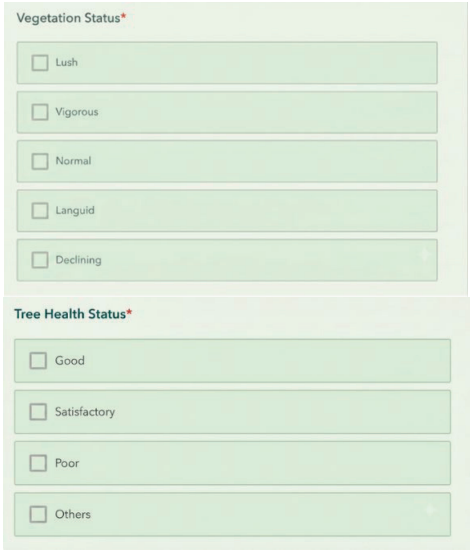


Figure 5. Tree Health Evaluation Interface

RESULTS AND DISCUSSIONS

By analysing this questionnaire within the Survey123 platform, it becomes possible to systematically evaluate all relevant aspects of a tree, with the results being summarized in the charts presented below. The Figure 6 shows a data table from a Survey123 questionnaire that tracks the frequency of individual words entered for scientific species names ("Denumire stiintifica specie"), which will automatically generate a word cloud once at least 20 responses are collected.

The column chart above (Figure 7) presents the distribution of tree origins ("Origine"), showing that out of 18 responses, 66.67% are classified as exotic ("Exotica") and 33.33% are native ("Indigena").

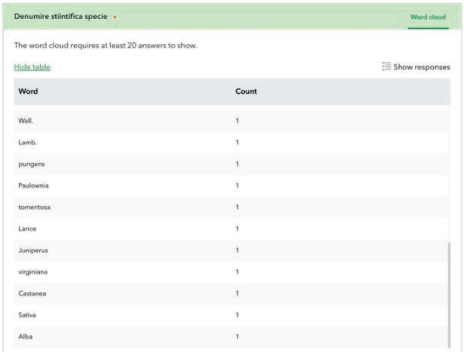


Figure 6. Scientific name of the species



Figure 7. Origin of the tree

The column chart and data table presented in Figure 8 summarize the provenance ("Prevenienţa") of the trees, showing that 72.22% originated through vegetative reproduction ("Vegetativă"), while the remaining 27.78% resulted from generative reproduction ("Generativă").

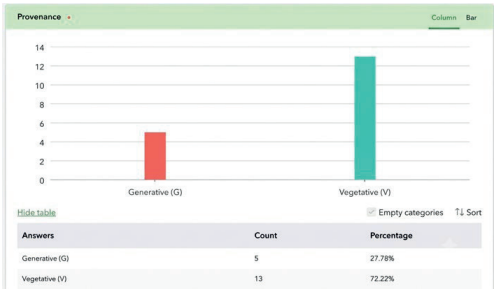


Figure 8. The tree provenance

The histogram and summary metrics display the distribution of tree heights ("Inaltime arbore") - Figure 9, indicating that the surveyed trees range from a minimum height of 4.8 to a maximum of 25, with an average height of approximately 17.22 m.



Figure 9. The height of the tree

The chart represented in Figure 10 illustrates the distribution of clear bole height ("Inaltime elagata"), showing values ranging from a minimum of 0.5 to a maximum of 10.4, with an average height of 4.66.

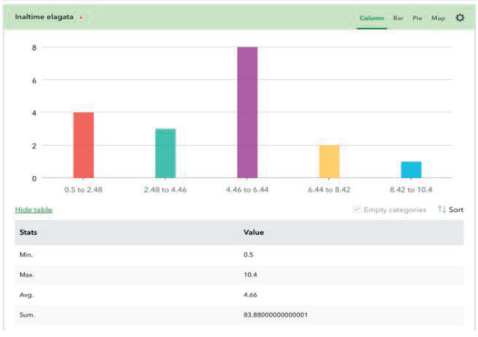


Figure 10. The distribution of clear bole height

The column chart and data table presented in Figure 11, illustrate the vegetative health status ("Stare de vegetație") of the surveyed trees, showing that a 44.44% majority are classified as normal, followed by luxuriant (27.78%), vigorous (22.22%), and sluggish/declining (5.56%), with no trees recorded in the dying category.



Figure 11. The vegetative health status

The column chart and data table below (Figure 12) depict the health status of the trees ("Starea de sănătate a arborelui"), showing that a significant majority of 72.22% are in good condition, while 22.22% are in poor condition, and 5.56% (1 tree) is rated as satisfactory.



Figure 12. The health status of the trees

The gallery section displays a visual inventory consisting of field photographs (Figure 13) used to document and verify the individual characteristics of each tree surveyed in the study.
With the help of GIS, it is also possible to create thematic maps, which are of significant practical value for data visualization and analysis.
The image (Figure 14) displays a thematic map generated within the survey platform, illustrating the spatial distribution and proportional heights of trees ("Inaltime arbore") mapped on the USAMV Cluj campus. The thematic map

underscores the spatial heterogeneity of tree heights, revealing critical correlations between environmental factors and vegetative growth.

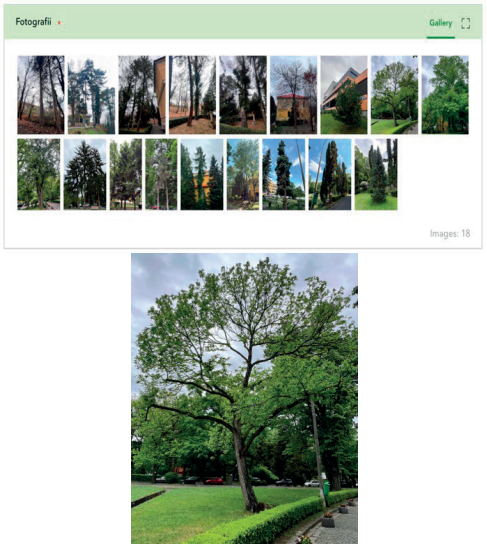


Figure 13. Visual Documentation of the Studied Dendrological Specimens

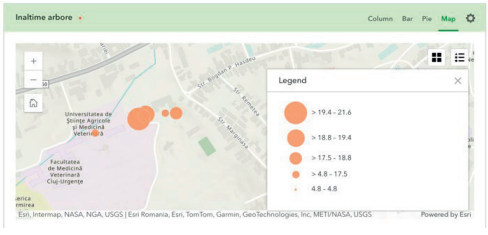


Figure 14. Thematic map illustrating the spatial distribution of tree height

The next map (Figure 15) utilizes graduated proportional symbols, where larger circles correspond to taller trees according to the map legend, allowing for an immediate visual comparison of tree heights across the localized study area.

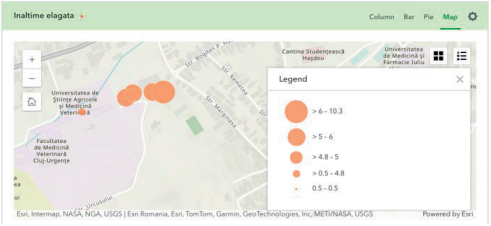


Figure 15. Thematic map illustrating the spatial variation of clear bole height within the forest stand

The provided orthophotomap, titled "Geospatial inventory and exact localization of arboreal specimens at the USAMV Cluj-Napoca campus" (Figure 16) illustrates a high-precision spatial mapping approach utilized to catalogue the urban forestry resources within the university grounds.



Figure 16. Geospatial inventory and exact localization of arboreal specimens at the USAMV Cluj-Napoca campus

By leveraging high-resolution aerial imagery overlaid with precise geographic coordinates, individual tree positions have been vectorized and marked with distinct red and yellow point indicators. The spatial distribution reveals a strategic arrangement of dendrological specimens, clustered primarily around infrastructure borders, open green spaces, and academic walkways. This cartographic layout serves as a fundamental baseline for urban ecosystem monitoring, allowing researchers to track spatial configurations and localized microclimatic impacts of individual specimens within the campus canopy. From a management and biometrical perspective, this precise geospatial localization provides indispensable data for the development of an integrated Green Cadastre for USAMV Cluj-Napoca. Identifying the exact spatial coordinates of each arboreal unit facilitates long-term monitoring of tree health, growth dynamics, and species-specific interactions within the campus ecosystem. Furthermore, this localized spatial framework enables precise field-to-map cross-referencing during dendrometric inventories. By linking these geographic points to a relational database containing biometric attributes - such as species composition, total height, and clear bole height - the institution can optimize its urban forestry management strategies, promoting both ecological biodiversity and environmental sustainability.

CONCLUSIONS

The digital transformation of tree inventorying through GIS highlights the significant potential of spatial technologies in establishing a 'green cadastre' for the USAMV Cluj-Napoca Campus, providing a solid foundation for sustainable management and well-informed decisions.

Looking ahead, future research directions will focus on integrating UAV photogrammetry and LiDAR data to automate tree feature extraction, expanding these models to support forest owners, institutions, associations, and local administrative units (UATs) through integrated solutions dedicated to monitoring green resources and protecting ecosystems, with the ultimate goal of achieving more efficient and responsible forest management.

Furthermore, the implementation of this advanced spatial framework facilitates a paradigm shift from reactive to proactive environmental stewardship within academic and urban ecosystems. By transforming raw geospatial data into actionable intelligence, the proposed green cadastre model enables campus administrators to simulate microclimate impacts, assess localized carbon sequestration capacity, and optimize tree maintenance schedules. This methodology not only standardizes the documentation of vegetative assets but also establishes a highly scalable blueprint that can easily be integrated into broader smart-city frameworks, effectively bridging the gap between localized institutional workflows and regional environmental goals.

Ultimately, the long-term viability and impact of these technological interventions rely on fostering participatory data environments and open collaboration. Future iterations of this system will aim to incorporate multi-user mobile platforms and interactive dashboards, allowing students, researchers, and local stakeholders to engage directly with the spatial database. By cultivating an accessible, dynamically updated ecological inventory, USAMV Cluj-Napoca can champion a collaborative approach to biodiversity conservation, ensuring that precision forestry and urban greening efforts remain resilient and highly adaptive in the face of accelerating climate challenges.

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USE OF GENERATIVE ARTIFICIAL INTELLIGENCE (GenAI)

The authors declare the use of Generative Artificial Intelligence (GenAI) tools in the preparation of this manuscript. GenAI was used exclusively for language editing and text refinement in the Introduction and Conclusions sections. All scientific content, data analysis, and interpretations were developed and verified by the authors.

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