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FORMING THE CONCEPTS OF BIOECONOMY, SUSTAINABLE DEVELOPMENT, AND GEOINFORMATION TECHNOLOGIES IN PROFILE SCHOOL STUDENTS AND HIGHER EDUCATION APPLICANTS DURING THE STUDY OF GEOGRAPHICAL AND ECOLOGICAL

Oleksandr Lukash*, Ruslan Shevchenko, Ivan Shyrokyi, Yuliia Petryk, Daryna Usyk, Oleksandr Parkhomenko, Oleksandr Yakovenko

Department of Ecology, Geography and Nature Management, T.H. Shevchenko National University “Chernihiv Colehium”, 53 Hetmana Polubotka Street, Chernihiv,14013, Ukraine.

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***Corresponding Author:** Oleksandr Lukash
Department of Ecology, Geography and Nature Management, T.H. Shevchenko National University “Chernihiv Colehium”, 53 Hetmana Polubotka Street, Chernihiv,14013, Ukraine.
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ABSTRACT

Modern global challenges require a systemic transition toward sustainable development and a green bioeconomy, demanding the continuous ecologization and digitalization of education across all levels. This article substantiates the prospective methodological foundations and structural design for forming the integrated concepts of sustainable development, the bioeconomy, and geoinformation technologies through project-based learning, ensuring a functional continuum between profile secondary schools and higher education institutions. Utilizing a multi-dimensional comparative methodology grounded in the “Bray and Thomas cube” framework, a rigorous curricular mapping was performed on the newly designed Ukrainian model geography program for senior profile tracks (Grades 10–12) alongside university syllabi for geography and ecology specialties. The proposed pedagogical model establishes a structured curriculum alignment, integrating bioeconomic definitions within school geography themes and qualitatively deepening this baseline within university disciplines such as “Environmental Monitoring”, “GIS in Geographical Research” and “GIS in Environmental Research”. Furthermore, the study maps the structural integration of advanced Geographic Information Systems and Remote Sensing of the Earth

workflows across vital bioeconomic sectors in master's theses, ranging from point-source heavy metal contamination modeling to closed-loop food waste valorization strategies. Ultimately, the modeled educational continuum effectively bridges the gap between abstract ecological theories and real-world territorial management safely rooted within planetary boundaries, while further research prospects lie in practical implementation during the upcoming stages of the New Ukrainian School reform and the integration of artificial intelligence with cloud-based remote sensing data processing.

KEYWORDS: Sustainable development; green bioeconomy; geoinformation systems; remote sensing of the Earth; economic and social geography; curriculum modeling; educational succession; geography course; ecology specialty.

1. INTRODUCTION

Modern global challenges, including the climate crisis, natural resource depletion, ecosystem degradation, and the critical need to secure food and energy supplies, demand a fundamental shift in the current economic paradigm. The traditional linear model of production and consumption, heavily reliant on finite fossil resources, has proven incapable of ensuring the long-term stability of the biosphere and human society. Under these conditions, the concept of sustainable development stands as an alternative-free vector for global progress, with bioeconomy emerging as a powerful practical instrument for its realization.

The concept of the bioeconomy has undergone a significant evolution over the recent decades. As highlighted by Birner et al. (2026), the understanding of this phenomenon has transformed from a mere replacement of fossil fuels (the resource substitution perspective) and the advancement of biotechnological innovations (the biotechnology innovation perspective) toward a systemic framework of the “green bioeconomy” and socio-biodiversity. Today, the bioeconomy is viewed not merely as a collection of technologies, but as a dynamic driver of deep societal and economic transformation operating safely within the ecological and planetary boundaries. It directly aligns with the United Nations Sustainable Development Goals (SDGs), focusing on ecosystem conservation, circularity, and social inclusion.

The practical dimension of this synergy is clearly observed in strategically vital sectors, particularly within the agro-industrial complex. Research by Samen and Kaldiyarov (2025) demonstrates that the integration of bioeconomy principles and Environmental, Social, and Governance (ESG) strategies significantly strengthens the environmental, economic, and social sustainability of the agricultural sector. Through the deployment of circular technologies, agricultural waste valorization, biofermentation, and precision farming, it becomes possible to achieve a measurable reduction in carbon and ecological footprints while simultaneously boosting production efficiency. This emphasizes that the concepts of sustainable development and the bioeconomy possess a distinct applied, spatial (geographical), and socio-economic character.

Implementing such a large-scale transition is impossible without fostering a new mindset in the younger generation. Lasting systemic changes require the continuous ecologization of education across all levels. A crucial aspect in this context is engaging youth in inclusive debates and problem-solving regarding the eco-oriented economy through interdisciplinary and inclusive

educational approaches. However, educational practices often suffer from a gap between students' theoretical acquisition of terms and their actual capacity to apply them to solve real-world territorial or industrial problems.

The research-based (inquiry-based) learning approach serves as an effective tool to bridge this gap. Within the system of general secondary education, the geography course in senior profile schools (grades 10–12) holds a powerful integrative potential, where through conducting mini-researches (educational projects), students learn to trace the interconnectedness between global trends and local processes within their territorial communities. The next, qualitatively higher level of this training is higher education, where master's students, while working on their master's theses, are capable of performing deep scientific analysis, spatial modeling, and designing specific strategies for the bioeconomic development of regions or enterprises.

Analysis of recent research and publications. The theoretical foundation linking food security, energy security, and environmental sustainability has been thoroughly explored in recent international literature (Akbari et al., 2022; Berry et al., 2015; Cherp & Jewell, 2014). The global significance of biodiversity in safeguarding critical ecosystem services has been recently synthesized on a massive empirical scale by Moffett et al. (2026), confirming that ecosystems require high levels of biodiversity to maintain functional stability, which aligns with modern ecological research challenges highlighted by Birkhofer et al. (2015). At the same time, the transition of educational systems toward sustainability and the introduction of green technologies into school and university curricula have been actively studied by a number of researchers (Mróz et al., 2018; Nölting et al., 2020; Zwolińska et al., 2022).

However, mapping, visualizing, and analyzing these complex socio-ecological and bioeconomic processes requires the mandatory application of modern spatial tools, namely **Geographic Information Systems (GIS)**. In modern geographical education, GIS is recognized not merely as a software tool, but as a core geo-technology that shapes spatial thinking and enables students to bridge the gap between abstract ecological models and real-world territorial management. As emphasized by Kerski (2015), the integration of GIS into education provides a pathway for inquiry-based learning, transforming students from passive consumers of data into active researchers of spatial relationships. While the conceptual framework of the bioeconomy (Birner et al., 2026) and the educational value of GIS (Milson et al., 2012) are well-documented separately, their pedagogical integration remains practically unexamined.

Formulation of the unsolved part of the problem. Despite the extensive literature on sustainable development (Kovtun, 2024; Shao et al., 2026) and the individual applications of GIS in geography education, there is a clear lack of research on how to methodologically combine the formation of bioeconomic concepts with digital spatial modeling tools. Educational practices lack a coherent, sequential model that ensures continuity between the primary spatial analysis conducted by profile school students according to new curriculum guidelines (Zapototskyi et al., 2026) and the advanced GIS modeling performed by university master’s students when analyzing regional eco-economic risks or agricultural transformations.

The purpose of this article is to substantiate the methodological foundations and practical experiences of forming the integrated concepts of sustainable development, the bioeconomy, and geo-information technologies in the face of modern global challenges using research activities: specifically, through mini-projects of profile school students in the geography course and master's theses of university students, thereby ensuring the continuity and succession of eco-economic and digital geographical education.

2. RESEARCH METHODOLOGY

To systematically investigate and substantiate the conceptual educational continuum between secondary profile schools and higher education institutions, this study employs a comprehensive project-based and comparative research methodology. The pedagogical architecture of this research is grounded in the structural frameworks of comparative education analysis established by Bray, Adamson, and Mason (2014). Specifically, the study utilizes the multi-dimensional analytical matrix known as the "Bray and Thomas cube," which enables the simultaneous examination of educational phenomena across geographic/locational levels (regional school communities vs. national university spaces), educational groups (profile school students vs. university master's students), and specific pedagogical aspects (the formation of integrated eco-economic concepts through digital geo-technologies). By adopting this comparative approach, we analyze how identical conceptual blocks – namely, sustainable development, the bioeconomy, and remote sensing – are sequentially transformed, deepened, and methodologically contextualized as students progress from secondary to higher education (Bray et al., 2014).

The research process is conceptualized as an advanced curriculum modeling and predictive pedagogical design. The investigation anchors on two distinct educational cohorts within the Chernihiv region (Ukraine): secondary education tracks represented by senior profile school students and higher education tracks represented by students enrolled in the Bachelor's and Master's programs within the specialties "Secondary Education (Geography)" and "Ecology" at the T.H. Shevchenko National University "Chernihiv Colehium". This dual focus enables a robust comparative analysis of the competence-based progression from initial spatial conceptualization to expert-level environmental modeling.

The research was operationalized through a complementary combination of theoretical and empirical methods, structured into two sequential stages.

The theoretical and curricular content mapping stage. This stage involved a decomposition and comparative analysis of current state educational standards and innovative model programs. Within secondary education, the research analyzed the newly designed "Model educational program for the school subject 'Geography. Grades 10–12. Advanced Level'" (Zapototskyi et al., 2026), identifying specific thematic entry points ("Primary Sector", "Secondary Sector", "Sustainable Development", and "Basics of Remote Sensing') for introducing bioeconomic terms. Within higher education, the syllabi of core professional disciplines (such as "Economic and Social Geography", "Environmental Safety", "Environmental Monitoring", "GIS in Geographical Research"and "GIS in Environmental Research") were structurally mapped to ensure content alignment and thematic succession based on the contemporary green bioeconomy framework (Birner et al., 2026).

The empirical integration and project design stage. During this phase, the inquiry-based learning approach was modeled and tested across both cohorts. The secondary school curriculum guidelines were utilized to design prospective geography mini-projects focusing on primary spatial analysis and raw material preservation within local territorial communities, utilizing open-access satellite visualization tools. Concurrently, within the higher education sector, actual university master's theses were examined to integrate advanced GIS and remote sensing data processing into deep scientific workflows. This included quantitative calculations of industrial carbon footprints, modeling the spatial dispersion of thermal power plant emissions, and tracing the long-term

temporal dynamics of protected ecosystems (such as the Mizyn National Nature Park) using multi-spectral satellite time series (Landsat, Sentinel-2), thereby practically demonstrating the empirical continuum of digital geographical education.

3. RESULTS AND DISCUSSION

3.1. Theoretical framework: intersecting concepts of sustainable development and bioeconomy

Conceptualizing heat-generating enterprises and energy security. Within the discourse of sustainable macro-economic transitions, a heat-generating enterprise (primarily operationalized as a thermal power plant or centralized combustion facility) is defined as a critical infrastructure unit that converts raw primary energy carriers into thermal and electrical energy. Beyond their basic functional definition as utility providers, contemporary literature conceptualizes these enterprises as complex micro-level economic entities whose operational paradigms are heavily constrained by carbon emission efficiencies (Fang et al., 2022) and fluctuating environmental performance parameters, particularly during systemic power crises (Pan et al., 2024). Because these facilities frequently rely on solid fossil fuels, their operational definitions are systematically linked to their socio-ecological externalities. Specifically, they serve as point sources for the release of heavy metals from industrial boilers (Tong et al., 2023), which induces significant heavy metal accumulation in surrounding topsoils (Kravchenko et al., 2025). Consequently, the modern academic definition of a heat-generating enterprise inherently integrates its broader environmental and public health footprint, accounting for the long-term biological risks imposed on adjacent residential communities (Vig et al., 2023).

Conversely, energy security is a multifaceted conceptual framework that has evolved far beyond the traditional metrics of uninterrupted supply. Early synthetic approaches defined the concept through systemic measurement frameworks across distinct institutional dimensions (Sovacool & Mukherjee, 2011). This expanded into a holistic paradigm that moves beyond the classical "Four As" (availability, accessibility, affordability, and acceptability), framing energy security as the management of vulnerabilities within interconnected sociotechnical security blankets (Cherp & Jewell, 2014). In modern energy economics, it is operationalized through the equilibrium between short-term grid resilience and long-term infrastructural reliance, heavily dependent on the systematic diversification of electricity-generating fuels (Kosai & Unesaki, 2020). Ultimately, contemporary definitions treat energy security as a dynamic management imperative that requires continuous state governance, policy adaptation, and international cooperation to shield national infrastructure from geopolitical shocks, military conflicts, and market volatility (Dykha et al., 2024).

Conceptualizing food security and agricultural processing valorization. In the paradigm of global subsistence strategy, food security is defined as a complex, multi-dimensional dynamic achieved when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life (Faizan Afzal et al., 2023). Historically rooted in the supply-side stabilization and commodity production indices of the 1970s (Godswill Makombe, 2023), the concept has undergone a comprehensive structural evolution (Akbari et al., 2022). It has expanded from a narrow focus on national agricultural yields to a multi-tiered framework comprising four pillars: availability, accessibility, utilization, and stability (Matemilola & Alabi, 2023). Contemporary scholarship emphasizes that food security cannot be isolated from broader socioeconomic equity issues,

including public health integration and accessibility for marginalized groups (Altintaş & Uçar, 2026). Furthermore, the modern operationalization of this concept demands a shift toward long-term nutritional sustainability, bridging the historical trade-offs between urgent humanitarian consumption demands and planetary boundaries (Berry et al., 2015; Hussain et al., 2025). As a result, food security is fundamentally conceptualized as a highly interconnected system vulnerable to climate volatility, distribution inefficiencies, and geopolitical conflicts (Gibson, 2012).

To address these vulnerabilities, agricultural product processing – specifically through the lens of food waste valorization – is conceptualized as a critical bridge that converts bio-industrial by-products and post-harvest residues into high-value systemic inputs. This process shifts agricultural processing from linear disposal models to closed-loop circular networks, transforming food waste streams into viable solutions for food security (Sarangi et al., 2024). Because approximately one-third of all food produced globally intended for human consumption terminates as waste, valorization practices focus on recovering valuable biological elements, such as dietary fibers, proteins, and polyphenols, from discarded vegetable, fruit, and grain matrixes (Worku et al., 2026). Utilizing green extraction methodologies and biofermentation allows processing enterprises to upcycle industrial fractions (such as peels, pomace, and seeds) that typically comprise 40% to 60% of the raw material mass, transforming them into functional food ingredients and biopolymers (Fufa & Negewo, 2026). Consequently, modern agricultural processing is no longer defined merely as raw commodity transformation, but as a technological enabler of the circular bioeconomy that simultaneously mitigates greenhouse gas emissions, establishes novel revenue streams, and preserves nutritional resources to maximize global food availability.

Integrating sustainable development, ecosystem services, and environmental protection. In the modern scientific discourse, sustainable development is conceptualized as an evolving, multi-dimensional meta-narrative that addresses the systemic failure of traditional economic frameworks to maintain an equilibrium between macroeconomic expansion, social equity, and biosphere preservation (Zeinab Ali Dashoor, 2025). Originating as a normative planning principle (Berke & Manta, 1999), its historical evolution and goal progression have shifted from basic definitions toward complex, indicator-driven global agendas operating safely within planetary boundaries (Hens, 2021; Shao et al., 2026). At the macro-territorial level, this paradigm is operationalized through urban sustainability indicator frameworks and healthy city metrics aligned with the United Nations Sustainable Development Goals (Michalina et al., 2021; Santa et al., 2023). Concurrently, at the micro-level, contemporary definitions treat sustainability as a harmonious, long-term socio-ecological and economic equilibrium of institutional operations, ensuring system resilience amidst highly turbulent global transformations (Kovtun, 2024). Critically, the realization of this paradigm requires systemic societal transfer and integration within higher education curricula, embedding transformative eco-economic mindsets within the student perspective (Nölting et al., 2020; Zwolińska et al., 2022).

Directly nested within this framework, ecosystem services are defined as the structural, functional, and landscape-based benefits that natural environments provide to sustain and enrich human well-being (Kirchhoff, 2025). The concept has undergone an extensive discourse-centered evolution, transitioning from an exploratory ecological economic tool to a prominent, albeit occasionally contested, policy framework (Chaudhary et al., 2015; Lele et al., 2013; Schröter et al., 2014). Contemporary ecological research emphasizes that robust biodiversity acts as the fundamental safeguard for sustaining these essential services and functions globally across both terrestrial and freshwater networks (Birkhofer et al., 2015; Deeksha & Shukla, 2022; Moffett et al., 2026).

Furthermore, the operationalization of ecosystem services relies heavily on localized management frameworks, requiring a deep alignment between global sustainability goals and the distinct perspectives of ecosystem and biosphere managers (Frazão et al., 2024).

From a pedagogical and methodological standpoint, these intersecting socio-ecological and bioeconomic frameworks are not merely theoretical abstractions; instead, they serve as the foundational thematic pillars for the practical research activities examined in this study. The dualism of these concepts establishes a structured framework for inquiry-based learning, where the conflict between economic operations (such as heat generation or agricultural production) and planetary boundaries is explicitly translated into spatial data. Consequently, these distinct thematic streams – ranging from point-source industrial soil contamination to closed-loop agricultural biomass upcycling – were operationalized as core experimental case studies. They provided the empirical substance for the geographic information systems (GIS) modeling, mapping tasks, and territorial strategy designs performed by both profile school students and university master's students during the empirical phase of this research.

To secure these natural flows, environmental protection is operationalized as a coordinated complex of regulatory, educational, and structural strategies designed to mitigate anthropogenic degradation, conserve natural resources, and optimize the ecological parameters of business economic growth (Ma & Liu, 2023). Rather than existing as an isolated defensive mechanism, environmental protection is conceptualized as an active driver of ecological modernization that harmonizes commercial activities with ecological parameters. Within the educational sector, it serves as a critical pedagogical foundation; its systematic inclusion in school curricula ensures that foundational ecological literacy is cultivated early in the educational lifecycle (Mróz et al., 2018). Consequently, environmental protection acts as the operational prerequisite that bridges the conceptual triad, directly preserving the biodiversity necessary to sustain ecosystem services, which in turn form the biophysical baseline for all sustainable development models.

Conceptualizing biodiversity and earth remote sensing. In contemporary environmental science, biodiversity is defined as an overarching and unifying concept that encompasses the complete variety and variability of life in all of its manifestations across all levels of biological organization – from genetic codes within populations to species richness, evolutionary lineages, and complex ecosystem frameworks (Hortal et al., 2022; Jarau, 2026; National Research Council, 1999). It functions as the “living fabric of the planet”, where natural processes and life forms are interlinked through intricate networks of ecological interactions (Joyard, 2026). While traditionally evaluated through patterns of geographic distribution and taxonomic richness (Díaz & Malhi, 2022; Springer, 2008), the conceptual framework of biodiversity has recently faced intense scrutiny due to definitions that fail to encompass its full, dynamic, and systemic nature (Zagorodniuk et al., 2023). In response, modern assessments have expanded to capture its multi-dimensional value across global supply chains (Maier et al., 2019) and within science-policy interfaces such as TEEB (Leibenath et al., 2020). From an educational and civic standpoint, fostering a robust understanding of biodiversity is essential to bridge the gap between adolescent perceptions of environmental utilization and protection (Schneiderhan-Opel & Bogner, 2019), cultivate public citizenship through socioscientific arguments (de Freitas et al., 2023), and counteract the “drifting baseline syndrome” – a cognitive phenomenon where generational changes in the perception of degraded ecosystems distort the true scale of biodiversity loss (Haluza & Wagner, 2025). Ultimately, a rich biodiversity acts as the fundamental safety net that stabilizes biosphere processes and safeguards human survival worldwide (Moffett et al., 2026).

To systematically track and measure these complex biological changes, Earth remote sensing (ERS) is conceptualized as a critical technological and analytical framework that enables continuous, large-scale, and non-invasive observations of our planet's biophysical parameters (Jung et al., 2020). In the era of big geospatial data, ERS has transitioned from simple aerial photography to advanced, GeoAI-driven digital structures that integrate machine learning algorithms with satellite observations to monitor environmental shifts in real time. Platforms such as the cloud-based Google Earth Engine (GEE) have fundamentally revolutionized this domain, establishing modern bibliometric trends by allowing researchers to seamlessly analyze petabytes of multi-spectral imagery across global ecosystems (Khachoo et al., 2026). Within the educational sector, ERS tools have emerged as highly effective pedagogical instruments; utilizing GEE code architectures allows instructors to teach computational programming while simultaneously training both STEM and non-STEM students to monitor real-world deforestation, land-use transformations, and climate-induced habitat degradation (Callejas et al., 2023). Consequently, Earth remote sensing serves as the primary observation framework that bridges the conceptual gap between local ecological degradation and global macroecology, providing the quantitative, spatially explicit data needed to document, analyze, and manage the biodiversity crisis in real time.

3.2. Methodological foundations for profile secondary education: project-based learning in the advanced geography course

The structural and functional integration of modern socio-ecological and bioeconomic concepts into secondary education requires a rigorous curricular alignment with state educational standards. Within the context of the Ukrainian educational reform, the baseline regulatory framework for this adaptation is the “Model educational program for the school subject ‘Geography. Grades 10–12. Advanced Level’ for institutions of general secondary education”, developed by Zapototskyi et al. (2026). This program shifts the pedagogical paradigm from the passive accumulation of factual geographic data toward competence-based inquiry and research-driven learning. To maximize the efficiency of forming integrated concepts, it is essential to map these definitions across specific thematic blocks of the curriculum, establishing clear geographical foci and cross-cutting analytical tasks.

In Grade 10, during the study of the theme “The Primary Sector of the Economy”, the instructional process is systematically linked to the definitions of agricultural product processing and food security. Within this component, food security is operationalized not merely as a country's aggregate production metric, but as a spatial and socio-economic equilibrium vulnerable to distribution bottlenecks and climate fluctuations (Gibson, 2012; Matemilola & Alabi, 2023). Students engage in this discourse through geographic mini-projects focused on the spatial organization of domestic agro-industrial clusters and the logistical networks of processing enterprises. The geographical focus centers on regional agricultural zones and their proximity to processing hubs, prompting students to evaluate the proximity factor in food preservation. The essence of this integration manifests in tasks where students analyze how advanced processing depth and the utilization of agricultural residues minimize raw material loss, directly reinforcing local food availability and establishing a foundation for circular bioeconomic mindsets at the secondary school level.

Concurrently, Grade 10 students explore the theme “The Secondary Sector of the Economy”, which serves as the optimal curricular entry point for conceptualizing a heat-generating enterprise and energy security. Here, a heat-generating enterprise is methodologically defined as a micro-

level economic entity that serves as a vital infrastructure node, yet concurrently operates as a concentrated point source of industrial point-source contamination (Fang et al., 2022; Tong et al., 2023). Energy security is introduced through the lens of sociotechnical vulnerability management and grid resilience (Cherp & Jewell, 2014). The geographic focus of this unit is directed toward the mapping of regional heating networks and local coal- or gas-fired thermal plants. Analytical tasks for students involve assessing the trade-offs between continuous urban thermal supply and the associated environmental externalities, such as the accumulation of heavy metals in adjacent topsoils (Kravchenko et al., 2025). The integrated outcome of this research activity allows students to grasp the complexity of energy security, realizing that sustainable energy provision requires a continuous diversification of electricity-generating fuels and stricter controls over industrial emissions (Kosai & Unesaki, 2020).

In Grade 12, the curriculum transitions toward deep holistic synthesis, beginning with the foundational theme “Sustainable Development: Theory and Practice”, which explicitly encapsulates the paradigms of sustainable development, environmental protection, and ecosystem services. This theme moves beyond normative definitions to frame sustainability as a harmonious, long-term socio-ecological and economic equilibrium operating safely within planetary boundaries (Hens, 2021; Kovtun, 2024). Students explore environmental protection as an active management strategy rather than a passive restrictive measure. The core research tasks require students to identify and categorize the localized landscape-based benefits that natural environments provide to sustain human well-being (Kirchhoff, 2025). The geographical focus is placed on municipal green infrastructure or adjacent protected areas, where students perform qualitative and quantitative evaluations of provisioning, regulating, and cultural ecosystem services (Moffett et al., 2026). The structural result of this educational project is that students learn to conceptualize nature as irreplaceable natural capital, whose economic valuation and preservation are essential for long-term territorial resilience.

The technological dimension of modern geographic inquiry is operationalized in Grade 12 through the specialized theme “Basics of Remote Sensing of the Earth”. Within this block, remote sensing of the Earth (RSE) is defined as a primary data acquisition method that provides objective, multi-spectral, and time-consistent geospatial imagery of the biosphere. The pedagogical task is to transform students from passive map readers into active users of spatial technologies, mirroring international practices highlighted by Kerski (2015). The geographical focus targets dynamic territorial transformations, such as urban sprawl, forest cover dynamics, or the visible expansion of open-pit mining operations. Students are tasked with analyzing multi-temporal satellite imagery (via open-access platforms like Google Earth Studio or Sentinel Hub) to detect surface changes and map environmental degradation patterns. The essence of this integration lies in demonstrating that RSE is an indispensable tool for modern bioeconomic monitoring, enabling real-time detection of ecological risks, calculation of vegetation indices, and the objective measurement of human-induced transformations across diverse geographical scales.

Finally, the Grade 12 theme “Water, Soil Resources, Biodiversity: Challenges and Sustainable Management” serves as the final synthesis block for the concepts of sustainable development and biodiversity. In this context, biodiversity is conceptualized as the core biological safeguard that ensures the continuous delivery of ecosystem services and preserves the structural integrity of both terrestrial and freshwater networks (Birkhofer et al., 2015; Moffett et al., 2026). The geographic focus narrows down to specific regional eco-corridors, river basins, or localized soil erosion zones. Research assignments direct students to investigate the impacts of intensive land-

use practices or thermal power plant externalities on local species richness and soil degradation patterns (Kravchenko et al., 2025; Vig et al., 2023). The result of this integration is the formation of a holistic system perspective, wherein students realize that the sustainable management of physical resources (water and soil) is ecologically interdependent with the preservation of genetic and species diversity, directly demonstrating how local ecosystem stability underpins global sustainability pathways.

3.3. Methodological foundations for higher education: integrating bioeconomic and ecological concepts into the educational process and master's theses

The structural and functional formation of an integrated system of knowledge regarding sustainable development, the bioeconomy, and geoinformation technologies within higher education institutions follows a two-tiered structure, encompassing both bachelor's and master's levels for the specialties "Secondary Education (Geography)" and "Ecology". Unlike in profile secondary education, where initial conceptualization occurs, the instructional process in higher education is oriented toward a deep, critical analysis of socio-ecological and economic trade-offs, as well as the mastery of sophisticated spatial modeling tools (Nölting et al., 2020; Zwolińska et al., 2022). During classroom activities (including lectures, laboratory sessions, and practical seminars), the selected concepts are analyzed through the prism of contemporary green bioeconomy definitions that operate safely within planetary and ecological boundaries (Birner et al., 2026). For students specializing in "Secondary Education (Geography)", the pedagogical emphasis shifts toward the methodology of translating these complex interrelationships into their future teaching practices. Conversely, for ecology students, the priority centers on the direct measurement of environmental effects, risk assessment, and the design of sustainable resource management strategies (Birkhofer et al., 2015).

A vital tool for reinforcing theoretical frameworks is the execution of interdisciplinary educational projects within specific academic disciplines. For future geography teachers, the foundational platforms comprise such courses as "Economic and Social Geography", "Geography of Global Challenges", and "Geourbanism and Industrial Complexes". Conversely, for ecology students, these concepts are analyzed with greater operational depth within the disciplines of "Environmental Safety", "Environmental Monitoring", "Environmental Impact Assessment", and "Economics of Nature Management". During the study of these courses and the realization of associated projects, the concepts of food security and energy security are transformed from declarative categories into dynamic objects of inquiry, the state of which depends heavily on regional logistics, climate fluctuations, and the diversification of electricity-generating fuels (Cherp & Jewell, 2014; Gibson, 2012).

A distinct place in the curricula of both specialties is occupied by remote sensing of the Earth (RSE), which is taught within specialized courses such as "Cartography with Foundations of Topography and GIS", "Basics of Remote Sensing of the Earth", and "GIS in Environmental Research" as a leading digital technology for acquiring primary spatial data. Students master the methods of satellite imagery interpretation, the calculation of vegetation indices (NDVI, EVI), and the monitoring of anthropogenic landscape transformations. This enables them to visualize the spatial distribution of ecosystem services and evaluate the state of **biodiversity** at both local and regional levels (Kirchhoff, 2025; Moffett et al., 2026). Consequently, this ensures a qualitative

transition from the passive study of ecological problems toward their precise instrumental modeling based on methodological approaches well-substantiated in international educational practices (Kerski, 2015).

The highest level of professional training for ecologists is achieved through the execution of master's theses, where theoretical concepts and RSE tools are integrated into real-world scientific research with a distinct regional focus. The process of forming and consolidating these concepts is clearly distributed across the specific stages and chapters of the master's theses. In the introduction and the first (theoretical-methodological) chapter, a critical analysis of definitions and the existing regulatory framework is conducted. In the second (analytical) chapter, based on field or historical data, a quantitative assessment of environmental effects or risks is performed utilizing GIS tools and RSE. In the third (project-recommendation) chapter, master's students design specific measures and models for transitioning enterprises or the region toward the principles of a circular economy and sustainable development.

The realization of this structural approach is clearly observed in the case of a master's thesis entitled **“Scientific foundations for studying the environmental effects of agricultural processing enterprises”,** where the primary objects of analysis are agricultural product processing and food security. Within the scope of this work, food security is examined in the context of minimizing biomass losses during the production and processing stages of raw materials (Matemilola & Alabi, 2023). In the analytical chapter, the master's student investigates the environmental externalities of food or processing industries, such as industrial emissions, waste generation, and wastewater discharges. The consolidation of these concepts occurs in the project chapter, where the student designs a model for the valorization of agricultural processing waste. The student proposes technological solutions for recovering valuable biological fractions or utilizing biofermentation to produce biopolymers and functional ingredients based on closed-loop circular networks (Fufa & Negewo, 2026; Worku et al., 2026). This directly demonstrates how the depth of agricultural processing minimizes ecological pressure on the environment while simultaneously optimizing resources to maximize global food availability.

The conceptual block encompassing heat-generating enterprises and energy security is thoroughly operationalized in the master's research project entitled **“Environmental impacts of heat-generating enterprises on the example of Chernihiv Thermal Power Plant”.** Here, the object of study is positioned as a complex infrastructure unit whose vital role in urban thermal supply is accompanied by significant negative socio-ecological consequences (Pan et al., 2024). In the methodological part, energy security is interpreted as an equilibrium between grid resilience and the long-term preservation of biosphere components (Kosai & Unesaki, 2020). In the analytical chapter, the master's student calculates greenhouse gas emissions and models the spatial dispersion of industrial air pollutants. Particular attention is paid to evaluating the accumulation of heavy metals from solid fuel combustion in adjacent topsoils and assessing the associated health risks for nearby residential communities (Kravchenko et al., 2025; Tong et al., 2023). The project part of the thesis is dedicated to substantiating the environmental modernization of the facility, fuel base diversification (including the integration of sustainable bioenergy), and the implementation of environmental management systems, which reinforces the skills required to manage the externalities of thermal power plants within urban agglomerations (Vig et al., 2023).

The master’s thesis on **“Mechanisms for ensuring the sustainable development of the Chernihiv region in the field of environmental protection”** serves as a practical platform for consolidating the paradigms of sustainable development and environmental protection.

Sustainable development at the macro-territorial level is operationalized as a harmonious, long-term socio-ecological and economic equilibrium that requires specific institutional and governance tools in the face of highly turbulent global transformations (Kovtun, 2024; Zeinab Ali Dashoor, 2025). Environmental protection is transformed in the student's mindset from a passive restrictive doctrine into an active strategic mechanism for preserving natural capital (Berke & Manta, 1999). In the practical chapters of the thesis, the master's student performs a comprehensive analysis of the region's environmental indicators, including pollution indices, waste dynamics, and forest cover, using urban sustainability indicator frameworks aligned with the United Nations SDGs (Michalina et al., 2021; Santa et al., 2023). The final outcome of the research is the development of a regional environmental strategy that harmonizes macroeconomic expansion with the biophysical boundaries and ecosystem integrity of the region (Hens, 2021; Shao et al., 2026).

The highest level of digital geoinformation technology integration is realized in the master's thesis entitled **“Spatial structure and dynamics of the forest edges of Mizyn National Nature Park based on remote sensing data”,** where the leading concepts are **biodiversity** and remote sensing of the Earth. Within this research framework, RSE technologies serve as the primary methodology, providing objective, multi-spectral, and time-consistent geospatial imagery of protected areas (Kerski, 2015). The master's student utilizes high-resolution satellite data (such as Sentinel-2 or Landsat) to perform an advanced space-time analysis of the national park's landscape structure. In the analytical chapter, using supervised classification methods and specific vegetation indices, the student models the edge effect at the forest borders and quantifies ecosystem dynamics. The concept of biodiversity is treated here as the core biological safeguard that ensures the continuous delivery of ecosystem services and preserves the structural integrity of terrestrial networks (Birkhofer et al., 2015; Moffett et al., 2026). By utilizing long-term time series of satellite imagery, the master's student traces the multi-year dynamics of plant communities, detecting patterns of forest degradation or recovery. The project chapter of the thesis contains recommendations for optimizing the functional zoning of Mizyn National Nature Park, identifying critical eco-corridors for rare species preservation, and developing a GIS project for real-time environmental monitoring, thereby practically proving the indispensability of RSE as an instrument for sustaining biotic diversity.

4. CONCLUSIONS

The synthesis of the theoretical modeling and curricular frameworks proposed in this study substantiates the strategic efficiency of the integrated pedagogical model. In the face of contemporary global challenges, the traditional boundaries of geographical and ecological education must expand to encompass the systemic, multi-dimensional paradigms of sustainable development and the green bioeconomy. This investigation demonstrates that forming these complex eco-economic mindsets cannot rely on passive, lecture-based instruction; instead, it requires a prospective inquiry-based learning framework driven by proactive educational projects and empowered by modern digital spatial tools, specifically GIS and RSE.

The primary core conclusion of this study is the verification of the conceptual continuity and educational succession modeled between profile secondary education (Grades 10–12) and higher education (Bachelor’s and Master’s programs). By alignment of the prospective research activities of profile school students within the geography course with the advanced scientific workflows of university master’s students, we established a functional learning continuum. At the secondary school level, according to the new curriculum guidelines (Zapototskyi et al., 2026), the model offers

an effective entry point for initial spatial conceptualization and localized qualitative analysis of biomass preservation within territorial communities. At the higher education level, within specialized disciplines (such as “Economic and Social Geography”, “GIS in Environmental Research”, “GIS in Geographical Research” and “Environmental Monitoring”), this baseline is qualitatively deepened, enabling master’s students to execute complex, instrumental, and multi-spectral environmental modeling of regional eco-economic risks, industrial carbon footprints, and protected landscape dynamics.

The proposed methodology effectively bridges the traditional gap between abstract ecological models and real-world territorial management. The analytical mapping of master's theses across vital bioeconomic sectors – ranging from industrial heavy metal topsoil contamination analysis to closed-loop food waste valorization models – proves that advanced geographical education serves as a technological enabler for the circular economy. Ultimately, the structural integration of GIS and RSE platforms within the curriculum ensures that future educators and ecologists transition from basic map reading to constructing predictive environmental strategies and regional sustainability models safely rooted within planetary boundaries.

Prospects for further research lie in the practical implementation of this modeled educational continuum during the upcoming stages of the senior school reform (New Ukrainian School). Furthermore, exploring the integration of artificial intelligence prediction algorithms with cloud-based remote sensing workflows within university curricula represents a promising avenue for securing the digital evolution of environmental and geographical education.

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