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DIGITAL AGRONOMY: SMART DECISION-SUPPORT WORKFLOW FOR CLIMATE-RESILIENT FARMING IN THE KYIV AGGLOMERATION

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Abstract. *Rapid metropolitan growth is reshaping agrarian viability in peri-urban regions. Using the Kyiv agglomeration as a data-rich testbed, this study couples a modular UAV–AI decision-support workflow with empirical constraints emerging from land use, labour markets, logistics, and land rents. Regional evidence shows agricultural land has been squeezed to 0.21% of the area (≈0.18 k ha), against >54% green zones; wage differentials (16,500 UAH food processing vs 14,000 UAH agriculture) and transport costs of 20–250 UAH/km undermine farm margins and labour retention, while prime-zone rents up to 25 million UAH/ha/year intensify conversion pressure (Kyiv & oblast baseline tables and figures). These structural frictions motivate digital agronomy that is explicitly policy- and cost-aware. We therefore prototype a decision-support workflow that fuses UAV/satellite imagery, in-field IoT, and historical climate/crop data with administrative-economic layers (rents, wage gradients, haulage costs). The system translates multisource inputs into actionable stress detection, irrigation timing, and input allocation recommendations. At the same time, a logistics module evaluates route/vehicle choices under peri-urban cost profiles—a stakeholder-co-design process (farmers, processors, and planners) anchors usability and transferability. We report (1) the peri-urban baseline for Kyiv (land, wages, logistics, enterprise distribution), (2) the architecture of the UAV–AI workflow and integration points with farm CRMs and public agri-data, and (3) an evaluation framework linking agronomic KPIs to spatial-economic constraints for resilient adoption. The approach is designed for cross-border replication (Ukraine - Germany) and to inform respectable policy outputs on digital land management and peri-urban agrifood resilience.*

Keywords: *precision agriculture, digital agronomy, UAV, AI decision support, peri-urban farming, land use change, logistics costs, Kyiv agglomeration, resilience, policy integration.*

Introduction

Rapid urbanisation and the digitalisation of economic processes are two defining trends of the 21st century. Together, they drive structural change in both advanced and transitional economies, altering the distribution of land use, enterprise activity, and labour flows. In Eastern Europe, particularly Ukraine, these processes are accelerated by geopolitical and economic shocks that expose vulnerabilities in agrarian and urban sectors.

The Kyiv metropolitan region provides a compelling case study. On the one hand, the area has experienced significant contraction in agricultural land, coupled with rapid growth in non-agricultural enterprises, logistics, and services. On the other hand, the development of innovative city initiatives—from urban transport optimisation to digital governance platforms—illustrates how the digital economy reconfigures how cities manage infrastructure and services.

This article seeks to merge two strands of inquiry: (I) spatial-economic analysis of agrarian-urban dynamics and (II) the development of middleware-driven innovative city architectures (Figure 1). The objective is to examine how digital solutions leveraging IoT, UAVs, and AI-based decision support can address empirical urban pressures.

Analysis of recent research and publications

Aligned with the current Agriculture 4.0 technological innovations, three technology domains - UAV imaging, IoT telemetry, and AI/ML analytics - form a sensor stack for operational agronomy. Review papers on unmanned platforms in precision agriculture record a steady expansion of the range of tasks: from early detection of stresses and water regime monitoring to disease mapping and yield forecasting [1, 2]. The combination of "smart sensors" and machine learning algorithms, summarized in a systematic review with IoT and AI, underpins the shift from point cases to end-to-end decision support solutions, consistent with the platform architecture presented in this article [3].

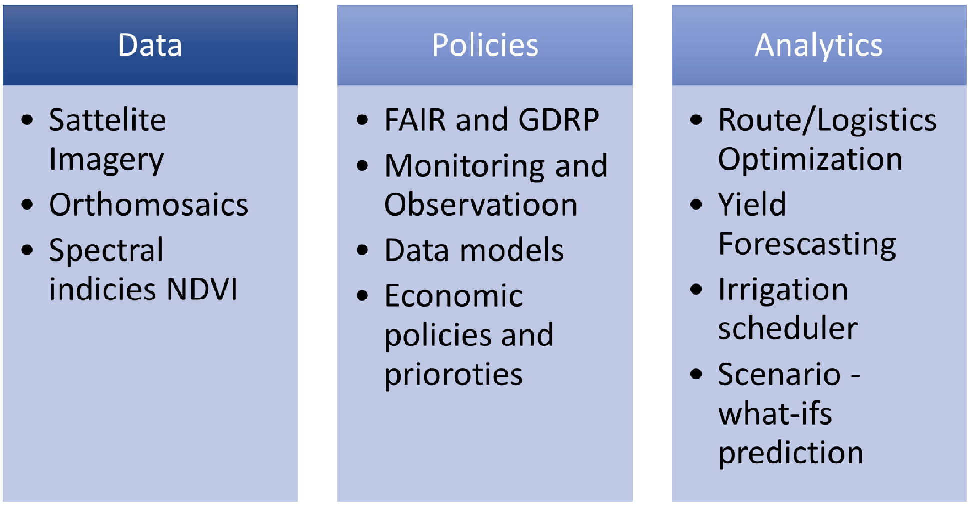

Fig. 1. Main components of an intelligent decision-support system (based on Nazarenko V. research data).

The second cluster of literature emphasizes the interoperability and role function of the middleware layer in cross-linking domain services and data. Work on aligning digital agricultural platform architectures and "pragmatic interoperability" in supply chains shows that standardized APIs, model schemes, and event-driven connectors provide scalability and manageability to complex ecosystems [4, 5]. The OGC SensorThings API standards and their industry enhancements demonstrate practical mechanisms for the interoperability of sensor data streams. The next-generation frameworks for "data spaces" and OPC UA automations outline the infrastructure for the secure exchange and reuse of agricultural data [6-8].

Finally, the latest directions—digital twins of farms, life cycle metrics, and technology adoption issues—shift the emphasis from purely technical efficiency to systemic effectiveness and sustainability. Reviews from digital twins and "smart" farming outline the potential of virtual replicas for simulating scenarios and optimizing resources. At the same time, LCA estimates point to the environmental and cost implications of implementing precision farming [9, 10]. In parallel, research on DSS and barriers to adoption highlights the importance of clear interfaces, transparent quality indicators, and economic feasibility for different manufacturers [11, 12]. This confirms the feasibility of the middleware architecture chosen in the article, with weighting criteria (time-cost-risk-quality) and contextual economic adjustment for the periurban conditions of the Kyiv agglomeration, where logistics costs and competition for land significantly affect operational decision-making.

Purpose. This study aims to develop and demonstrate a modular decision-support workflow that integrates geospatial and economic data to enhance the resilience and competitiveness of peri-urban agriculture under the pressures of rapid metropolitan growth. Using the Kyiv agglomeration as an applied case, the research aims to establish a robust empirical baseline of land use, labour, logistics, and rent dynamics that shape the viability of farming systems; design and prototype a UAV–AI–IoT platform capable of fusing multi-source spatial, climatic, and operational data with administrative-economic indicators; and evaluate how weighted routing and cost-sensitive analytics can inform stress detection, irrigation scheduling, and logistics optimization.

Methods and research data

The study draws on statistical data for the Kyiv region between 2000 and 2022, including land cadastre records, wage statistics, enterprise distribution, and transportation costs (Figure 2). Baseline findings include agricultural land reduction, green zone distribution, prime-zone land rent prices, average monthly wages, transport costs for logistics, and other data (Table 1).

A three-layer middleware architecture for bright city service orchestration was modelled: Application Layer (services for mobility, governance, energy, and environmental monitoring); Middleware Layer (event-driven routing, weighted decision parameters, API gateways); Core Services (data storage, IoT device management, security, and redundancy mechanisms). The parametric routing model applies weights to service requests to optimize real-time response time and resource allocation.

1. Key research data findings for Kyiv and Kyiv region (Kyiv agglomeration zone)*

Category	Data (2022)
Agricultural land	reduced to 0.21% of the total area
0.18 k ha	0,21
Green zones	Green zones account for 54% of the land.
Prime-zone land rents	25 million UAH/ha/year
Average monthly wages in food processing	16,500 UAH
Average monthly wages in agriculture	14,000 UAH in agriculture
Transport costs for logistics	20–250 UAH/km.

* prepared by Nazarenko V. based on the research data [13-14]

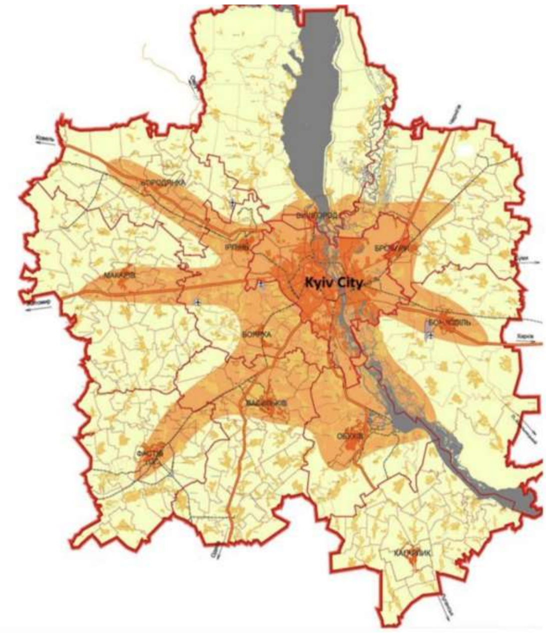

Fig. 2. Boundaries of the Kyiv agglomeration (based on Nazarenko V. research data) [16]

A comparative method was used to connect empirical urban pressures with middleware capabilities. Interviews with local stakeholders (farmers, IT providers, municipal planners) informed usability considerations. The research interview was conducted via personal communication and an interview, as well as an online form. The full survey results have not yet been disclosed to the general public.

It is important to note the current limitations on using uncrewed aerial vehicles (UAVs) in Ukraine under wartime conditions. Due to security restrictions, regulatory controls, and risks of interception, large-scale UAV deployment for agricultural monitoring and data collection is not always feasible. Therefore, while UAVs remain a crucial component of digital agronomy and long-term sustainability measurement, their application in the near term should be considered cautiously. In such cases, alternative sources such as satellite imagery, ground-based IoT sensors, and administrative-economic datasets can partially compensate for the limited aerial data. This reservation emphasizes the need for flexible, multi-source architectures to maintain decision-support functions despite temporary technological constraints.

Results

The contraction of agricultural land and the steep increase in land rents have undermined the viability of peri-urban farming. Wage disparities further reduce the attractiveness of agricultural employment, while logistics costs undermine competitiveness. The result is a structural shift toward service and logistics enterprises in peri-urban zones.

The growth of innovative city initiatives has been driven by demand for more efficient governance and citizen services. Pilot projects in Kyiv include traffic monitoring systems, digital municipal services, and environmental IoT deployments. The middleware frame-

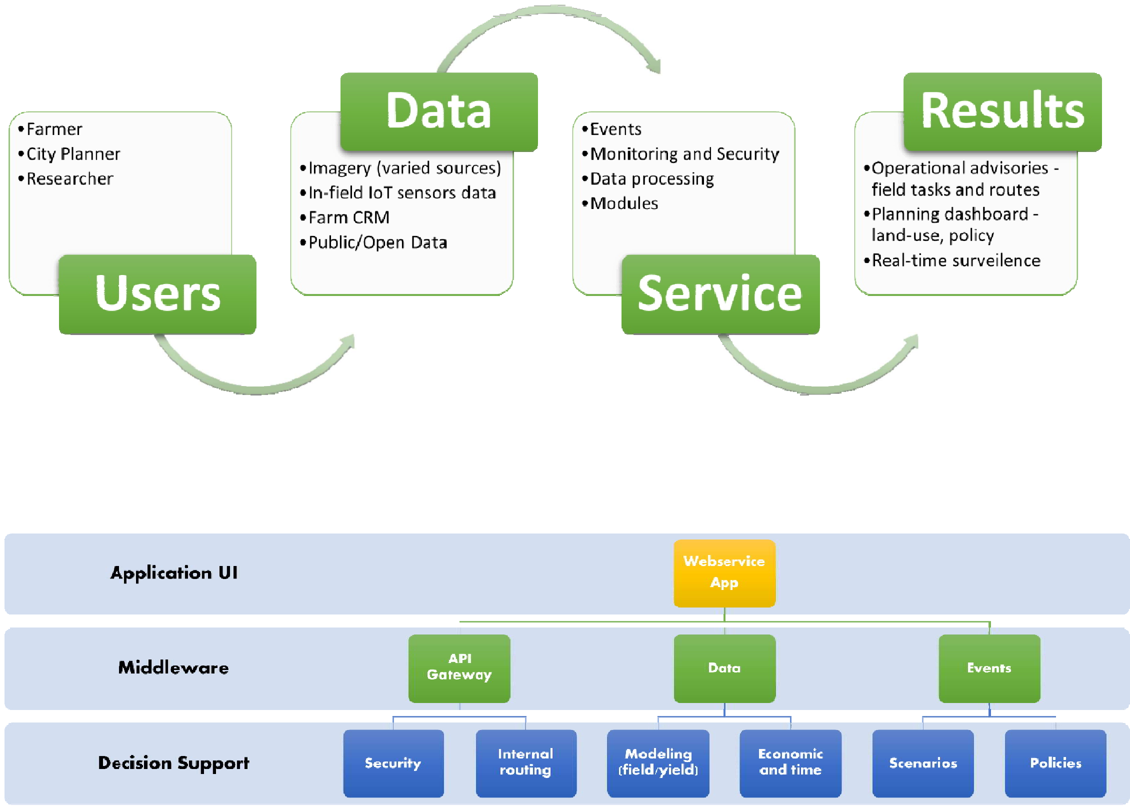

Fig. 3. Smart decision support system architecture, the main functions of the software system – top image, the three-level architecture of the software – bottom image (based on Nazarenko V. research data)

work addresses challenges such as scalability, interoperability, and resilience.

The middleware framework addresses three central challenges in innovative city service management: scalability, interoperability, and resilience. Scalability is achieved by supporting the growing volume of IoT devices and data streams that must be processed in real time [15]. Interoperability ensures that diverse services and platforms can communicate effectively by adopting common data standards. At the same time, resilience guarantees that operations can continue despite technical failures or external shocks. These features create a robust foundation for integrating complex urban systems within a single, adaptive digital environment.

The simulation of routing scenarios further demonstrates how middleware optimisation improves logistics and service delivery (Figure 3). The system enhances performance across multiple domains by applying weighted parameters to balance cost, time, and resource constraints. In logistics, this translates into reduced costs per kilometre and more efficient routing under congestion conditions. In governance, the model enables faster and more effective responses to citizen requests, improving service delivery and public trust. In agriculture, integrating UAV and sensor data into urban planning processes supports more precise land-use decisions and strengthens the resilience of peri-urban farming systems.

The findings illustrate how innovative city solutions can partly mitigate urbanisation challenges. For example, integrating UAV data into the middleware

2. Middleware routing algorithm for smart city and smart agriculture platform design *

Category	Details
System events	UAV tile ready sensor threshold breach farmer CRM ticket batch model retrain route-planning request policy/KPI query
System services	image pre-proc crop-stress model irrigation scheduler yield forecaster route optimizer data mart writer policy dashboard API
Main data parameters (input)	peri-urban cost profiles (e.g., 20–250 UAH/km) wage differentials (e.g., 16,500 versus 14,000 UAH) land-use pressure (agricultural land = 0.21%) used to weight economic risk/time sensitivity for Kyiv agglomeration pilots
Weights and algorithm data	time (latency) cost (CPU or UAH) per request accuracy range (%) economic data task/step priority

* prepared by Nazarenko V. based on the author's research data and materials

system provides real-time visibility of land use changes, allowing planners to anticipate and manage peri-urban expansion. Similarly, optimised logistics can reduce food system vulnerabilities by lowering transportation costs.

The smart agriculture and city middleware platform must orchestrate heterogeneous agricultural data flows (UAV imagery, in-field IoT, cadastral/administrative datasets, climate and market feeds) and route requests to the optimal analytic or storage microservice under explicit cost–time–risk–quality constraints. We adapt the three-layer architecture (Applications <-> Middleware <-> Core Services) with an event-driven dispatcher and weighted messages, proven in the Smart-City context, to agricultural use cases and peri-urban Kyiv conditions (logistics costs, wage/rent gradients, land-use pressure). The base presentation of the middleware systems' parameters and functions is outlined in Table 2 (we omitted technical details, as it is outside the topic of the present research, but they will be presented in future research publications). Algorithm usage scenario- peri-urban Kyiv farm requests optimal harvest-day routing (event - route-planning request) during congestion, 80 km round-trip, current band = 120–250 UAH/km. The system picks an optimal route planning path based on weights, and the route choice is based directly on economic criteria (set up in advance), resulting in faster/cheaper computation when transport is expensive.

From a practical standpoint, the resilience of the proposed data-centric architecture lies in its distributed and adaptive design. Each layer of the middleware platform—data ingestion, processing,

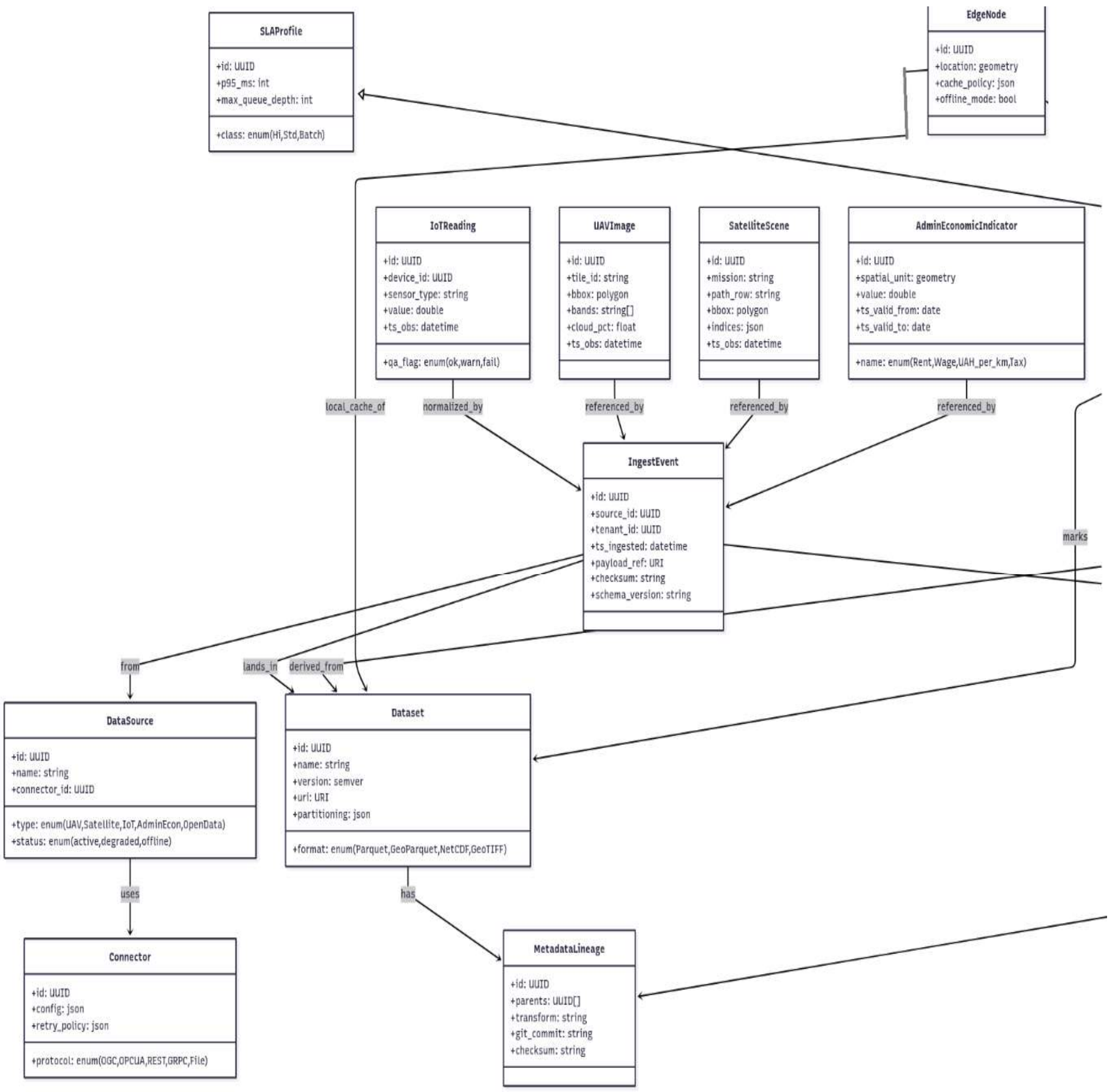

Fig. 4. Class diagram of Data-Centric Resilience Model
(based on Nazarenko V. research data)

and service orchestration—operates under modular redundancy, allowing system components to remain functional even if parts of the infrastructure are temporarily degraded. Edge computing nodes can execute essential analytics locally when connectivity to central servers is interrupted, while asynchronous message queues ensure incoming data is cached and synchronized once the network stabilizes. Adopting open standards (OGC SensorThings, ISO, OPC UA) enables quick substitution of data sources and services without rewriting the core logic. Furthermore, using multi-source inputs - satellite imagery, IoT telemetry, administrative datasets, and economic indicators - ensures continuity of decision-support functions when specific data channels (such as UAV imagery) are unavailable (Figure 4). Collectively, these mechanisms maintain operational stability, safeguard data integrity, and preserve analytical continuity under transient conditions, confirming the platform's applicability for resilience planning and crisis-adaptive agriculture.

However, deploying such systems

requires careful attention to several critical factors. Data governance must be ensured through adherence to FAIR data principles and compliance with GDPR, guaranteeing transparency, accessibility, and protection of sensitive information. Equally important is user adoption, which depends on designing interfaces that are intuitive and accessible to a wide range of stakeholders, from municipal administrators to farmers and citizens. Interoperability also plays a decisive role, requiring local platforms to align with international standards such as ISO and OGC to facilitate integration across systems and borders. These considerations position the study within broader debates on innovative city development and the digital economy, underscoring the importance of cross-sector integration and international collaboration.

Discussion

Urbanisation in Kyiv illustrates the pressures of metropolitan growth on agriculture and regional sustainability. Digital economy tools, particularly middleware-driven innovative city platforms, offer viable pathways to manage these challenges. By combining empirical urban-economic data with algorithmic service orchestration, this research demonstrates how data-centric architectures can support resilience and sustainability in transitional contexts.

Future research should extend platform testing across borders (e.g., Ukraine–Germany), incorporate UAV-based precision agriculture, and evaluate policy implications for urban-rural governance. The study advances SDGs 9, 11, 12, and 17 by promoting innovation, sustainable cities, responsible production, and global partnerships (SDG 9 - Industry, Innovation, and Infrastructure; SDG 11 - Sustainable Cities and Communities; SDG 12 - Responsible Consumption and Production; SDG 17 - Partnerships for the Goals) [17].

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Назаренко В.А.

ЦИФРОВЕ ЗЕМЛЕРОБСТВО: ПРОЦЕС ПІДТРИМКИ ПРИЙНЯТТЯ РОЗУМНИХ РІШЕНЬ ДЛЯ СТІЙКОГО ДО ЗМІНИ КЛІМАТУ СІЛЬСЬКОГО ГОСПОДАРСТВА В КИЇВСЬКІЙ АГЛОМЕРАЦІЇ

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Анотація*. Швидке зростання мегаполісів суттєво змінює життєздатність аграрного сектора економіки у приміських регіонах. Використовуючи Київську агломерацію як багатий на дані випробувальний полігон, це дослідження поєднує модульний робочий процес підтримки прийняття рішень за допомогою БПЛА та штучного інтелекту з емпіричними обмеженнями, що виникають у сфері землекористування, ринків праці, логістики та земельної ренти. Регіональні дані свідчать, що сільськогосподарські угіддя* *скоротилися до 0,21% площі (≈0,18 тис. га), проти >54% зелених зон; різниця в оплаті праці (16 500 грн харчова промисловість проти 14 000 грн у сільському господарстві) та транспортні витрати на рівні 20–250 грн/км підривають маржу фермерських господарств та утримання робочої сили, тоді як орендна плата в прайм-зоні до 25 млн грн/га/рік посилює тиск на конверсію (базові таблиці та цифри Києва та області). Ці структурні розбіжності мотивують розвиток цифрового землеробства, яка явно враховує політику та витрати. Тому запропоновано створити прототип робочого процесу підтримки прийняття рішень, який поєднує аналіз знімків БПЛА/супутників, польовий Інтернет речей та історичні дані про клімат/врожай з адміністративно-економічними рівнями (орендна плата, градієнти заробітної плати, витрати на перевезення). Інформаційна система перетворює вхідні дані з кількох джерел у швидке та результативне виявлення проблемних моментів, час поливу та рекомендації щодо розподілу вхідних даних. У той же час, системний (програмний) модуль бізнес-логіки оцінює вибір маршруту/транспортного засобу відповідно до профілів витрат у приміському регіоні — процес спільного проектування зацікавленими сторонами (фермери, переробники та планувальники) визначає зручність використання та передачу. В дослідженні представлено (1) базовий рівень приміського розвитку Києва (земля, заробітна плата, логістика, розподіл підприємств), (2) архітектуру робочого процесу БПЛА-штучного інтелекту та точок інтеграції з CRM-системами для ферм та публічними даними аграрного виробництва, а також (3) систему оцінювання, яка пов'язує KPI аграрного сектору та промисловості з просторово-економічними обмеженнями для стійкого впровадження. Цей підхід розроблений для транскордонного реплікації (Україна – Німеччина) та для інформування про ефективні результати політики щодо цифрового управління земельними ресурсами та стійкості приміських агропродовольчих фондів.*

Ключові слова: *точне землеробство, цифрове землеробство, БПЛА, підтримка прийняття рішень штучним інтелектом, приміське землеробство, зміна землекористування, логістичні витрати, Київська агломерація, стійкість, інтеграція політик.*