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DIGITAL TRANSFORMATION OF LAND RESOURCE MANAGEMENT IN UKRAINE: FROM GEOGRAPHIC INFORMATION SYSTEMS TO INTELLIGENT AGENTS

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Abstract. *The article examines the evolution of digital tools for land resource management in Ukraine through the lens of changing technological paradigms. Three successive generations of digital solutions are distinguished: the first, based on geographic information systems and digital soil mapping; the second, on machine-learning methods and the digital-twin concept; and the third, on generative artificial intelligence and large-language-model (LLM) agents. The study analyses the state of the national regulatory framework, data infrastructure and human capacity in the land-cadastre domain. It is shown that the transition to the third generation is not merely a quantitative improvement of individual indicators but a qualitative redefinition of the human role in spatial analysis: the analyst shifts from operator to* *task-setter, while the agent autonomously plans and performs the analytical process. Using a unified set of parameters, a comparative characterisation of the three generations is compiled, and a matrix of barriers and opportunities is formed across five domains — data, human capacity, regulation, financing and security. Key prerequisites for a technological-leapfrogging trajectory are substantiated in the context of post-war reconstruction and European integration, together with the imperative of a human-in-the-loop principle for legally significant cadastral data.*

Keywords: *digital transformation, land resource management, geographic information systems, machine learning, LLM agents, land cadastre, artificial intelligence, Autonomous GIS.*

Relevance

Ukraine's land fund exceeds 60 million hectares — one of the largest among European countries. At the same time, the system for managing this resource has long been characterised by fragmented information flows, duplication of registers, and limited analytical capacity for well-grounded decision-making [1]. The accumulation of large volumes of geospatial information without adequate mechanisms for its processing and interpretation not only fails to improve the quality of managerial decisions but also generates new organisational risks.

Over the past decade, the technological toolkit of land management has expanded substantially: from the introduction of the State Land Cadastre in electronic form to the development of the national geospatial data infrastructure [12] and the adoption of Earth remote sensing and machine-learning methods for monitoring agricultural land [3]. Yet, against the backdrop of the global acceleration of generative artificial intelligence, domestic practice is only beginning to grasp the opportunities of the new technological generation.

The relevance of the topic is reinforced by the context of post-war reconstruction, whose total recovery and reconstruction needs were estimated at almost USD 588 billion as of the end of 2025 [16]: a significant part of the land fund in de-occupied territories requires prompt inventory under conditions of damaged or missing primary documentation. It is precisely here that the potential of LLM agents — capable of working with incomplete, contradictory, and heterogeneous data — acquires particular practical significance [4].

Analysis of recent research and publications

First generation: GIS and digital soil mapping.

The emergence of the digital era in land management is associated primarily with the development of geographic information systems and the methodology of digital soil mapping (DSM). This paradigm, whose theoretical foundations were laid in the works of Minasny and McBratney [5], was based on converting field surveys into digital formats and building statistical models of the spatial distribution of soil properties. A fundamental achievement of this stage was the formalisation of dependencies between soil characteristics and soil-formation factors through quantitative models, which made it possible to perform spatial prediction based on a limited sample of point observations.

In Ukraine, the first generation of digital technologies materialised in the introduction of the State Land Cadastre (SLC) in electronic form, the development of the national geospatial data infrastructure, and the gradual automation of land-management procedures. In a fundamental study of the ecological and economic foundations of information support for land resource management, Taratula [1] demonstrated that an effective land-information system is not a static data repository but a dynamic process of organising purposeful information flows. At the same time, the author identified a systemic problem: the information subsystems of the land cadastre, monitoring, and land management functioned in isolation, which precluded their synergistic effect.

Studying the mechanisms of land resource management of agricultural enterprises, Poltavets [2] identified another significant first-generation problem — the gap between the quality of Ukrainian soils (objectively higher than in most EU countries) and the productivity of land use. According to the author, the technological backwardness of production processes, rather than natural conditions, is the main factor constraining the realisation of the country's agro-production potential. This conclusion underscores that the information-technology gap has direct ecological and economic consequences.

Second generation: machine learning and digital twins.

A qualitative leap in geospatial data analysis occurred with the convergence of machine-learning methods, cloud computing, and the digital-twin concept. At the conceptual level, Nasirahmadi and Hensel [6] proposed a model for applying Digital Twin technology in the agricultural sector, where a digital twin acts as a dynamic virtual representation of a real object that is continuously updated through data streams from sensors and satellites. This concept fundamentally changed the approach to land monitoring — from discrete snapshots to continuous observation.

The practical effectiveness of the second generation is confirmed by specific cases. Using the example of a digital twin of the island of Tobago, Ramsewak et al. [8] demonstrated that land-cover classification with the Random Forest algorithm based on multispectral satellite imagery integrated with a LiDAR-derived terrain model achieves an accuracy of 97% — a figure unattainable by first-generation methods. Scandurra et al. [9] showed the effectiveness of integrating BIM, GIS, and Business Intelligence for managing public real-estate assets, where the key advantage was the ability to generate interactive KPI dashboards to support managerial decisions.

In Ukraine, the second technological level was reflected in the works of the Institute of Land Use of the NAAS [3]. The researchers developed algorithms for processing Sentinel-1 and Sentinel-2 imagery [15] on the Google Earth Engine platform to identify crops across the entire territory of the country, including temporarily occupied areas. An important practical result was the determination of a 20.8% reduction in sown areas in government-controlled territories in 2022 — data obtained exclusively by remote methods without the possibility of field access. This experience acquired particular significance precisely under the conditions of armed conflict.

On the threshold of the third generation: LLM agents and Autonomous GIS.

The emergence of large language models (LLMs) opened a fundamentally new dimension in geospatial analysis. Whereas the first and second technological generations automated the execution of pre-programmed operations, LLM agents are able to independently interpret a task formulated in natural language, plan a sequence of actions, generate program code, and verify results. In a seminal work, Li et al. [7] conceptualised this paradigm as Autonomous GIS — a new generation of geographic information systems in which the LLM plays the role of the decision-making core rather than merely a data-processing tool.

The fundamental difference of the third generation from the previous ones lies in the change in the architecture of human–system interaction. In the first and second generations, the human analyst remains at the centre of the process: configuring algorithms, interpreting results, and making decisions. In the third generation, the human shifts from the role of operator to that of task-setter — it is sufficient to formulate an analytical problem, and the agent independently finds data, selects methods, performs calculations, and presents results. This inversion lowers the qualification threshold for access to complex spatial analysis, which is of strategic importance for countries facing a shortage of GIS specialists.

Analysing the prospects for implementing AI in cadastral and land-management processes, Malanchuk, Muzyka, Kravchuk, and Lukianchenko [4] recorded an ambivalent picture: despite recognition of the considerable potential of the new technologies, their practical application is constrained by insufficient data standardisation, the absence of adapted legislation, and a shortage of specialists able to effectively integrate AI into production processes. The researchers emphasise that the key condition for successful implementation is not only technological readiness but also the organisational and legal maturity of institutions.

Aim and objectives of the study

The aim of the article is to systematise the evolution of digital tools for land resource management in Ukraine and to substantiate the preconditions for the transition to a new technological generation based on agentic artificial-intelligence systems.

The objectives of the study are: to characterise the three generations of digital technologies in land management; to analyse the state of domestic information and analytical support for land resource management; to identify the barriers to and opportunities for implementing LLM agents in domestic practice; and to formulate recommendations on priority directions of digital transformation in light of the reconstruction context.

Materials and methods

The study is built on a combination of several methodological approaches. The core is systems analysis, which allows land resource management to be considered as an integral socio-technical system whose components are interconnected and interdependent. Retrospective analysis is applied to reconstruct the sequence of technological changes and to identify regularities in the transition between generations of digital solutions.

Comparative analysis is used to juxtapose the characteristics of the three technological generations against a unified set of parameters: key technology, the role of the human, qualification requirements, productivity, and scalability. The analysis of the domestic context is based on a critical review of the research results of NULES, the NAAS, Lviv NAU, and Sumy NAU, as well as regulatory documents of the State Geocadastre and the Ministry of Digital Transformation.

For a structured assessment of implementation prospects, an original matrix of barriers and opportunities was developed across five domains: data, human capacity, regulation, financing, and security. This structure makes it possible to identify not only individual obstacles but also the interrelationships among them and systemic ways to overcome them.

Results

Comparative characteristics of the technological generations.

Based on the systematisation of scientific data, a comparative characterisation of the three generations of digital technologies for land resource management was compiled (Table 1). The time indicators specified for the third generation correspond to preliminary estimates based on published data on LLM-agent performance [7] and are subject to further verification.

Table 1. Comparative characteristics of the generations of digital technologies for land resource management

Comparison criterion	**First generation (GIS/DSM)**	**Second generation (ML/Digital Twin)**	**Third generation (LLM agents/Autonomous GIS)**
Key technology	Statistical models + GIS	Machine learning, IoT, cloud platforms	Generative AI, LLMs, agent systems
Role of the human	Central — data collection, analysis, decisions	Analysis + verification	Task formulation + verification
Operator qualification	MSc in GIS + field experience	GIS + ML/Python	Domain expertise + prompt engineering
Analysis speed (LULC 100 km²)	120–200 h	24–60 h	2–8 h*
Scalability	Low (1–2 analyses/month/FTE)	Medium (4–10)	High (20–60*)
Adaptability to incomplete data	High (expert-based)	Low	Potentially high*
Examples of application in Ukraine	SLC, GIS land management	Sentinel monitoring, Google Earth Engine [3]	At the implementation stage [4]

** — preliminary estimates based on published data on LLM-agent performance; subject to verification in pilot projects.*

A characteristic feature of the transitions between generations is their fundamentally different nature. The shift from the first to the second generation is evolutionary: more operations are automated, accuracy increases, and scale expands

— but the human remains the central link of the analytical process. The transition to the third generation is revolutionary in essence, since the very logic of interaction changes: the system acquires the capacity for autonomous goal-setting within the bounds of the assigned task.

State of domestic information and analytical support.

Analysis of the available research allows us to state that the domestic land resource management system currently remains predominantly at the boundary of the first and second technological generations. The SLC operates in electronic form and provides a basic level of digitisation of cadastral data. Individual institutions, in particular the research farms of the NAAS, successfully apply machine-learning and Earth remote-sensing methods for monitoring agricultural land [3].

At the same time, researchers note a number of systemic problems that constrain further technological progress. The land-information subsystems (cadastre, monitoring, land management, statistical accounting) operate without proper horizontal data exchange. There is no unified metadata standard, which makes automated integration of heterogeneous geospatial information sources impossible — in contrast to the harmonised EU approach introduced by the INSPIRE Directive [13]. The human capacity of land-management authorities is oriented predominantly towards servicing existing systems rather than mastering new analytical tools [4].

The full-scale invasion added new critical challenges to this list. According to estimates by the Institute of Land Use of the NAAS [3], the reduction in sown areas in 2022 was recorded predominantly by remote methods, since field access across large territories is impossible. Part of the cadastral archives in temporarily occupied and de-occupied territories has been damaged or lost. The task of restoring land documentation in the post-conflict period will require new approaches that go beyond the capabilities of the first and second technological generations.

Barriers to and opportunities for implementing LLM agents.

The systematisation of the main obstacles and ways to overcome them across five domains is presented in the matrix (Table 2).

Table 2. Matrix of barriers to and opportunities for implementing LLM agents in land resource management in Ukraine

Domain	Identified barriers	Opportunities for overcoming
Data	Heterogeneous formats of cadastral registers; partial digitisation of archival materials	Prioritising API integrations of the SLC; engaging volunteer mapping initiatives
Human capacity	Shortage of LLM-integration specialists in land authorities	Targeted educational programmes; partnership of NULES with the IT sector
Regulation	Absence of regulation for AI-generated cadastral data	Concept for AI Development in Ukraine [14] as a framework; adaptation of the EU experience (INSPIRE Directive [13])
Financing	Priority of defence expenditures; limited IT budget of the State Geocadastre	EU/World Bank reconstruction programmes; targeted grant mechanisms (USAID Land, etc.)
Data security	Risks of using external APIs for sensitive geospatial data	Development of the national LLM “Siaivo”; edge deployment of Gemma-family models (offline)

The analysis above indicates that none of the barriers is insurmountable in the medium term. The key condition is systemic coordination among land-management authorities, educational institutions, the IT sector, and international reconstruction partners. Particularly promising is the inclusion of LLM-integration tasks for the land cadastre within the broader programmes of Ukraine’s digital reconstruction financed by the EU and the World Bank.

The scientific novelty of the obtained results lies in the proposed three-wave periodisation of the digital transformation of land resource management with a unified set of comparison parameters, as well as in the structured matrix of barriers to and opportunities for implementing agentic systems, adapted to the domestic context of reconstruction and European integration.

Discussion

The obtained results allow several conceptual observations to be formulated regarding the nature of technological transitions in land management. First, the change of generations is not linear progress along a single dimension — it is a multidimensional transformation that simultaneously affects the technological, organisational, and institutional levels of the system.

Second, Ukraine occupies a non-trivial starting position for implementing the third generation of technologies. On the one hand, the lag in the second generation (limited diffusion of ML workflows in land authorities) is an obvious shortcoming. On the other hand, the absence of inertia from large-scale investments in outdated solutions opens the possibility of a technological-leapfrogging strategy, in which a country moves directly to the newest level, bypassing intermediate stages. It was precisely this trajectory that was chosen by certain African countries, which moved from the absence of banking infrastructure directly to mobile payment systems.

Third, the Concept for the Development of Artificial Intelligence in Ukraine [14] and the "agentic state" concept proclaimed by the Ministry of Digital Transformation [11] form an institutional framework which, subject to effective implementation, can substantially accelerate the adoption of LLM agents in land management. It is essential that this framework arises from a systemic vision rather than as a reaction to individual technological trends.

The ecological and economic dimension of the transition requires separate attention. On the one hand, digital tools increase the efficiency of land use (more precise irrigation, more justified application of agrochemicals, faster analysis). On the other hand, large language models themselves have their own ecological footprint, so a correct comparison of their impact with alternative scenarios of intellectual labour requires a separate life-cycle assessment [10].

At the same time, it is necessary to remain sober in assessing the risks. Hallucinations of LLM models in the context of legally significant cadastral data pose a serious threat and require mandatory adherence to the human-in-the-loop principle. No automated decision in the field of land law can take effect without verification by a competent specialist — at least at the current level of technological development. This requirement does not negate the potential of LLM agents but changes their role: they are a tool to support decision-making, not to replace human responsibility.

Conclusions and prospects for further research

1. The digitisation of land resource management in Ukraine has passed through two completed technological generations — from GIS and DSM to machine-learning and remote-sensing methods — and is at the beginning of a third, associated with agentic systems based on large language models.

2. There is a fundamental qualitative difference between the second and third generations: whereas the transition from the first to the second generation is evolutionary (more automation while retaining the human operator), the third generation inverts the interaction model — the human shifts from operator to task-setter, while the agent independently plans and performs the analytical process.

3. The domestic land resource management system has leapfrogging potential, but realising this potential requires the simultaneous resolution of five groups of problems: data quality and interoperability, human capacity, regulation, financing, and cybersecurity.

4. The context of post-war reconstruction is not only a challenge but also a catalyst for technological modernisation: the scale of the tasks of restoring land documentation in de-occupied territories objectively requires tools that go beyond the capabilities of traditional approaches.

5. Prospects for further research include developing the methodological foundations for assessing the readiness of specific land authorities to implement LLM agents and pilot-testing such systems on real cadastral datasets of de-occupied territories.

Declaration on the use of artificial intelligence

During the preparation of this manuscript, the authors used a generative artificial-intelligence tool (Claude, Anthropic) for language and stylistic editing, structuring the presentation, and translating the abstract into English. After using this tool, the authors personally checked, edited, and reviewed the content and bear full responsibility for the scientific accuracy, data, interpretations, and conclusions. The AI tool was not used to generate scientific results, sources, citations, or numerical data.

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ЦИФРОВА ТРАНСФОРМАЦІЯ УПРАВЛІННЯ ЗЕМЕЛЬНИМИ РЕСУРСАМИ В УКРАЇНІ: ВІД ГЕОІНФОРМАЦІЙНИХ СИСТЕМ ДО ІНТЕЛЕКТУАЛЬНИХ АГЕНТІВ

Анотація. *У статті досліджується еволюція інструментів цифровізації управління земельними ресурсами в Україні крізь призму зміни технологічних парадигм. Виокремлено три послідовні покоління цифрових рішень: перше — засноване на геоінформаційних системах та цифровому картографуванні ґрунтів; друге — на методах машинного навчання та концепції цифрових двійників; третє — на технологіях генеративного штучного інтелекту та агентів на основі великих мовних моделей (LLM). Проаналізовано стан вітчизняної нормативно-правової бази, інформаційної інфраструктури та кадрового потенціалу у сфері земельного кадастру. Показано, що перехід до третього покоління є не лише кількісним покращенням окремих показників, а якісним переосмисленням ролі людини у процесі просторового аналізу: аналітик переходить від функції оператора до функції постановника завдання, тоді як агент самостійно планує та виконує аналітичний процес. За уніфікованим* *набором параметрів складено порівняльну характеристику трьох поколінь технологій та сформовано матрицю бар'єрів і можливостей за п'ятьма напрямами — дані, кадри, нормативне регулювання, фінансування та кібербезпека. Обґрунтовано передумови траєкторії технологічного стрибка (leapfrogging) у контексті повоєнної відбудови та євроінтеграції, а також імператив дотримання принципу «людина в контурі» (human-in-the-loop) для юридично значущих кадастрових даних.*

Ключові слова: *цифрова трансформація, управління земельними ресурсами, геоінформаційні системи, машинне навчання, LLM-агенти, земельний кадастр, штучний інтелект, Autonomous GIS.*