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GEOINFORMATION WEB SYSTEM FOR ASSESSING THE STATE OF CARPATHIAN FOREST ECOSYSTEMS USING REMOTE SENSING DATA

Abstract. The article addresses the pressing issue of developing modern software tools for automated monitoring of forest ecosystem dynamics in the Ukrainian Carpathians. It is emphasized that traditional forest inventory approaches, based on periodic field expeditions, are insufficiently responsive and economically burdensome, particularly in complex mountainous terrain. The feasibility of integrating Earth remote sensing (ERS) technologies and geographic information systems (GIS) into forestry practices is substantiated. The research aims to develop a web-based information system capable of processing satellite imagery (notably Sentinel-2), calculating spectral vegetation indices (NDVI), and visualizing analytical results through interactive cartographic layers. The paper presents the architecture of the proposed solution, which is grounded in a microservice approach utilizing the FastAPI framework, the PostgreSQL/PostGIS spatial database, and the Leaflet mapping library. The process of designing the logical geodatabase model, ensuring efficient storage of both vector objects (forest compartments and subcompartments) and raster image metadata, is described in detail. The practical implementation of the application's server-side components is showcased, including mechanisms for asynchronous request handling, JWT authentication, and NDVI calculation algorithms employing the Rasterio and NumPy libraries. The section on specialized calculations provides a comparative performance analysis of spatial SQL queries with and without GiST indexing, confirming a speed enhancement exceeding 100 times. Furthermore, a validation of the vegetation index calculation accuracy was conducted by comparing results with ground-based spectrometry data. It has been established that deploying the developed system reduces the time required for forest area monitoring by a factor of 5–7 compared to traditional ground survey methods,

thereby demonstrating the high economic and environmental efficiency of the proposed approach.
Keywords: geographic information systems, remote sensing, PostGIS, FastAPI, NDVI, forest monitoring, spatial data, web mapping.

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ГЕОІНФОРМАЦІЙНА ВЕБСИСТЕМА ОЦІНЮВАННЯ СТАНУ ЛІСОВИХ ЕКОСИСТЕМ КАРПАТ ЗА ДАНИМИ ДИСТАНЦІЙНОГО ЗОНДУВАННЯ

Анотація. У статті розглядається актуальна проблема створення сучасного програмного інструментарію для автоматизованого спостереження за динамікою лісових екосистем Українських Карпат. Наголошується, що класичні підходи до лісовпорядкування, які базуються на періодичних польових експедиціях, є недостатньо оперативними та економічно витратними, особливо в умовах складного гірського рельєфу. Обґрунтовано доцільність інтеграції технологій дистанційного зондування Землі (ДЗЗ) та геоінформаційних систем (ГІС) у практику ведення лісового господарства. Метою дослідження є розробка веборієнтованої інформаційної системи, яка дозволяє обробляти супутникові знімки (зокрема, Sentinel-2), обчислювати спектральні вегетаційні індекси (NDVI) та візуалізувати результати аналізу у вигляді інтерактивних картографічних шарів. У роботі представлено архітектуру запропонованого рішення, що базується на мікросервісному підході з використанням фреймворку FastAPI, просторової бази даних PostgreSQL/ PostGIS та картографічної бібліотеки Leaflet. Детально описано процес проєктування логічної моделі бази геоданих, яка забезпечує ефективне зберігання як векторних об'єктів (лісові квартали та виділи), так і метаданих растрових зображень. Наведено результати практичної реалізації серверної частини застосунку, зокрема механізми асинхронної обробки запитів, JWT-автентифікації та алгоритми розрахунку NDVI із застосуванням бібліотек Rasterio та NumPy. У розділі спеціальних розрахунків здійснено порівняльний аналіз продуктивності просторових SQL-запитів з використанням GiST-індексів та без них, що підтвердило зростання швидкодії у понад 100 разів.

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Також проведено валідацію точності обчислення вегетаційного індексу шляхом порівняння з даними наземної спектрометрії. Встановлено, що впровадження розробленої системи дозволяє скоротити часові витрати на моніторинг лісових масивів у 5–7 разів порівняно з традиційними методами наземного обстеження, що свідчить про високу економічну та екологічну ефективність запропоно-ваного підходу.

Ключові слова: геоінформаційні системи, дистанційне зондування, PostGIS, FastAPI, NDVI, моніторинг лісів, просторові дані, вебкартографія.

Problem statement. The forest tracts of the Ukrainian Carpathians represent a strategic natural asset, fulfilling essential water regulation, climate control, and recreational functions. Nevertheless, the current condition of these ecosystems is marked by escalating anthropogenic and climatic pressures, notably the spread of spruce forest dieback, illegal logging activities, and the aftermath of windthrow events.

The existing forest observation framework in Ukraine predominantly relies on ground-based taxation methods, with update intervals extending to 10-15 years [1]. Such infrequent data refreshment is critically inadequate for the timely identification and mitigation of dynamic adverse processes. Moreover, a substantial portion of mountainous terrain remains largely inaccessible for systematic field surveys, thereby fostering an environment conducive to the accumulation of latent threats and impeding the implementation of sustainable forest management practices predicated on precision and promptness.

An efficacious alternative to conventional methodologies lies in the application of Earth remote sensing (ERS) technologies. Specifically, satellite data acquired through the European Copernicus program’s Sentinel-2 mission provides multispectral imagery characterized by a spatial resolution of up to 10 meters and a revisit frequency of approximately five days [2]. Spectral reflectance analysis facilitates a quantitative assessment of photosynthetically active biomass via the computation of vegetation indices, such as the Normalized Difference Vegetation Index (NDVI). Nonetheless, a substantial gap persists between the availability of raw satellite data streams and the capacity of forestry practitioners–who frequently lack advanced proficiency with professional GIS software suites–to harness this information effectively. Consequently, there exists a pressing imperative to engineer a specialized, accessible, and functionally robust information system designed to automate the acquisition, processing, and interpretation of geospatial data tailored explicitly to the monitoring requirements of the Carpathian region’s forests.

Analysis of recent research and publications. The utilization of GIS and remote sensing technologies within the forestry domain has been the subject of

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extensive scholarly inquiry, encompassing both national and international research efforts. Within the global scientific community, sophisticated cloud-based platforms such as Google Earth Engine are widely adopted, offering access to vast petabyte-scale archives of satellite imagery coupled with integrated analytical capabilities. Commercial solutions, including EOSDA Crop Monitoring, although primarily engineered for agricultural land surveillance, can be adapted to evaluate forest vegetation health [3]. Furthermore, the market offers comprehensive desktop GIS packages (e.g., QGIS, ArcGIS) endowed with exhaustive geoprocessing functionalities; however, these tools demand significant user expertise and substantial hardware resources [1].

A critical evaluation of these resources reveals that the majority of extant solutions are either excessively complex for the intended end-user (such as a district forester or an environmental inspector) or possess a generic character that fails to accommodate the specific nuances of localized forest inventory data. Non-governmental forestry organizations and state forest enterprises require a tailored instrument capable of integrating proprietary spatial datasets (e.g., compartment networks, subcompartment boundaries) with current satellite imagery, obviating the need to master intricate GIS software environments.

This particular niche–the development of a lightweight, scalable web application featuring an open API and an intuitive user interface–remains insufficiently explored, particularly concerning the regional characteristics of the Ukrainian Carpathians.

The present study introduces an approach grounded in a contemporary technological stack comprising Python, FastAPI, and PostGIS, which is specifically designed to surmount the identified limitations.

Research objective. The objective of this paper is to elucidate the processes involved in the design, development, and performance evaluation of a web-oriented information system engineered to automate the monitoring of forest vegetation health within the Ukrainian Carpathians, utilizing geospatial data analysis and satellite imagery interpretation.

Presentation of the main research material. The architectural foundation of the developed system is predicated upon a classical three-tier model, which ensures a distinct separation of concerns among its constituent components: the presentation layer (client-side web interface), the business logic layer (application server), and the data persistence layer (geodatabase). Interaction between these layers is orchestrated via a RESTful API, with the standardized GeoJSON format employed for the transmission of geometric entities.

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Fig. 1. Component architecture of the vegetation monitoring information system

As the cornerstone of the server-side implementation, the asynchronous FastAPI web framework was selected [4]. This choice is predicated on its exceptional performance in handling input/output-bound operations (such as file uploads and database queries), its inherent data validation mechanisms facilitated by Pydantic models, and its capability for automatic generation of interactive API documentation (Swagger UI). The latter feature markedly accelerates the development and testing lifecycle of API endpoints. The application adheres to a modular design philosophy, wherein distinct routers are designated for managing authentication (JWT-based), handling forestry data (CRUD operations for subcompartments and compartments), and processing satellite imagery.

For the storage and manipulation of spatial information, the PostgreSQL database management system augmented with the PostGIS extension was deployed [5]. PostGIS transforms a conventional relational database into a fully-fledged spatial database management system (DBMS), compliant with Open Geospatial Consortium (OGC) standards, thereby enabling the storage of vector geometries and the execution of complex geospatial queries. In the context of this research, a logical data model was meticulously designed, the primary entities of which include: "Forestry District", "Compartment", "Subcompartment" (comprising attributes such as dominant species, age, site index, and Polygon-type geometry referenced in the UTM coordinate system), "Satellite Image" (metadata), and "Analysis Result". To guarantee high-performance execution of spatial queries (e.g., intersection searches, point-in-polygon checks), GiST indexes were systematically created on the relevant geometry columns.

The interface between the Python application and the PostGIS database is mediated by the SQLAlchemy Object-Relational Mapper (ORM) and its geospatial extension, GeoAlchemy2 [6]. This architectural decision permits developers to interact with database records as native Python objects, with automated serialization

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of geometries into Well-Known Binary (WKB) or Well-Known Text (WKT) representations. This approach substantially enhances code security and long-term maintainability.

Among the most computationally intensive modules within the system is the satellite data processing component. This module implements the algorithm for calculating the Normalized Difference Vegetation Index (NDVI) according to the standard formula::

$$NDVI = (NIR - RED) / (NIR + RED) \quad (1),$$

where NIR denotes spectral reflectance in the near-infrared band (Sentinel-2 Band 8), and RED represents reflectance in the red band (Sentinel-2 Band 4) [2].

The processing workflow entails loading a GeoTIFF file utilizing the Rasterio library [7], extracting the requisite spectral bands as NumPy arrays, and performing element-wise computation of the index. To derive aggregated statistical measures for individual forest subcompartments, a raster masking technique is employed, wherein the raster dataset is clipped using the subcompartment’s polygon geometry. Subsequently, the arithmetic mean NDVI value within the masked area is calculated, with NoData pixel values explicitly excluded from the computation.

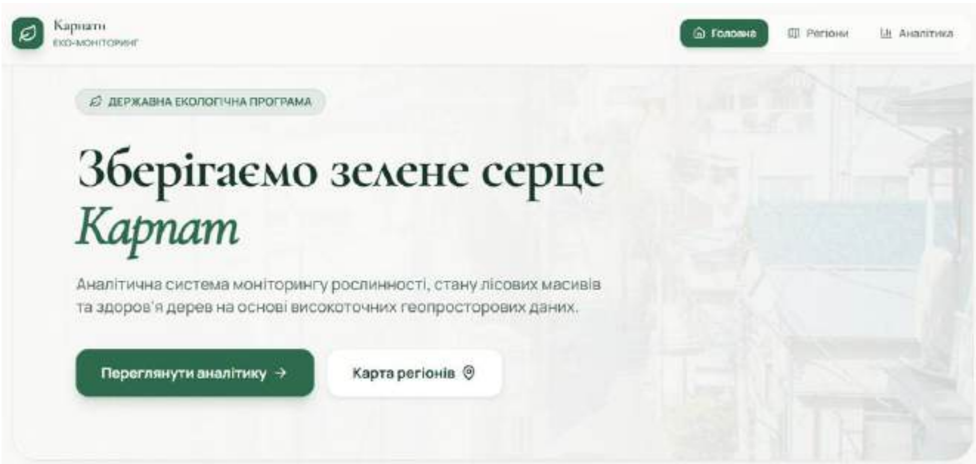

Fig. 2. Main interface of the web application

The client-side component is implemented as a Single Page Application (SPA), with an interactive map powered by the Leaflet library serving as its central element. The map dynamically fetches vector layers in GeoJSON format from the server-side API and renders them atop a base layer (e.g., OpenStreetMap or satellite imagery basemap). Thematic mapping functionality has been realized, enabling the conditional coloring of subcompartment polygons based on the calculated NDVI

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value ranges: from red (indicating critically low vegetation vigor or stress) to dark green (denoting healthy, dense forest cover). Users are afforded the capability to retrieve attribute information pertaining to a specific subcompartment via a popup window and to examine the temporal evolution of NDVI through a graphical representation of historical data spanning the entire observation period.

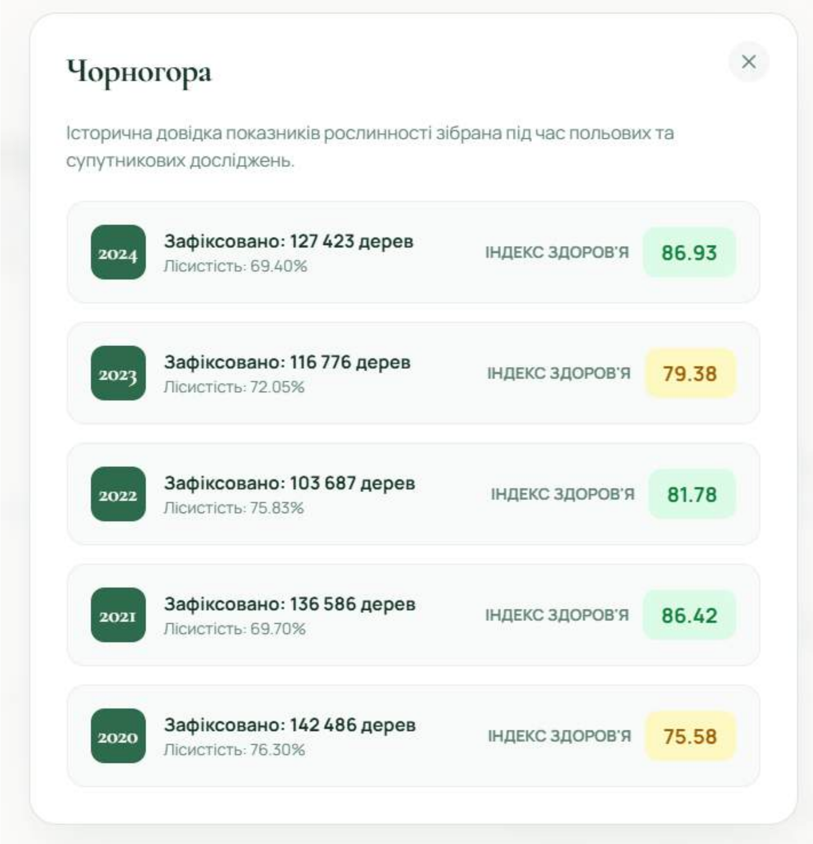

Fig. 3. Thematic coloring of forest subcompartments based on NDVI values

A dedicated segment of this study addresses specialized calculations that substantiate the efficacy of the proposed technical solutions. The initial phase involved an empirical investigation into the performance characteristics of spatial queries executed within the PostGIS environment. For the purpose of this experiment, a synthetic test dataset comprising 50,000 polygons–representative of forest subcompartments–was generated. The execution time of representative query types (bounding box searches, point-in-polygon containment checks, and spatial joins) was systematically compared under two conditions: in the absence of a spatial index and following the creation of a GiST index on the geometry column. The empirical results demonstrated that the implementation of a spatial index accelerates query execution by factors ranging from tens to hundreds of times. For instance, while polygon intersection queries required several seconds (up to 15 seconds) to execute without

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an index, the indexed execution time was reduced to mere tens of milliseconds. Such performance gains are deemed essential for ensuring the responsiveness and interactivity of the web-based user interface.

A subsequent critical aspect involved the assessment of NDVI calculation accuracy based on Sentinel-2 imagery. A comparative analysis was conducted, juxtaposing NDVI values generated by the developed software module against ground-truth measurements acquired using a field spectroradiometer across ten designated test sites.

The computed mean relative error across all test plots was determined to be 7.8%, a margin considered acceptable for the purposes of operational forest health surveillance. The most pronounced discrepancies (reaching up to 12.5%) were observed on plots characterized by sparse tree cover, where soil background exerts a substantial influence on the composite spectral signature. For closed-canopy forest stands, the observed accuracy was considerably higher.

The economic viability and practical expediency of system deployment are corroborated by a quantitative analysis of time expenditure required for forest area assessment. For a notional forestry district encompassing an area of 5,000 hectares, conventional comprehensive ground patrolling necessitates the involvement of a ranger team for a period ranging from two to three weeks. Conversely, the utilization of the developed web application facilitates an automated analysis of a satellite image within a timeframe of 15 to 30 minutes, enabling the swift identification of zones exhibiting anomalous NDVI values–areas with a high probability of underlying issues. Subsequent field verification activities can then be confined exclusively to these pre-identified, localized zones, thereby reducing the total inspection duration to a mere one to two days. Consequently, a five- to seven-fold enhancement in monitoring efficiency is achieved.

Conclusions. The conducted research culminated in the development and validation of a prototype web-oriented information system tailored for the monitoring of forest vegetation health utilizing geospatial data. The proposed solution, built upon a modern technological foundation comprising FastAPI, PostgreSQL/PostGIS, and Leaflet, successfully automates critical workflows: from the import and persistent storage of spatial forest inventory data to the processing of Sentinel-2 satellite imagery and the subsequent visualization of computed NDVI results.

It has been empirically demonstrated that the adopted three-tier architecture, incorporating the asynchronous FastAPI framework alongside the PostGIS spatial DBMS, delivers the requisite scalability and operational performance. The strategic implementation of GiST indexes on geometric attribute columns yielded a greater than 100-fold acceleration in spatial query execution, thereby ensuring seamless and responsive user interaction with cartographic data, even when managing substantial data volumes.

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A comprehensive data processing pipeline has been successfully implemented, encompassing user authentication, management of cartographic layers, automated NDVI computation, and analytical report generation. The intuitive web interface, underpinned by the Leaflet library, effectively democratizes access to sophisticated geospatial analysis, rendering it accessible to forestry professionals lacking specialized GIS training.

Accuracy assessments have indicated that the margin of error for NDVI calculations derived from Sentinel-2 data does not exceed 12.5%, a threshold deemed adequate for the timely detection of adverse trends in forest stand health. A comparative analysis of time expenditure confirms that system deployment yields a five- to seven-fold reduction in the time required for primary forest area assessment. This translates into tangible economic benefits and substantially enhances the expediency of managerial decision-making processes.

Prospects for future research endeavors are oriented toward the functional augmentation of the system. This includes the integration of supplementary spectral indices (such as the Normalized Difference Moisture Index for water stress evaluation) and the implementation of machine learning algorithms for automated tree species classification and the detection of illegal logging activities through time-series analysis of satellite imagery. Furthermore, optimization of raster data processing workflows is envisioned through the potential offloading of computational tasks to the database layer via the utilization of PostGIS Raster capabilities

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