

ГЕОІНФОРМАТИКА

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GIS-BASED MODELING OF SPATIALLY EXPLICIT AGRICULTURAL MACHINERY MOVEMENT IN PRECISION AGRICULTURE SYSTEMS

(Представлено членом редакційної колегії д-ром геол. наук, ст. дослідником О.І. Меньшовим)

Background. The development of precision agriculture technologies is accompanied by a rapid increase in the volume of spatial-temporal data that characterizes not only the state of agroecosystems but also the operational parameters of agricultural machinery. In this context, the use of Global Navigation Satellite System (GNSS) data for analyzing machinery movement regimes within individual fields becomes particularly important.

Methods. An approach to the spatial-temporal analysis of agricultural machinery movement based on GNSS trajectories using geographic information systems is presented. The study relies on representing the movement trajectory as a set of elementary spatial-temporal segments for which metric, temporal, and speed characteristics are determined. This makes it possible to move from purely temporal or average indicators to a spatially oriented interpretation of movement parameters.

Results. The study was conducted using a production agricultural field located in the western region of Ukraine as a case study. Based on GNSS data, machinery movement trajectories were reconstructed, segmented, and average movement speeds were calculated for individual segments. The results were visualized in the form of thematic maps and graphs that reflect the spatial variability of speed regimes within the field.

The analysis revealed pronounced within-field heterogeneity in machinery speed, caused by field configuration, the organization of passes, and maneuvering zones. The spatial representation of speed parameters made it possible to identify and visualize zones of stable operation, deceleration, and turning, which are not always detectable through tabular or purely temporal data analysis.

Conclusions. The obtained results confirm the feasibility of using segmented spatial-temporal analysis of GNSS trajectories to study the movement of agricultural machinery and substantiate the applicability of this approach in precision agriculture technologies for evaluating the efficiency of field operations and supporting management decision-making.

Keywords: precision agriculture, Global Navigation Satellite System (GNSS), geographic information systems (GIS), machinery movement trajectory, spatial-temporal analysis.

Background

One of the key components of modern precision agriculture technologies is the use of satellite positioning systems such as Global Navigation Satellite Systems (GNSS) and GPS, which provide highly accurate spatial positioning of objects within agricultural lands. The application of GNSS data has led to the development of the precision agriculture concept, which is oriented toward site-specific field management using variable rate application, prescription maps, and spatially differentiated agrotechnological decisions. Due to the capability of continuous real-time coordinate determination, GNSS technologies form the foundation for spatially informed management of production processes and improved resource-use efficiency in agriculture.

GNSS/GPS systems, including global and regional satellite constellations, are integrated with Geographic Information Systems (GIS) and specialized software, enabling field mapping, monitoring of agricultural machinery movement, automated control of machine-tractor units, and analysis of field operation performance. The use of GNSS receivers allows high-precision recording of soil sampling locations, execution of technological operations, and the formation of spatially referenced datasets related to yield, agro-landscape conditions, soil moisture availability, and other agroecological indicators.

Precision agriculture is aimed at creating an integrated decision support system that enhances the efficiency and sustainability of agricultural practices (Zatserkovnyi et al., 2025a). The development of precision agriculture technologies

is accompanied by a rapid increase in spatial-temporal data characterizing both agroecosystem conditions and operational parameters of agricultural machinery. GIS and GNSS are considered fundamental tools for collecting, processing, and analyzing information necessary to improve the efficiency of agrotechnological operations (Hofmann-Wellenhof, Lichtenegger, & Wasle, 2008; McBratney et al., 2005).

Geographic Information Systems play a leading role in collecting, processing, and analyzing data applied in precision agriculture systems. They enable the integration of geospatial information within a unified environment, providing a basis for informed management and optimization of agricultural production processes.

It is important to note that modern precision technologies not only enhance agricultural efficiency but also contribute significantly to environmental protection. They reduce ecosystem pressure, optimize the use of fertilizers and pesticides, and support biodiversity conservation (Gebbers, & Adamchuk, 2010).

One of the important applications of GNSS technologies in agriculture is the monitoring of machine-tractor unit movement during field operations. GNSS-based trajectory data include spatial coordinates and timestamps, allowing machinery movement to be treated as a spatiotemporal process. The analysis of such data enables assessment of speed regimes, duration of technological operations, detection of idle periods and inefficient maneuvers, as well as optimization of machinery fleet utilization (Godwin et al., 2003; Zhang, & Pierce, 2013).

Machinery speed significantly affects the quality of field operations, energy consumption levels, and overall agricultural productivity (Bochtis, Sørensen, & Busato, 2014). At the same time, effective use of GNSS data requires spatially oriented processing, since analysis based solely on averaged or purely temporal indicators does not fully capture intra-field heterogeneity of operating conditions.

Therefore, the development of methods for spatially detailed analysis of agricultural machinery movement parameters using GIS is highly relevant and consistent with modern concepts of precision agriculture and digital transformation of the agricultural sector in Ukraine. The application of spatiotemporal GNSS data analysis enables the transition from purely temporal evaluation of machinery movement to the identification of intra-field variability in technological operations.

The purpose of this study is to test and validate an approach to spatiotemporal analysis of GNSS data for assessing variability in machinery speed regimes and generating speed variability maps.

GNSS data are used for quantitative assessment of operational parameters of agricultural units, including travel speed, operation duration, and idle time. For instance, Zandonadi et al. (2021) applied GNSS data to analyze operational efficiency of combine harvesters, tractors, self-propelled sprayers, and other agricultural machinery, where travel speed was considered one of the performance indicators of technological operations.

Trajectory analysis based on GNSS data is widely used to determine operating modes of agricultural machinery, evaluate the duration of individual technological operations, and plan fieldwork. Within this framework, spatiotemporal characteristics of machinery movement serve as an informational basis for managerial decision-making in precision agriculture systems, particularly for optimizing the utilization of machine-tractor units (Catania, & Vallone, 2020).

However, in most existing studies, GNSS data are analyzed predominantly in the temporal domain without

detailed spatial generalization within agricultural fields. Time-series speed analysis allows identification of productive and non-productive operational modes, as well as detection of stops, maneuvering, and technological pauses, which is practically important for improving machinery organization and performance (Chen, Wang, & Zhang, 2023).

Within telematic systems, GNSS data are integrated with additional onboard sensor measurements, including fuel consumption, engine revolutions, working implement status and position, and inertial measurement units, enabling more comprehensive interpretation of agricultural machinery operating modes (Aubry, Berruto, & Busato, 2019).

At the same time, several studies emphasize the need to move beyond purely temporal analysis toward spatial trajectory interpretation. Kowalczyk, & Hadas (2024) demonstrate that GNSS data enhanced with Real-Time Kinematic (RTK) positioning allows the generation of spatially accurate machinery trajectories suitable for advanced GIS-based analysis, including assessment of intra-field variability in movement regimes.

Methodological foundations for spatial generalization of discrete geodata have been extensively described in the Ukrainian scientific literature. In the monograph by Burachek et al. (2011), approaches to transformation and interpretation of spatial data within GIS are presented, which are relevant for converting discrete GNSS observations into linear process models. Similar methodological approaches are applied in studies by Guo et al. (2018), where GNSS data are combined with geoinformation technologies for analysis of agrotechnological processes.

In addition to temporal analysis, several studies propose spatial interpretation of GNSS data using cartographic methods. GNSS trajectories are considered a basis for high-precision agricultural mapping, where coordinate and speed parameters are generalized into spatial models that allow analysis of field operation characteristics considering field configuration and movement conditions (Bettucci, Lindia, & Trunfio, 2026).

Summarizing the above, a methodological framework for utilizing GNSS data in agricultural machinery movement analysis has been established in scientific research. This framework includes temporal analysis of speed indicators, spatial modeling of trajectories, and cartographic interpretation of results. These approaches provide theoretical preconditions for constructing machinery movement variability maps within individual agricultural fields.

Methods

Methodological approaches to the analysis of agricultural machinery movement based on GNSS data in scientific research are grounded in spatiotemporal trajectory modeling and subsequent geoinformation interpretation (Gebbers, & Adamchuk, 2010; McBratney et al., 2005).

Spatiotemporal analysis of agricultural machinery movement relies on GNSS trajectories, which represent a sequence of discrete spatial positions recorded at specific time intervals. This type of data is widely used for analyzing transport and agricultural production processes, as it enables quantitative assessment of movement parameters under real operational conditions (Catania, & Vallone, 2020; Chen, Wang, & Zhang, 2023).

To transition from discrete GNSS observations to a generalized spatial representation of movement, the trajectory is modeled as a sequence of adjacent segments formed between two consecutive recorded positions of the machinery. The length of an individual trajectory segment is calculated as the Euclidean distance between two

consecutive points in a planar coordinate system (see equation 1):

$$L_i = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}, \quad (1)$$

where x_i, y_i and x_{i+1}, y_{i+1} – denote the coordinates of adjacent GNSS points, L_i – represents the length of the i -th trajectory segment.

Representing the trajectory as a sequence of elementary segments corresponds to commonly accepted practices in GIS-based movement analysis. Metric and temporal characteristics of segments are used to identify operational modes (working pass, turning, idle periods) and to perform further spatial generalization within the field boundary.

In spatiotemporal trajectory analysis, formalizing movement as a set of elementary segments with defined metric and temporal characteristics constitutes a key methodological stage (Catania, & Vallone, 2020; Chen, Wang, & Zhang, 2023).

The machinery speed within an elementary trajectory segment is determined as the ratio of the traveled distance to the time required to traverse that distance. This approach is widely adopted in moving-object analysis and GIS-based modeling of transport systems and spatial flows.

The use of a metric coordinate system allows direct application of calculated distance values in further computations, which is a standard approach in GNSS navigation and geospatial analysis studies (Zandonadi, Milan, & Molin, 2021).

The temporal duration of movement within a segment is defined as the difference between timestamps of consecutive GNSS records and is calculated as follows (see equation 2):

$$\Delta t_i = t_{i+1} - t_i, \quad (2)$$

where t_i and t_{i+1} – represent the time of registration of the corresponding machinery positions.

In cases of uniform GNSS recording frequency, typical for most telematic systems, the value of Δt_i remains constant or varies within a narrow range, which simplifies subsequent speed analysis (Chen, Wang, & Zhang, 2023; Aubry, Berruto, & Busato, 2019).

The average speed of machinery within an individual trajectory segment is calculated as the ratio of traveled distance to the duration of movement (see equation 3):

$$v_i = \frac{L_i}{\Delta t_i}, \quad (3)$$

where v_i – denotes the average speed within the i -th trajectory segment.

The presented approach to speed estimation is widely applied in studies evaluating the performance efficiency of agricultural machinery, as it allows localization of movement regime changes along the trajectory and their correlation with spatial characteristics of the field (Catania, & Vallone, 2020; Zandonadi, Milan, & Molin, 2021).

The obtained speed values for individual trajectory segments are treated as spatially distributed movement characteristics. Their further aggregation and visualization are performed using thematic cartography methods within a GIS environment, enabling analysis of intra-field variability in speed regimes and identification of zones characterized by reduced or increased machinery speed for subsequent interpretation.

In this study, speed regime analysis was performed using a segmented spatiotemporal approach to GNSS trajectory data. For each trajectory segment, speed was calculated as the ratio of traveled distance to the time interval between GNSS observations. The resulting values were spatially referenced and used to generate a speed variability map within the study field.

The proposed approach is independent of machinery type and can be adapted for analyzing movement of various agricultural units, provided sufficient temporal resolution of trajectory data. All calculations and the construction of the speed variability map were performed using ArcMap software.

Study Area. The study was conducted within a production field with an area of 117 hectares, located near the village of Shypivtsi, Zalishchyky district, Ternopil region, Ukraine (Fig. 1).



Fig. 1. Geographic location of the study area within Zalishchyky district, Ternopil region (based on Google Earth data)

The soil cover of the study area is predominantly represented by typical low humus chernozems and their degraded light loamy varieties. These soils combine high agricultural production potential with increased sensitivity to moisture variations and structural disturbances. Spatial variability of soil texture, microrelief characteristics (Fig. 2),

and heterogeneity of the water regime result in noticeable differences in agricultural production processes throughout the entire crop-growing cycle. The combination of these factors allows the study site to be considered a representative object for testing and validating approaches within precision agriculture technologies.

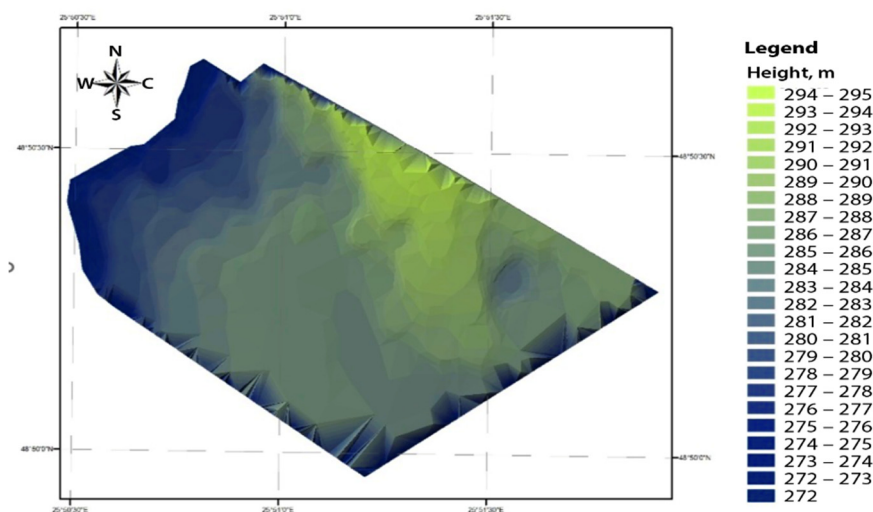


Fig. 2. Microrelief model of the field (scale 1:10,000), generated in ArcMap based on data provided by AgroSEM LLC

Results

As a result of the conducted spatiotemporal analysis of GNSS trajectories of agricultural machinery movement, a dataset of speed characteristics was obtained, reflecting variations in the operational regimes of the machinery unit within the study field. Spatial generalization of the calculated indicators enabled the generation of a speed variability map.

The constructed map revealed pronounced spatial heterogeneity in speed regimes. Areas characterized by stable speed values were identified alongside zones exhibiting increased variability, indicating differences in movement patterns across distinct parts of the field.

The obtained results make it possible to move beyond the analysis of individual GNSS records toward a generalized assessment of the spatial structure of technological operations. Spatial interpretation of speed characteristics can be applied to evaluate the organization of field operations and to assess operational regimes of machine-tractor units.

Within the study field, a dense set of GNSS-based points representing the machinery trajectory during field operations was mapped. The resulting point network forms a detailed spatial pattern corresponding to the actual working passes of the machinery and reflects movement directions, turning maneuvers, and headland operations. Visualization of

GNSS observations allows tracing the spatial structure of technological operation performance and serves as a basis for further speed analysis and construction of movement variability maps.

For a more detailed analysis of the spatial structure of machinery movement and to reduce redundancy in the initial dataset, a representative sample of GNSS observations was formed, ensuring uniform trajectory coverage. The presented subset of GNSS points was generated through systematic reduction of the original dataset to 5,000 positions (Fig. 3). This reduction was applied as a technical procedure to standardize subsequent calculations and improve GIS processing efficiency without compromising the overall geometry of the route.

The reduction was performed uniformly according to the chronological sequence of GNSS recordings, preserving the spatial structure of working passes, turning segments, and headland areas, which play a critical role in shaping speed regimes. The resulting set of attribute parameters forms an analytical basis for spatiotemporal interpretation of machinery movement, combining coordinating information with temporal intervals and derived speed indicators. This enables the transition from individual GNSS observations to quantitative analysis of movement regimes along the machinery trajectory.



Fig. 3. Subsample of GNSS points (n=5,000) used for further calculations of machinery movement parameters (John Deere models S770 and S670)

Overall, the described approach ensures comparability of results across individual passes and technological operations, provided that a unified trajectory segmentation algorithm is applied. The presented segment clearly reflects the linear component of agricultural machinery movement within an individual field pass and serves as the initial dataset for subsequent spatiotemporal calculations. The sufficient density and orderly distribution of points allow accurate determination of segment lengths, temporal intervals between consecutive records, and derived speed characteristics of machinery movement.

The presented fragment of the GNSS-based trajectory demonstrates regularity in spatial position recording and

adequate point density for further movement segmentation. This confirms the suitability of the original GNSS dataset for calculating metric and temporal parameters of trajectory segments without significant loss of geometric accuracy. The obtained results indicate that even after reduction of the initial GNSS dataset, an adequate level of trajectory detail is preserved, which is necessary for subsequent speed parameter analysis and thematic mapping of variability.

Figures 4–5 present the results of spatial visualization of GNSS-based machinery movement trajectories within the designated study field. The points and linear segments represent the sequence of machinery passes during the execution of the field operation.

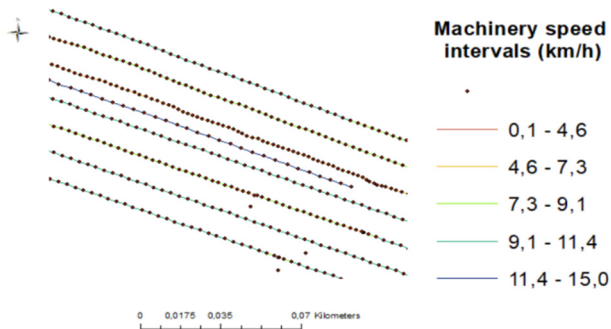


Fig. 4. Spatial distribution of agricultural machinery speed along working passes (straight-line passes)

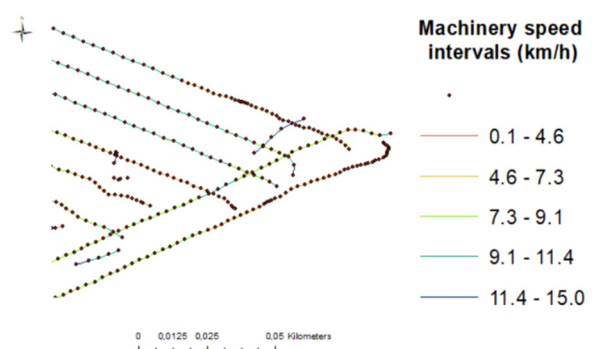


Fig. 5. Fragment of GNSS-based machinery movement trajectories illustrating variations in speed regimes within maneuvering and turning segments

The color coding corresponds to interval classification of movement speed (km/h), enabling clear visualization of variability in speed regimes both along individual passes and between them. The predominance of parallel lines indicates systematic organization of machinery movement in accordance with field configuration, whereas local deviations and directional changes are associated with maneuvering in headland areas and trajectory adjustments during turning operations.

Fragmented color variations along the trajectories indicate uneven speed even within a single pass. Such variability may be influenced by micro-relief conditions, soil heterogeneity, or specific characteristics of the technological process. In this context, spatial representation of speed

parameters allows transition from generalized statistical indicators to detailed analysis of intra-field variability in machinery movement.

Analysis of the spatial distribution of speed along trajectories demonstrates that even under an overall regular pass pattern, speed regimes remain heterogeneous. This suggests the presence of intra-field factors affecting machinery movement characteristics that cannot be identified solely through average or purely temporal indicators.

Segments characterized by changes in color correspond to transitions between different speed intervals associated with maneuvering, turning, and organizational aspects of the technological process (Fig. 6).



Fig. 6. Spatial distribution of segmented GNSS-based machinery movement trajectories within the study field

Figure 7 visualizes selected fragments of the spatial structure of agricultural machinery movement trajectories derived from GNSS data, illustrating different types of movement organization and corresponding speed regimes within a single field. In the marginal (headland) areas of the field, trajectory geometry becomes more complex, characterized by transitions from linear movement to curvilinear segments, local directional changes, and short-term stops accompanied by reduced speed values (Fig. 7a). These segments are associated with turning operations, machine alignment, and trajectory adjustments near field boundaries, which are typical during the completion or initiation of working passes.

In the central part of the field, an ordered system of parallel passes dominates, forming a clearly expressed linear trajectory structure (Fig. 7b). These segments are characterized by stable and relatively higher speed values. Minor local deviations in speed within such passes are episodic in nature and are generally caused by short-term steering corrections or specific technological features of field operations, without disrupting the overall regularity of the cultivation scheme.

Transition zones between main working passes and maneuvering areas are characterized by a combination of linear segments with localized changes in direction and speed (Fig. 7c), reflecting the simultaneous influence of operational factors and spatial characteristics of the field.

The presented examples confirm that machinery movement within a single field is heterogeneous both in trajectory geometry and in speed regimes. Cartographic representation of segmented GNSS data provides a foundation for identifying zones of stable operation, maneuvering, and speed reduction within precision agriculture technologies.

The illustrated fragments demonstrate clear differences in spatial movement patterns: working passes are characterized by parallel linear segments with stable speed; turning operations are represented by local loops or arcs with short-term decelerations; technological pauses appear as clusters of points or very short segments with minimal displacement. These areas account for most of the non-productive time and influence overlaps in the headland zones of the field.

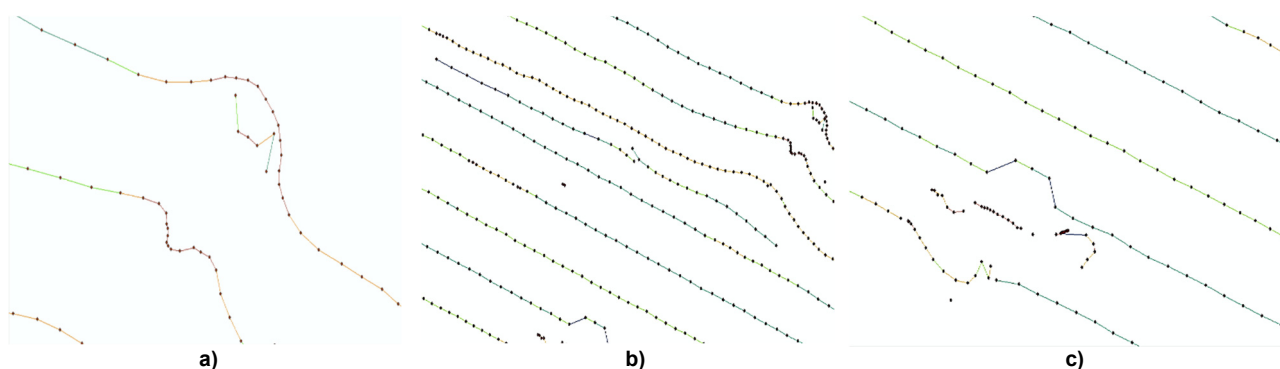


Fig. 7. Selected fragments of GNSS-derived agricultural machinery movement trajectories illustrating spatial differentiation of speed regimes

For further analysis, a thematic spatial visualization of the calculated speed parameters can additionally be presented, where trajectory segments are classified according to average movement speed using a graduated color scale within the field.

Figure 8 presents a cartogram of agricultural machinery pass density constructed because of GNSS telemetric data

recorded during the execution of field operations. The resulting visualization characterizes spatial heterogeneity of machinery movement within the field and enables quantitative assessment of pass intensity across different zones.

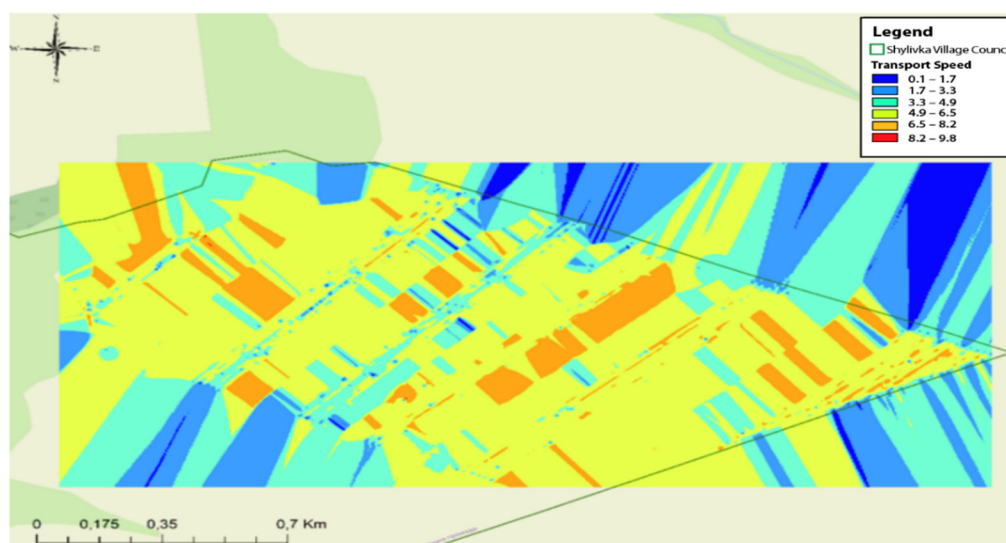


Fig. 8. Map of variability in agricultural machinery movement speed

Areas with the lowest number of passes (0.1–3.2), highlighted in blue and light-blue tones, correspond to zones of episodic or single-pass machinery movement. Such areas may be associated with headland operations, isolated technological maneuvers, or field sections not fully incorporated into the primary cultivation scheme. Their spatial distribution indicates uneven field coverage in certain segments of the route.

Most of the field area is represented by yellow and light-green zones with pass density values ranging from 4.3 to 6.5, corresponding to stable operational movement regimes. These areas reflect the core working scheme of the operation, characterized by relatively uniform movement without significant overlaps or repeated passes. This structure indicates an overall organized routing pattern across most of the field.

At the same time, orange and red zones with increased pass density (8.7–9.8) form localized clusters of excessive movement intensity. Their occurrence is associated with repeated entries, turning operations, field boundary configuration, and local trajectory corrections. Spatial

clustering of such zones allows identification of potentially problematic areas where time and energy resources are overdosed.

The constructed cartogram serves as a basis for spatial assessment of machinery movement organization within the field and enables identification of areas with inefficient pass schemes. From an applied perspective, the results can be used to evaluate the effectiveness of existing routing strategies, compare alternative movement schemes, and justify optimization measures in field logistics aimed at reducing overlap and improving the uniformity of agrotechnical load distribution.

The constructed temporal graph of average movement speed (Fig. 9) illustrates variations in machinery speed regimes during the execution of field operations and serves as a tool for analyzing the sequence of movement along the trajectory. Unlike cartographic models that capture the spatial distribution of parameters, this graph allows tracking speed dynamics in chronological order of GNSS observations.

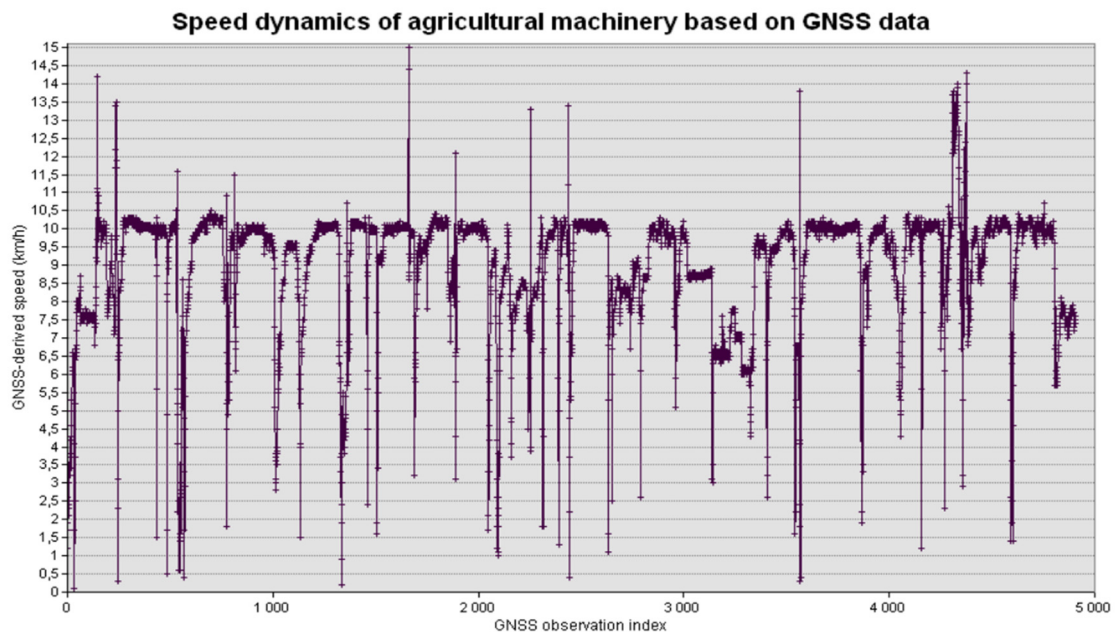


Fig. 9. Average movement speed graph (km/h) based on 5,000 GNSS observations

The x-axis represents the GNSS observation index corresponding to the sequential movement of the machinery along the route, while the y-axis displays the average speed calculated for adjacent trajectory segments. The predominant concentration of values within the operational speed range indicates relative stability of movement during the main working passes across the field. At the same time, the graph clearly reveals sharp short-term decreases in speed associated with turning operations, stops, maneuvering, or technological pauses during the execution of agricultural operations.

The alternating pattern of stable and transitional speed segments reflects the internal structure of the agrotechnological process and corresponds with spatial zones of increased pass density identified in the variability cartograms. Thus, the temporal graph of average speed complements the cartographic analysis by enabling comparison between spatial movement characteristics and their temporal manifestations, providing a more

comprehensive interpretation of GNSS data in the context of field operation assessment.

Within the framework of precision agriculture, this approach enables quantitative evaluation of operational stability and facilitates identification of deviations from optimal movement regimes. The integration of temporal speed characteristics with spatial trajectory models establishes an analytical basis for further optimization of machinery routing schemes, reduction of non-productive intervals, and improvement of engine resource efficiency.

Overall, it should be noted that the accuracy and reliability of the results obtained using the proposed method depend on the quality of the original GNSS data and the frequency of their registration. In the presence of temporal gaps, reduced positioning accuracy, or irregular recording intervals, local errors in speed estimation may occur.

Discussion and conclusions

The study demonstrates the potential of GNSS data for spatially detailed analysis of agricultural machinery

movement within an individual field. The proposed approach enables transition from purely temporal or averaged speed indicators to their spatial interpretation, which is fundamentally important in the context of precision agriculture technologies.

Based on GNSS data, machinery and machine-tractor unit trajectories were reconstructed and segmented into elementary spatio-temporal segments. For each segment, length, time duration, and average speed were calculated, providing the basis for further classification of speed regimes and their cartographic representation.

The results of spatial visualization confirmed that machinery movement speed within a single field is not uniform and varies significantly depending on field configuration, pass patterns, and maneuvering zones. Stable speed regimes with relatively similar values dominate in the central parts of the field, whereas noticeable speed reductions and increased variability are observed in headland areas and turning zones.

The constructed speed variability maps provide spatially detailed interpretation of machinery operational regimes and allow clear localization of zones of deceleration, turning, and transitions between different technological modes. Such spatial characteristics of movement organization cannot always be identified through purely tabular or temporal GNSS data representations, as the latter do not reflect their spatial context.

Geoinformation-based interpretation of segmented GNSS trajectories enables analysis of intra-field heterogeneity of speed regimes in direct relation to field configuration, machinery routing schemes, and maneuvering zones. This confirms the relevance of GIS not only as a visualization tool but also as an analytical framework for generalized interpretation of GNSS data in assessing field operation organization and efficiency.

The obtained results indicate that segmented spatio-temporal analysis of GNSS-based trajectories is an effective tool for evaluating intra-field organization of agricultural machinery movement. It can be applied to optimize routing schemes, improve operational efficiency, and facilitate further integration with remote sensing and productivity data within decision-support systems in precision agriculture.

Authors' contribution: Vitaliy Zatserkovnyi – conceptualization, methodology, writing; Victor Vorokh – remote sensing data processing, methodology; Olexandr Nikolaienko – geoinformation analysis, data processing, writing; Tetiana Pastushenko – data analysis and processing, writing (review and editing); Iryna Siuiva – data analysis and processing.

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ГІС-МОДЕЛЮВАННЯ ПРОСТОРОВО-ДЕТАЛІЗОВАНОГО РУХУ СІЛЬСЬКОГОСПОДАРСЬКОЇ ТЕХНІКИ В ЗАДАЧАХ ПРЕЦИЗІЙНОГО ЗЕМЛЕРОБСТВА

Вступ. Розвиток технологій прецизійного землеробства супроводжується зростанням обсягів просторово-часових даних, що характеризують не лише стан агроєкосистем, але й параметри функціонування сільськогосподарської техніки. У цьому контексті особливого значення набуває використання даних глобальних навігаційних супутникових систем (ГНСС) для аналізу режимів руху агротехніки у межах окремих полів.

Методи. Розглянуто підхід до просторово-часового аналізу руху сільськогосподарської техніки на основі траєкторій за ГНСС із застосуванням геоінформаційних систем. Дослідження ґрунтується на представленні траєкторії руху у вигляді сукупності елементарних просторово-часових сегментів, для яких визначаються метричні, часові та швидкісні характеристики. Це дає змогу перейти від суто часових або усереднених показників до просторово орієнтованої інтерпретації параметрів руху.

Результати. Дослідження виконано на прикладі виробничого сільськогосподарського поля Західного регіону України. На основі даних GNSS сформовано траєкторії руху агротехніки, виконано їх сегментацію руху та здійснено розрахунок середньої швидкості руху для окремих сегментів. Отримані результати візуалізовано у вигляді тематичних карт і графіків, що відображають просторову варіабельність швидкісних режимів у межах поля.

Результати аналізу засвідчили наявність вираженої внутрішньопольової неоднорідності швидкості руху техніки, зумовленої конфігурацією ділянки, особливостями організації проходів та зонами маневрування. Просторове подання швидкісних параметрів дозволило ідентифікувати та візуалізувати ділянки стабільної роботи, уповільнення та розворотів, які не завжди виявляються при аналізі табличних або часових даних.

Висновки. Отримані результати підтверджують доцільність використання сегментованого просторово-часового аналізу траєкторій за ГНСС для дослідження руху сільськогосподарської техніки та обґрунтовують можливість застосування такого підходу в технології прецизійного землеробства для оцінювання ефективності польових операцій і підтримки управлінських рішень.

Ключові слова: прецизійне землеробство, глобальна навігаційна супутникова система (ГНСС), геоінформаційні системи (ГІС), траєкторія руху техніки, просторово-часовий аналіз.

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