








Article

Development of a GIS-Based Methodological Framework for Regional Forest Planning: A Case Study in the Bosco Della Ficuzza Nature Reserve (Sicily, Italy)

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Abstract

Effective forest planning in Mediterranean environments requires tools capable of managing ecological complexity, socio-economic pressures, and fragmented governance. This study develops and applies a GIS- and GNSS-based methodological framework for regional forest planning, tested in the “Bosco della Ficuzza, Rocca Busambra, Bosco del Cappelliere, Gorgo del Drago” Regional Nature Reserve (western Sicily, Italy). The main objective is to create a multi-layered Territorial Information System (TIS) that integrates high-resolution cartographic data, a Digital Terrain Model (DTM), and GNSS-based field surveys to support adaptive, participatory, and replicable forest management. The methodology combines the following: (i) DTM generation using Kriging interpolation to model slope and aspect with ± 1.2 m accuracy; (ii) road infrastructure mapping and classification, adapted from national and regional forestry survey protocols; (iii) spatial analysis of fire-risk zones and accessibility, based on slope, exposure, and road pavement conditions; (iv) the integration of demographic and land use data to assess human–forest interactions. The resulting TIS enables complex spatial queries, infrastructure prioritization, and dynamic scenario modeling. Results demonstrate that the framework overcomes the limitations of many existing GIS-based systems—fragmentation, static orientation, and limited interoperability—by ensuring continuous data integration and adaptability to evolving ecological and governance conditions. Applied to an 8500 ha Mediterranean biodiversity hotspot, the model enhances road maintenance planning, fire-risk mitigation, and stakeholder engagement, offering a scalable methodology for other protected forest areas. This research contributes an innovative approach to Mediterranean forest governance, bridging ecological monitoring with socio-economic dynamics. The framework aligns with the EU INSPIRE Directive and highlights how low-cost, interoperable geospatial tools can support climate-resilient forest management strategies across fragmented Mediterranean landscapes.

Keywords: GIS; GNSS; territorial information system (TIS); digital terrain model; forest planning; Mediterranean ecosystems



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1. Introduction

Mediterranean forest ecosystems are complex socio-ecological systems that deliver a wide array of ecosystem services, including timber and fuelwood provisioning, carbon sequestration, water regulation, erosion control, biodiversity conservation, and recreational opportunities [1,2]. These landscapes have been shaped by centuries of human interaction, resulting in a delicate balance between ecological integrity and socio-economic use. In recent decades, forest planning paradigms have evolved from extractive, timber-centric models to more integrated approaches that recognize the multifunctionality of forest landscapes. This transition emphasizes biodiversity conservation, ecosystem service valuation, climate change adaptation, risk mitigation, and stakeholder engagement as essential pillars of sustainable forest management [3].

This shift is particularly significant in Mediterranean regions such as Sicily, where forest ecosystems are ecologically sensitive and exposed to overlapping administrative governance complexities and socio-economic pressures. The Bosco della Ficuzza reserve is surrounded by rural municipalities (Corleone, Godrano, Marineo, Mezzojuso, Villafrati), where historical depopulation, urban expansion, and recreational pressures have strongly influenced land use dynamics. Understanding the interplay between population change and forest dynamics is therefore crucial for developing effective management strategies. In this context, forest planning must reconcile conservation objectives with fragmented land tenure, competing land uses, and the accelerating impacts of climate change, including increased drought frequency, wildfire risk, altered phenology, and biodiversity loss [4]. Recent studies highlight how GIS-based spatial analyses can contribute to modelling these impacts and identifying adaptive management strategies [5,6].

Despite the growing importance of data-driven planning, adaptive spatial forest management plans have not yet been fully implemented within the Bosco della Ficuzza reserve. Current management is guided by regional forest regulations and Natura 2000 plans, which provide only partial frameworks. This gap underscores the urgent need for methodological innovation. Our proposed framework is designed as a pilot adaptive model that can support future planning in Mediterranean protected areas.

Geographic Information Systems (GIS) and Global Navigation Satellite Systems (GNSS) have become foundational technologies in modern forest management, enabling planners to integrate diverse datasets, conduct spatial analyses, and improve the accuracy of field surveys. GIS platforms support scenario modeling, monitoring of landscape changes, and optimization of silvicultural and conservation strategies [7–12], while GNSS ensures precise georeferencing of ecological features and infrastructures, improving real-time decision-making [13]. However, despite their increasing use, many GIS-based forest planning systems remain fragmented and sectoral, often limited to specific applications such as wildfire risk mapping, biodiversity assessment, or infrastructure inventories [8,9]. These approaches typically lack interoperability, show weak integration between field-based surveys and high-resolution cartography, and are seldom structured to cope with the multi-level governance complexities typical of Mediterranean forest reserves. Moreover, most existing studies rely on static tools, which restrict their adaptability to dynamic and participatory planning processes [10–12].

As outlined in Table 1, our proposed methodological framework seeks to overcome these limitations—namely fragmentation, poor interoperability, static orientation, and limited governance adaptability—by integrating high-resolution topographic analysis, thematic cartography, and GNSS-based field surveys into a multi-layered Territorial Information System (TIS) specifically designed for Mediterranean protected areas. In contrast to previous sectoral or static approaches, this framework is conceived to be adaptive, participatory, and replicable, thereby enhancing infrastructure management, environmental

monitoring, fire-risk mitigation, and stakeholder engagement. Applied to the “*Bosco della Ficuzza, Rocca Busambra, Bosco del Cappelliere, Gorgo del Drago*” Regional Nature Reserve, it provides a scalable and innovative model that can be transferred to other Mediterranean forest ecosystems facing comparable ecological and governance challenges.

Table 1. Comparative overview of existing GIS-based forest planning approaches and the proposed integrated methodological framework for Mediterranean protected areas. The table highlights the main characteristics and weaknesses of existing approaches (fragmentation, sectoral focus, static design, and limited governance adaptability) compared with the proposed Territorial Information System (TIS), which integrates high-resolution topography, thematic mapping, and GNSS-based surveys to provide an adaptive, participatory, and replicable planning tool.

Aspect	Existing Approaches	Proposed Framework
Scope	Sectoral focus (wildfire risk, biodiversity, infrastructure) [6,7]	Integrated multi-layered Territorial Information System (TIS)
Data Integration	Limited integration between field surveys and cartography	Fusion of GNSS-based field surveys, high-resolution topography, and thematic mapping
Governance Adaptability	Weak consideration of multi-level governance complexities	Tailored to Mediterranean protected areas, adaptable to fragmented governance structures
Planning Approach	Static, non-participatory [8–10]	Adaptive, participatory, and replicable
Transferability	Context-specific, limited scalability	Scalable and replicable model for other Mediterranean forest ecosystems

In Italy, forest governance is highly decentralized, with regional administrations holding primary authority over environmental planning and resource management [14]. This has led to a mosaic of forest planning instruments and operational practices across the national territory, generating inconsistencies in methods, data standards, and implementation. Within this framework, regional nature reserves represent strategic test sites for the development of integrated forest planning methodologies. Their ecological richness and institutional relevance make them ideal contexts for piloting innovative approaches that can later be adapted to broader territorial scales.

This study addresses these gaps by proposing a GIS- and GNSS-based methodological framework for territorial forest planning that overcomes the limitations of existing approaches. Unlike previous studies, the framework integrates high-resolution topographic analysis, thematic mapping, and GNSS-based field surveys of infrastructures into a multi-layered TIS. This combination ensures both spatial accuracy and functional integration, enabling planners to manage roads, monitor ecological conditions, mitigate fire risks, and engage stakeholders in participatory decision-making within a single platform. The novelty of this framework lies in its replicability, adaptability, and operational focus, offering a scalable model that responds to the ecological sensitivity and governance challenges of Mediterranean protected forests.

The methodological framework was applied to the “*Bosco della Ficuzza, Rocca Busambra, Bosco del Cappelliere, Gorgo del Drago*” Regional Nature Reserve in western Sicily, one of the most important biodiversity hotspots in the Mediterranean basin [15]. Covering over 8500 hectares, the reserve provides an ideal case study for testing the potential of an integrated TIS to enhance decision-making in protected areas. The main objective of this research is to demonstrate how a multi-layered, GIS- and GNSS-based planning framework can contribute to more dynamic, data-driven, and participatory forest management across Mediterranean landscapes [16,17].

2. Materials and Methods

2.1. Study Area

The study was conducted within the “Bosco della Ficuzza, Rocca Busambra, Bosco del Cappelliere, Gorgo del Drago” Regional Nature Reserve, located in the western Sicilian Apennines, Italy (Figure 1). The reserve covers approximately 7398 ha and extends across six municipalities in the Metropolitan City of Palermo. Elevations range from 400 m to 1613 m a.s.l., resulting in a markedly heterogeneous landscape characterized by limestone-dominated relief, karstic morphologies, steep slopes, and rocky escarpments. These geomorphological features strongly condition soil formation, hydrological processes, and the accessibility of forest stands.

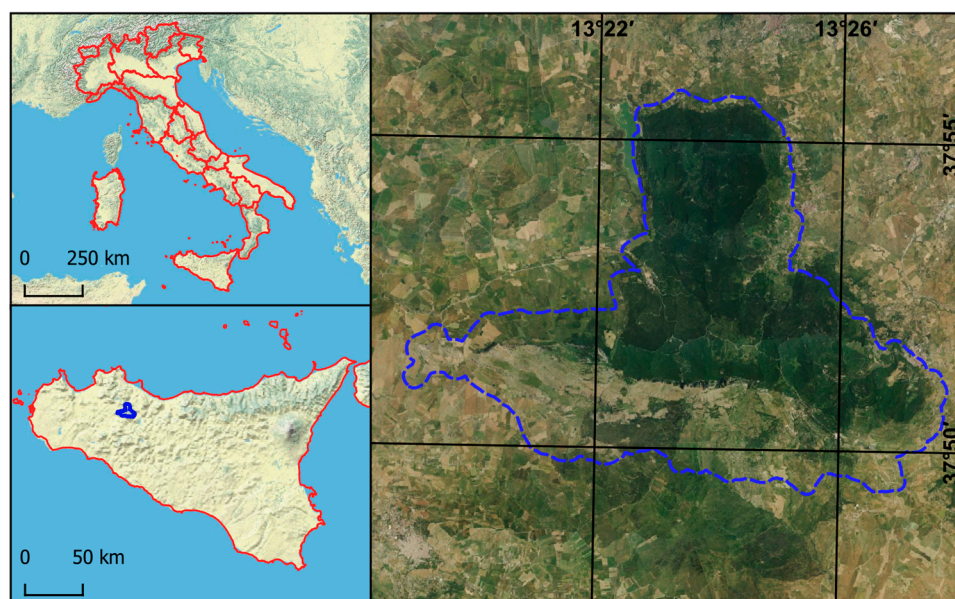


Figure 1. Localization of study area: “Bosco della Ficuzza, Rocca Busambra, Bosco del Cappelliere, Gorgo del Drago” Regional Nature Reserve.

The climate is typically Mediterranean, with mean annual precipitation between 900 and 1100 mm, concentrated in the autumn–winter months, and prolonged summer droughts that may extend for up to three to four months. Average annual temperatures range between 12 and 16 °C, with cold winters at higher elevations and hot summers in lower sectors, where maximum values often exceed 35 °C. This climatic regime contributes to recurrent wildfire risk, biodiversity shifts, and phenological changes, making the reserve particularly sensitive to climate change impacts.

Vegetation is dominated by native broadleaved species such as *Quercus ilex* L., *Quercus pubescens* Willd., *Fraxinus ornus* L., and *Castanea sativa* Mill., complemented by mid-20th century reforestation efforts with *Pinus nigra* J.F. Arnold and *Cedrus atlantica* Endl. for soil protection and landscape restoration. The reserve is a designated Natura 2000 site (ITA020010) and represents one of the most important biodiversity hotspots in the Mediterranean basin.

Culturally, the area is notable for the Real Casina di Ficuzza, built in 1799 by Ferdinand IV of Naples and Sicily, around which a small settlement developed. The reserve also plays an essential hydrological role, contributing to regional water regulation and landscape identity, and is managed under strict conservation measures by the Sicilian Regional Forestry Department.

2.2. Cartographic and Geospatial Data Sources

The geospatial support system developed for forest planning in the “*Bosco della Ficuzza, Rocca Busambra, Bosco del Cappelliere, Gorgo del Drago*” Regional Nature Reserve was based on the integration of diverse cartographic, topographic, and remote sensing datasets within a GIS environment. By combining vector and raster formats, we constructed a multi-layered Territorial Information System (TIS) capable of supporting advanced spatial analyses for forest governance and adaptive management.

The numerical Regional Technical Map (RTM, 1:10,000 scale) of Sicily constitutes the fundamental cartographic reference framework, providing high-resolution vector data on both natural and anthropogenic features, including hydrography, orography, vegetation, transportation networks, land use categories, buildings, infrastructures, technological systems, and administrative boundaries. Owing to its high metric precision and cartographic quality, the RTM is particularly suited for applications in territorial and urban planning, preliminary design of infrastructures, and the production of thematic maps. The dataset is represented in the Gauss projection, framed within the Unified European Geographic System, with plane coordinates referenced to the national Gauss-Boaga system. The territory of the reserve is included in nine sections of RTM (607080, 607160, 607120, 608050, 608060, 608090, 608100, 608130 and 608140),

To complement and validate these data, five topographic map sheets at 1:25,000 scale produced by the Italian Military Geographical Institute (IGM) were employed. These legacy maps were fundamental for cross-checking road alignments, slope configurations, and elevation features, ensuring continuity between historical cartographic sources and modern datasets.

The IGM maps, or “Topographic Map of Italy” at scale 1:25,000, consist of 2298 sections published until the end of the 90s. In this map are indicated roads, populated places, technological networks, vegetation, hydrography, and relief. Relief is indicated by contours at 25 m intervals, with shading. International and administrative (Region, Province and Municipality) boundaries are delineated. The projection is UTM conformal (Transverse Mercator) with reduction factor 0.9996. The study area is included in sections 258 I NE, 258 I SO, 258 I SE, 258 II NE, 259 III NO, and 259 IV SO.

To refine the representation of vegetation cover and anthropogenic features, we integrated high-resolution orthophotos (TerraItaly IT2000, 1 m spatial resolution) with aerial imagery from AGEA (Italian National Paying Agency). These remote sensing products allowed a more accurate classification of land cover and improved the detection of small-scale infrastructures that were not readily identifiable in vector datasets.

A Digital Terrain Model (DTM) was generated from digitized contour lines and spot heights using the Triangulated Irregular Network (TIN) method (Figure 1). This technique, widely applied in spatial modeling of complex terrains [16,17], enabled the reconstruction of the heterogeneous relief of the reserve and provided the basis for deriving key terrain attributes, including slope gradients, aspect orientations, and elevation zones. The calculation of slope and aspect was performed using the Spatial Analyst extension of ArcGIS 10.2 (Esri Inc., Redlands, CA, USA), applying standard raster-based surface analysis tools.

All geospatial layers were harmonized using the Gauss-Boaga projection (EPSG:9067, ETRF2000 datum), ensuring interoperability with national cartographic frameworks and compliance with Italian technical standards. This alignment was essential for guaranteeing compatibility with regional and national spatial data infrastructures and for facilitating future data sharing in accordance with the INSPIRE Directive (European Commission, 2007) [18].

2.3. GIS and Spatial Analysis Workflow

The GIS-based workflow adopted in this study was implemented in ArcGIS Desktop 10.8 (Esri Inc.), combining both vector and raster data processing to support forest planning activities within the reserve. The workflow began with the digitization and georeferencing of topographic features from scanned IGM maps and high-resolution orthophotos. This step ensured the alignment of legacy cartographic sources with current spatial datasets, thereby improving the positional accuracy and consistency of the base layers.

A Digital Terrain Model (DTM) was subsequently generated using the Triangulated Irregular Network (TIN) method within the ArcGIS 3D Analyst extension. The DTM provided the foundation for the derivation of key topographic parameters, including slope, aspect, and elevation, which are widely recognized in forestry literature as fundamental drivers of forest distribution, accessibility, and ecological vulnerability [19]. The complete topographic processing workflow—from elevation data to geomorphometric derivatives—is illustrated in Figure 2.

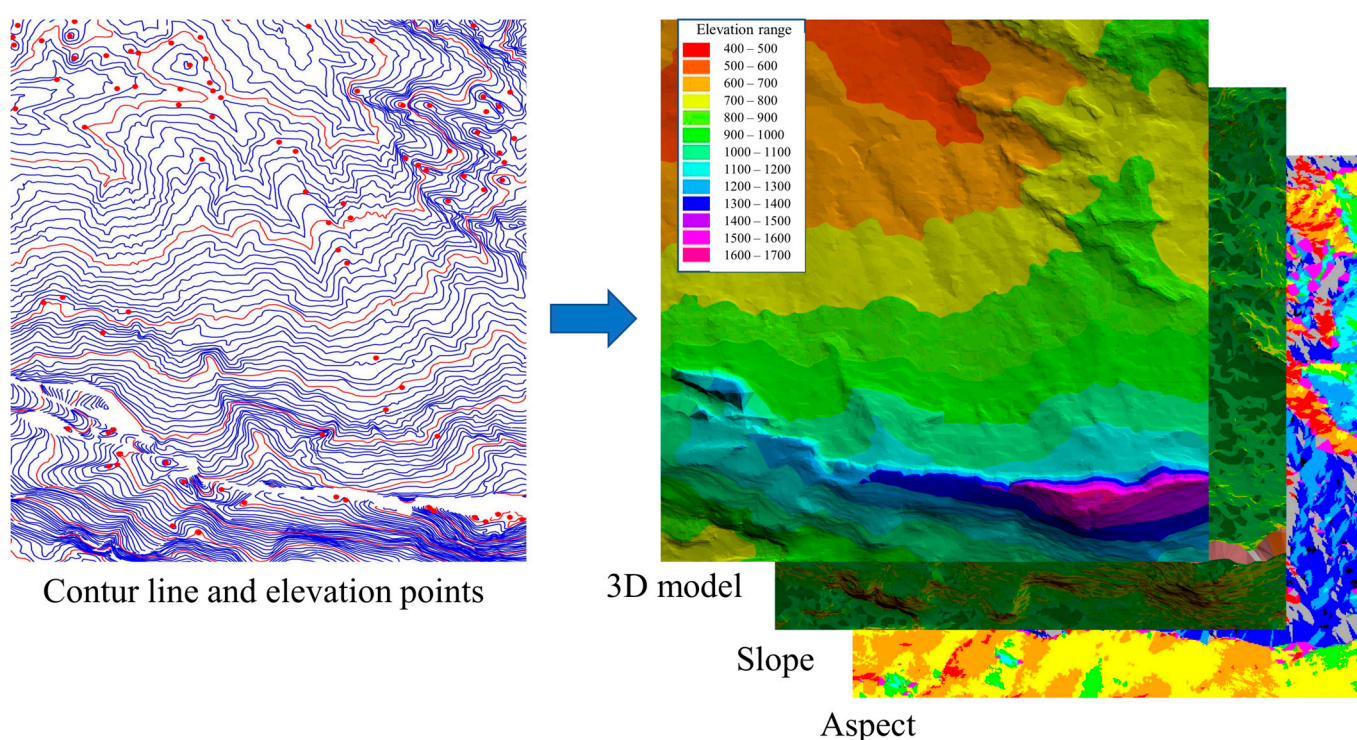


Figure 2. Workflow for terrain modeling and topographic analysis. Starting from contour lines and elevation points (left), a 3D terrain model is generated, which is then used to derive key geomorphometric layers such as slope and aspect (right). These outputs support spatial analysis in environmental planning and landscape characterization.

To support operational forest management, the derived terrain attributes were classified into zonal categories. Slope gradients were grouped into three classes ($<15^\circ$, $15\text{--}30^\circ$, $>30^\circ$), reflecting established thresholds for silvicultural feasibility, mechanized accessibility, and erosion risk. Aspect orientations and elevation bands were similarly categorized to capture variations in solar radiation exposure, soil moisture regimes, and species distribution potential. These thematic layers were then integrated into the Territorial Information System to assist in management zoning, fire-risk assessment, and conservation prioritization.

The geodatabase structure was designed following the standards of the INSPIRE Directive, incorporating consistent naming conventions, topology rules, and detailed metadata. This approach ensured interoperability, scalability, and long-term usability, allowing the database to function as a dynamic platform for future updates, data sharing, and integration with broader regional and national spatial data infrastructures.

Overall, this workflow enabled the GIS platform to provide multi-layered visualization and spatial analysis of forest resources, terrain characteristics, and infrastructure networks. By doing so, it established a robust analytical basis to support adaptive forest management and decision-making in the complex ecological and governance context of the Mediterranean protected area.

2.4. Road Infrastructure Survey

A comprehensive inventory of the forest road network and associated infrastructure within the reserve was carried out through systematic GNSS-based field surveys [20]. This activity was essential for mapping transportation assets that play a critical role in forest management, wildfire prevention, biodiversity monitoring, and visitor accessibility, while also testing the operational feasibility of low-cost geospatial technologies in forestry applications.

Field campaigns were conducted over three survey periods (2023–2025). Data acquisition employed an ArduSample receiver (Andorra la Vella, Andorra) equipped with a U-Blox ZED-F9P chip (Zurich, Switzerland), paired with a Samsung Galaxy Tab A9 tablet. Despite relying on consumer-grade components, the system delivered robust performance, achieving average horizontal accuracies of ± 1.5 m in standalone mode and better than ± 0.9 m with SBAS corrections, even under conditions of canopy cover and rugged topography. This accuracy was deemed sufficient for the mapping of secondary and tertiary forest roads, where sub-meter precision is not operationally required. These findings corroborate previous research highlighting the suitability of affordable GNSS solutions for participatory mapping and resource-limited contexts [20–22].

The tablet was equipped with QField software (version 2.7, OPENGIS.ch GmbH, Laax, Switzerland), which facilitated the direct capture of positional data, assignment of attributes, and integration with GIS workflows. Data were stored in shapefile (.shp) format and subsequently integrated into the geodatabase for spatial analysis.

Each road segment and point feature was classified following a standardized coding system adapted from the FAO Forest Roads Manual [23]. Attributes recorded for linear road features included surface type (asphalt, aggregate, improved, natural), width, drainage condition, slope gradient, transitability class, and canopy interference. Ancillary infrastructure such as bridges, signage, access gates, water collection points, fire lookout towers, shelters, and scenic viewpoints was also georeferenced and described (Table 2).

The collected data were then incorporated into a topologically consistent geodatabase (Figure 3). This integration allowed for spatial querying and multi-criteria evaluation of infrastructure conditions, accessibility, and functional significance. Furthermore, the road network was overlaid with slope and vegetation layers derived from the DTM, enabling the identification of segments most exposed to erosion processes, accessibility constraints, and wildfire vulnerability.

The resulting geospatial dataset represents a critical baseline for adaptive forest management, supporting operational planning, prioritization of maintenance, emergency response strategies, and long-term restoration efforts within the protected area.

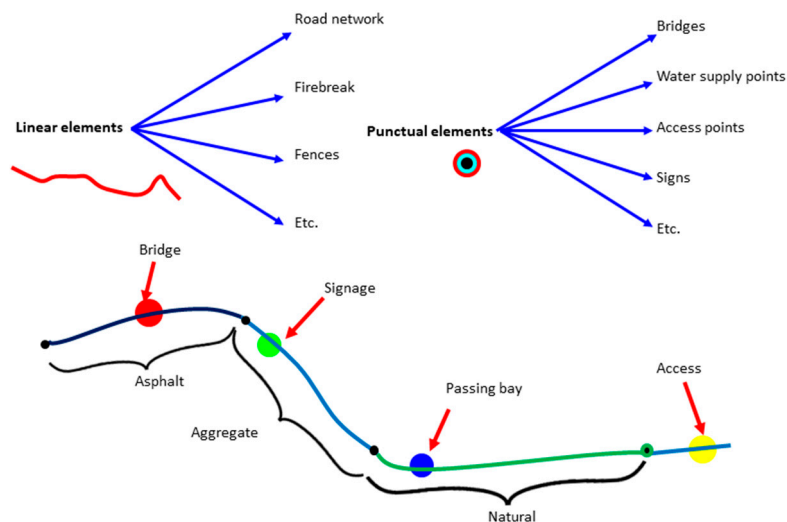


Figure 3. Linear and point features surveyed via GNSS technology, with a schematic representation of the elements as visualized within a GIS environment.

Table 2. Attributes of features acquired during the field survey. The left section displays the parameters recorded for forest road infrastructures (linear features), while the right section presents a selection of surveyed point features along with their respective characteristics.

Road Network		Punctual Element		
Parameter	Value	Element	Type	Condition
Road surface	Asphalt	Bridge	Wood	Excellent Good Mediocre Poor
	Aggregate		Concrete	
Transitability	Improved	Signage	Steel	
	Natural		Road	
	Excellent		Reserve zones	
Width	Minimum	Forest Infrastructure	Trails	
	Medium		Information	
Canopy interference	Yes	Forest Infrastructure	Fire lookout tower	
	No		Shelter	
			Storage	
			Other	

3. Results

The GIS-based methodological framework developed for this study allowed for the construction of a structured, and multi-thematic geospatial database supporting forest planning, infrastructure management, and environmental risk assessment within the Bosco della Ficuzza Regional Nature Reserve. The combination of terrain analysis, digital cartography, and field-based GNSS surveys produced a consistent set of outputs capable of informing spatially explicit decision-making processes. Figure 4 illustrates three key results derived from this integrated approach. Panel (a) shows the forest road network, classified into primary, secondary, tertiary roads, and overlaid on the terrain background within the boundaries of the nature reserve. Panel (b) presents the georeferenced locations of critical infrastructure and resource points, including water sources, lookout towers, barracks, and access structures, all essential for forest operations and fire prevention planning. Panel (c) provides a 3D elevation model of the area, with elevation bands to reflect topographic variability and support terrain-based analyses such as accessibility and erosion risk. To-

gether, these outputs demonstrate the operational potential of a GIS- and GNSS-based system in developing comprehensive and adaptable forest management tools for protected Mediterranean landscapes.

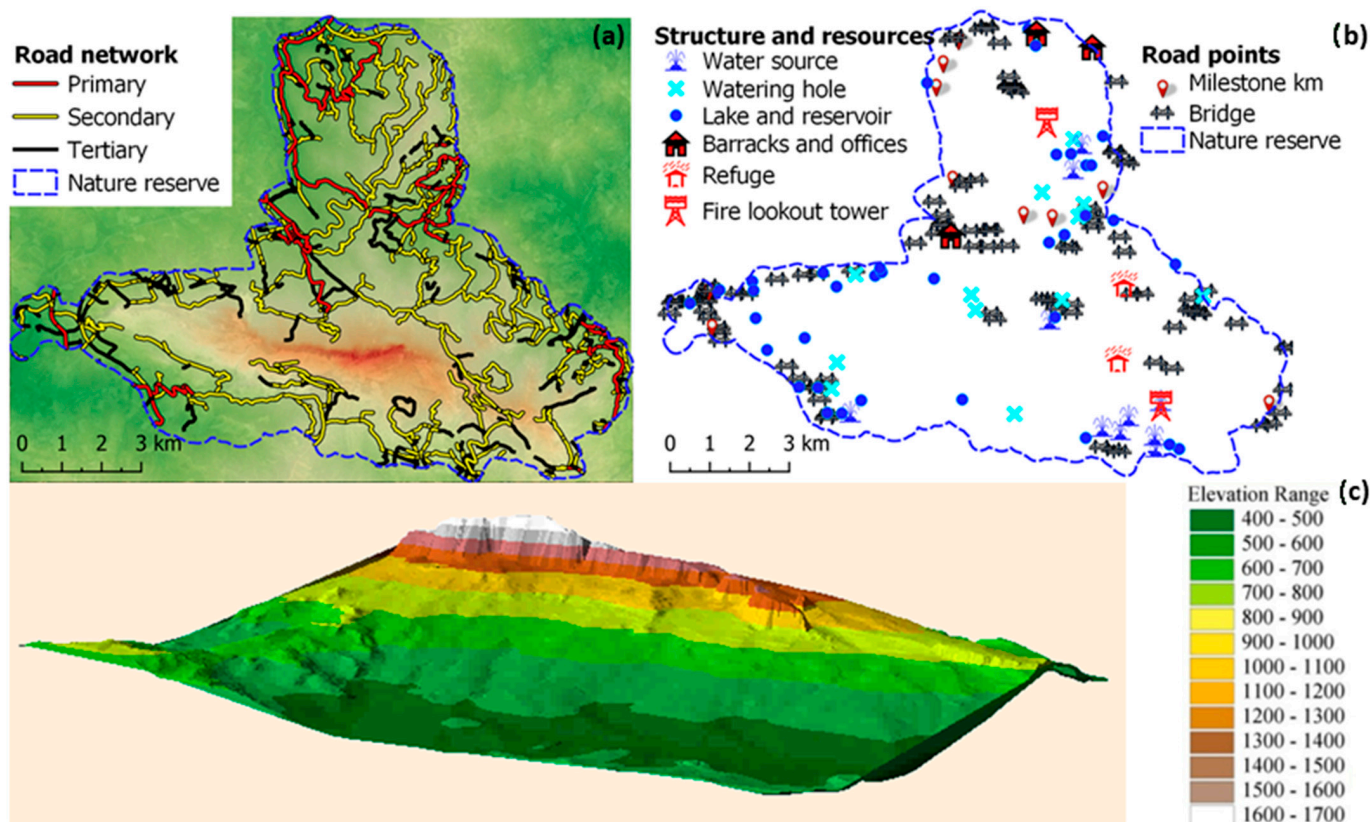


Figure 4. Results of GIS-Based Forest Planning and Road Network Assessment. Spatial and quantitative outputs from the GIS-based forest planning analysis in the “Bosco della Ficuzza, Rocca Busambra, Bosco del Cappelliere, Gorgo del Drago” Regional Nature Reserve. (a) Road network map showing the classification of primary, secondary, and tertiary roads. (b) Location of major structures and resources, including bridges and milestones. (c) 3D altimetric map showing the altimetric distribution of the area, in which the Rocca Busambra massif (1613 m above sea level) is clearly visible.

3.1. Digital Terrain Model and Thematic Layers

A high-resolution DTM was generated using the TIN approach, based on digitized contour lines with a 10 m interval and geodetic benchmarks collected during the GPS surveys. The resulting DTM demonstrated strong vertical consistency, achieving an error (differences between the estimated and the certain values) that in 66% of cases was contained within ± 1.2 m.

From the DTM, several key topographic layers were derived, including slope, aspect, and elevation maps. The slope analysis showed that steep slopes ($>30^\circ$) characterize more than 37% of the reserve’s surface area, highlighting significant constraints on accessibility, erosion risk, and fire management. Aspect analysis indicated a predominance of south-facing slopes, accounting for about 42% of the total area. These slopes, more exposed to solar radiation, represent critical zones in terms of fire risk and water stress, requiring targeted silvicultural interventions and conservation strategies. Elevation was classified into five altitudinal zones: less than 600 m (27% of the area), 600–800 m (35%), 800–1000 m (25%), 1000–1200 m (11%), and above 1200 m (2%). This stratification supports habitat characterization, forest typology zoning, and the design of altitudinally adapted management prescriptions.

The integration of these topographic layers with land use and vegetation data enabled the delineation of forest compartments and management units tailored to the biophysical variability of the reserve.

3.2. Forest Road Inventory and Accessibility Analysis

The field surveys resulted in the comprehensive mapping and classification of 173 road segments, encompassing approximately 284 km of linear infrastructure within the reserve (road density 33.4 m ha^{-1}). The road network was classified into three functional categories based on the role and structural characteristics of each segment. The first category includes the primary access roads, which represent 19% of the total network and serve as the main transportation corridors. The second category consists of secondary forest roads, accounting for about 37% of the network. These routes provide access to key forest management areas and are essential for routine silvicultural operations. The third category comprises tertiary service tracks, covering 30% of the mapped infrastructure. These tracks are primarily used for operational and maintenance purposes. This classification system serves as the foundation for evaluating road accessibility of the reserve, identifying priority areas for road maintenance, and informing the planning emergency response strategies in the context of forest protection and risk mitigation. A summary of the distribution of road types, associated road elements, and critical infrastructure and resource features within the protected area is provided in Table 3. Beyond the linear road network, the survey georeferenced 192 points of infrastructure features critical to forest management and visitor use. These included access gates, bridges, fire lookout stations, water collection points, and panoramic viewpoints, etc. Each infrastructure element was systematically described and classified according to its structural condition, functional role, and level of integration within the reserve's overall management framework, providing a spatially explicit inventory to support operational decision-making.

Table 3. Distribution of road network types (km) and road density (m ha^{-1}), road elements (no), structure (no) and resources (no) within the protected area.

Routes, Road Element and Density			Structure and Resources	
Primary roads	55 km	6.4 m ha^{-1}	Water source (no)	12
Secondary roads	104 km	12.2 m ha^{-1}	Watering hole (no)	14
Tertiary road	84 km	9.9 m ha^{-1}	Lake and reservoir (no)	36
Pathway	41 km	4.8 m ha^{-1}	Barracks and offices (no)	4
Milestone (no)	11		Refuge (no)	6
Bridge (no)	102		Fire lookout tower (no)	3

GNSS data accuracy evaluation demonstrated good performance of the ArduSample GNSS system, consistently achieving horizontal accuracy of approximately $\pm 0.58 \text{ m}$ and vertical accuracy of $\pm 0.85 \text{ m}$. The receiver demonstrated acceptable levels of accuracy for general mapping purposes, with greater deviations observed in forested and topographically complex areas. These results are consistent with the findings of [21,22], who similarly documented the performance of consumer-grade GPS in environments characterized by canopy cover and variable terrain. Despite its limitations, the low-cost GNSS device proved to be operationally suitable for the mapping of secondary and tertiary roads, particularly in scenarios where financial or technical resources are constrained.

The spatial integration of the road network with terrain slope and vegetation cover data enabled the identification of critical accessibility constraints and areas requiring urgent maintenance. This analysis yielded valuable insights for prioritizing infrastructure upgrades and directly supported the formulation of fire prevention strategies and ecological

plans within the reserve. The final output of the GIS workflow was a multi-layered geodatabase structured according to INSPIRE Directive principles, ensuring compliance with metadata and topology standards for spatial data management. This geodatabase incorporates vector layers representing roads, infrastructure elements, hydrography, hiking trails, vegetation units, and protected area boundaries, alongside raster layers depicting terrain attributes such as slope, aspect, and elevation.

The architecture of the TIS is designed to support advanced spatial querying, enabling users to filter road segments by slope class, evaluate accessibility in relation to road conditions, and analyze the spatial overlap between vegetation types and topographic exposure. This analytical functionality provides a versatile foundation for a wide range of forest planning applications. Specifically, the system facilitates the optimization of fire service and maintenance routes through least-cost path analysis. It also supports the identification of forest compartments that require silvicultural interventions by overlaying analyzed terrain data with ecological indicators. Additionally, it allows for the generation of accessibility heat maps, which help prioritize road maintenance activities and manage visitor circulation more effectively across the reserve.

3.3. Integration into a GIS-Based Territorial Information System

The final result of the methodological framework was the creation of a multi-layered GIS geodatabase, designed and organized according to INSPIRE-compliant metadata standards and topology rules. This geospatial database combines both vector and raster data, forming a reliable TIS capable that supports forest planning, infrastructure management, and environmental risk assessment within the reserve.

The vector layers include detailed representations of the road network, infrastructure elements, hydrography, hiking trails, vegetation polygons, and the delineation of protected area boundaries. Complementing these vector datasets, raster terrain models derived from the DTM provide continuous spatial coverage of key topographic attributes such as slope, aspect, and elevation. Each spatial feature is linked to attribute tables that enable advanced spatial queries, allowing users to filter data according to road condition, slope class, and infrastructure accessibility, thereby supporting targeted management interventions. The analytical capabilities of the geodatabase were demonstrated through several advanced spatial modeling applications. Least-cost path analysis was used to optimize the routing of fire service vehicles, ensuring quick access to high-risk areas while reducing exposure to difficult terrain. Overlay analysis combined topographic and vegetation data to identify forest compartments needing silvicultural interventions, helping prioritize management actions in areas most vulnerable to erosion, fire, or ecological stress. Additionally, accessibility heatmaps were created to visualize variations in road and infrastructure accessibility across the reserve, supporting strategic maintenance planning and informing visitors flow management.

The operational relevance and usability of the TIS were validated through a series of consultations with local forestry managers and reserve planners. Feedback from these stakeholders confirmed that the system addressed critical planning needs and provided a practical, scalable tool for improving spatial decision-making in the context of Mediterranean protected areas.

4. Discussion

The integration of GIS and GNSS into forest planning frameworks has emerged as a key driver of spatially explicit, data-driven decision-making, particularly in ecologically sensitive and topographically complex Mediterranean environments. These technologies enable the transformation of fragmented spatial data into coherent information systems,

supporting the analysis of terrain characteristics, infrastructure networks, and ecological constraints. The case study of the Bosco della Ficuzza Reserve illustrates how a structured geospatial methodology can facilitate the creation of a TIS that is not only multi-purpose—addressing silviculture, conservation, and fire prevention—but also multi-scale, adaptable to both site-specific interventions and broader landscape-level planning. Such systems are fundamental for advancing sustainable forest governance in protected areas, where competing environmental, social, and institutional factors must be reconciled through integrative and transparent planning processes.

4.1. Significance of Topographic and Terrain Analysis

Creating a high-resolution DTM was pivotal in deriving key topographic features—such as slope, aspect, and elevation—that critically inform spatial forest planning. These variables are not only key to understanding the landscape's biophysical limitations but also essential for guiding management strategies related to fire prevention zoning, erosion risk reduction, and the placement of forest infrastructure. Terrain analysis provides the basis for predicting ecological vulnerabilities and operational challenges, allowing forest managers to develop targeted interventions that address site-specific conditions.

Comparable methodologies have been successfully applied in forest planning across mountainous regions of Europe and the Mediterranean, where steep and heterogeneous terrains present significant management complexities [24,25]. These studies consistently highlight the role of terrain modeling in supporting ecologically sensitive interventions, particularly in areas affected by soil erosion, wildfire risk, and biodiversity conservation pressures. In the Bosco della Ficuzza Reserve, terrain analysis revealed that more than 37% of the area is characterized by steep slopes exceeding 30%, which significantly limits mechanized access and increasing vulnerability to surface runoff and landslides. In addition, the predominance of south-facing slopes, covering approximately 42% of the reserve, exposes these areas to intense solar radiation and prolonged drought stress during the Mediterranean dry season. Such exposure conditions exacerbate fire risk and influence vegetation structure and species composition.

These findings are consistent with broader Mediterranean forest ecology literature, which underscores the role of terrain exposure and elevation gradients on species distribution, ecosystem resilience, and fire dynamics [26,27]. In this context, terrain-adapted silvicultural practices, including selective thinning, erosion control measures, and firebreak placement, are essential for enhancing forest resilience and reducing the vulnerability of steep, south-facing slopes.

4.2. Road Network Assessment and GNSS Applications

The systematic inventory and classification of the forest road network, carried out through GNSS-supported field surveys, established a reliable spatial baseline for infrastructure management and accessibility planning. The deployment of GNSS technology enables the precise mapping of critical infrastructure assets with centimeter-level accuracy, particularly valuable for documenting primary access routes and strategic service points. The study also demonstrates that consumer-grade GNSS devices, despite their lower positional accuracy, yielded results sufficiently robust for general road mapping tasks. This finding underscores the operational viability of low-cost geospatial technologies in supporting basic infrastructure surveys, especially in less critical areas or when budgetary constraints limit access to high-precision equipment.

The demonstrated performance of low-cost GNSS receivers reinforces their applicability in participatory mapping and community-based forest monitoring, where local stakeholders or non-specialist users can contribute to data collection with minimal technical

barriers. This approach aligns with previous studies advocating for the democratization of geospatial data acquisition, particularly in resource-limited contexts [22,28]. In rural Sicilian landscapes, where public investment in forestry infrastructure is often limited, integrating open-source GIS platforms and affordable GNSS technologies represents a pragmatic pathway to expanding operational capacity and enhancing data-driven decision-making.

The road classification framework used in this study not only standardizes the categorization of road types based on their structural features and functional roles but also supports spatial querying and scenario analysis. When combined with terrain slope and vegetation cover data, this classification system allows for multi-criteria assessments of road maintenance needs and accessibility risks. These analyses help forest managers identify infrastructure segments that need urgent repairs, evaluate their vulnerability to erosion or blockage, and improve maintenance planning in relation to ecological sensitivity. This integrative approach is consistent with the emerging trend in European forest planning toward multi-criteria decision support systems (DSS), which aim to balance infrastructure functionality, ecological risk mitigation, and financial constraints in the formulation of forest management strategies [29,30]. The application of such systems in protected areas enhances the capacity for informed, transparent, and adaptive planning, particularly in landscapes where competing conservation and operational objectives exist.

4.3. Replicability and Scalability of the GIS-Based Framework

A central outcome of this study is the development of a modular and adaptable GIS-based methodology that can be readily replicated in other Mediterranean protected areas characterized by similar ecological and governance complexities. The geodatabase architecture, designed with a modular structure and compliant with the INSPIRE Directive's interoperability standards [16,31], ensures the long-term usability, scalability, and integration of the system within broader spatial data infrastructures at the regional, national, and European levels. The flexibility of the TIS is further enhanced by its capacity to incorporate additional thematic layers beyond the core forestry and terrain data. Additional data layers, such as biodiversity monitoring datasets, fire regime histories, habitat suitability models, and tourism infrastructure inventories, can be seamlessly integrated into the system. This capacity extends the applicability of the framework beyond traditional forestry-focused planning toward a more holistic approach to land use management, supporting both conservation objectives and socio-economic development. The resulting multi-functionality positions the framework as a dynamic decision support tool, capable of addressing the interconnected challenges of protected area governance, sustainable tourism, and climate adaptation.

The replicability of this approach is particularly relevant in the context of European Union biodiversity policies and green infrastructure strategies, which emphasize spatial planning as a foundational element of sustainable land use management [31]. By aligning forest planning practices with these policy frameworks, local and regional authorities in Mediterranean landscapes such as Sicily can enhance their eligibility for funding under European environmental programs, including LIFE+, Horizon Europe, and the European Green Deal. Furthermore, the methodological framework supports the implementation of ecosystem-based adaptation strategies, which encourage the use of spatially explicit planning tools to enhance the resilience of natural systems and local communities to climate change impacts [32]. Through its replicable structure and interoperability, the proposed GIS-TIS offers a scalable platform for Mediterranean forest landscapes facing similar ecological pressures, institutional fragmentation, and socio-economic vulnerabilities.

4.4. Institutional Implications and Capacity Building

The successful implementation and long-term sustainability of a GIS-based Territorial Information System (TIS) are not solely dependent on technological robustness, but equally on institutional capacity, interdisciplinary collaboration, and the establishment of effective governance frameworks. While the technical architecture developed in this study provides a solid foundation, its long-term relevance requires sustained investment in human capital. This includes specialized training in geospatial technologies, data management, and spatial analysis for forestry personnel and decision-makers.

Integrating the TIS into existing regional forest inventories and planning tools is vital to prevent fragmentation and ensure alignment with ongoing management efforts. Incorporating the system into institutional workflows will promote its use as a routine planning resource instead of a standalone technological solution. Additionally, establishing continuous feedback between the digital platform and on-the-ground forest management is essential for keeping spatial data up-to-date and reflective of real-world conditions. This ongoing process supports adaptive planning, allowing forest managers to improve strategies in response to shifting environmental conditions and operational challenges. In the context of the Bosco della Ficuzza Reserve, future advancements should prioritize the integration of biodiversity monitoring datasets, including indicators such as species richness, habitat quality, and ecological connectivity. Incorporating fire regime analyses, based on both historical and real-time fire data, would improve the system's ability to support fire prevention and post-disturbance recovery planning. Equally important is encouraging stakeholder participation, which can be achieved through the development of WebGIS portals, open-access data platforms, and citizen science initiatives. These participatory tools would democratize access to spatial information, increase transparency, and empower local communities and stakeholders to contribute to forest governance.

By transitioning from a static mapping environment to a dynamic and participatory planning platform, the TIS can support a more inclusive and resilient approach to forest management. This change aligns with larger trends in environmental governance, emphasizing the co-production of knowledge, collaborative decision-making, and the use of digital tools to boost transparency and accountability in protected area management.

5. Conclusions

This study presented a GIS- and GNSS-based methodological framework to support territorial forest planning in Mediterranean protected areas, with a specific application to the Bosco della Ficuzza Regional Nature Reserve in Sicily. By integrating high-resolution terrain analysis, thematic mapping, and field-based infrastructure surveys into a multi-layered Territorial Information System (TIS), the framework moves beyond fragmented and sectoral approaches—such as wildfire-only mapping, biodiversity inventories, or static infrastructure records—by offering a dynamic, interoperable, and participatory tool. The results demonstrate how this integration improves spatial decision-making, enabling managers to address critical priorities such as fire prevention, erosion control, habitat preservation, and infrastructure maintenance in a holistic manner.

The topographic analysis identified key geomorphological constraints, while the comprehensive road network inventory confirmed the feasibility of scalable monitoring approaches using both high-precision and low-cost GNSS technologies. Importantly, the inclusion of consumer-grade receivers underlines the potential for participatory mapping and cost-effective data collection in resource-limited contexts, expanding the accessibility of advanced planning tools to a wider range of stakeholders. Unlike static cartographic products, the resulting TIS operates as a flexible platform, compliant with INSPIRE standards, that can support multi-criteria spatial analysis, least-cost path modeling, and risk

assessment, thereby aligning operational forest planning with European biodiversity and climate adaptation strategies.

Nevertheless, several limitations remain. The framework has not yet incorporated multispectral remote sensing data or systematic ecological field validation, and GNSS accuracy proved to be reduced under dense canopy conditions. Furthermore, stakeholder participation in the current stage was limited, and the temporal analysis was static, preventing full evaluation of dynamic forest processes. Addressing these aspects in future developments will require the integration of time-series environmental monitoring (e.g., fire history, land cover dynamics), advanced remote sensing, and participatory WebGIS platforms, fostering adaptive and collaborative governance.

In conclusion, the proposed methodological framework contributes to the digital transformation of Mediterranean forest planning, offering a replicable and operational model that reconciles ecological sensitivity with institutional complexity. By addressing both technical and governance challenges, it provides a foundation for more adaptive, participatory, and sustainable management of protected landscapes.

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