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# Adaptation of precision agriculture systems to conditions of labor shortages in agriculture

**Volodymyr Olkhovsky**,
CEO, AGAIA LLC, 69035, 147 Soborny Ave., Zaporizhzhia, Ukraine,
https://orcid.org/0009-0004-3719-6315

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**Abstract.** The study's relevance is driven by the increasing shortage of human resources in agriculture, shaped by demographic changes, labor migration, shifts in the age structure of the agricultural workforce, and growing qualification requirements. Under these conditions, traditional agricultural production models are losing effectiveness, underscoring the need for scientifically grounded adaptation of precision agriculture systems to compensate for labor constraints and enhance the stability and controllability of production processes. The **purpose of the article** is to substantiate directions and practical instruments for adapting precision agriculture systems to conditions of labour shortages in agriculture to increase the efficiency, autonomy, and resilience of agroproduction processes. **Methods**. The study applies a systemic and structural-functional approach, comparative analysis, and analytical generalization. These methods enabled examining the impact of labour shortages on the organization of agricultural production, assessing the functional potential of precision agriculture systems to reduce labour intensity, and generalizing approaches to adapting digital and automated agrotechnologies with limited personnel involvement. **Results**. It has been established that labour shortages in agriculture are systemic and affect both the execution of technological operations and the quality of managerial decision-making. It has been proven that precision agriculture systems can compensate for human resource constraints through process autonomy, algorithmisation of management decisions, and standardization of agrotechnological operations. Key scientific and practical problems of adaptation and implementation have been identified, including managerial inertia, mismatch between technological complexity and staff competencies, fragmentation of digital solutions, technological risks, and difficulties in substantiating economic efficiency. **Conclusions**. It has been substantiated that effective use of precision agriculture systems under labour shortages is achievable only through the combination of technological autonomy with organizational transformation of agricultural enterprises and a clear redistribution of functions between human operators and technological systems. The expediency of transitioning from fragmented digital implementation to a systemic adaptation of agrotechnologies has been proven. Prospects for further research include developing quantitative models to assess the impact of autonomous agrotechnologies on labour productivity and the economic sustainability of agricultural enterprises, determining optimal levels of technological autonomy, and analyzing the long-term organizational consequences of digital transformation in the agricultural sector.

**Keywords**: digitalization of agricultural production, automation of technological processes, agrotechnological autonomy, production process management, labour productivity, organizational transformation, workforce constraints, resilience of agricultural enterprises.

## Адаптація систем точного землеробства до умов дефіциту людських ресурсів у сільському господарстві

**Ольховський Володимир Вікторович,**
директор (2018–2021), ТОВ «АГЕЯ» (2010–2021),
м. Запоріжжя, Україна, https://orcid.org/0009-0004-3719-6315

**Анотація.** Актуальність дослідження зумовлено посиленням дефіциту людських ресурсів у сільському господарстві, що формується під впливом демографічних змін, трудової міграції, несприятливих змін вікової структури кадрового потенціалу аграрного сектору та зростання вимог до кваліфікації персоналу. За таких умов традиційні моделі агровиробництва втрачають ефективність, що актуалізує потребу в науково обґрунтованій адаптації систем точного землеробства як інструменту компенсації кадрових обмежень. **Метою статті** є наукове обґрунтування напрямів і практичних інструментів адаптації систем точного землеробства до умов дефіциту людських ресурсів у сільському господарстві, спрямованих на підвищення ефективності, автономності та стійкості агровиробничих процесів. У процесі дослідження використано системний, структурно-функціональний, порівняльний та аналітичний **методи**, що дали змогу узагальнити підходи до цифровізації агровиробництва, проаналізувати вплив кадрових обмежень на організацію виробничих процесів і оцінити потенціал автоматизованих агротехнологій у зниженні трудомісткості та мінімізації людського фактора. **Результати**. Установлено, що дефіцит людських ресурсів має системний характер і впливає як на виконання технологічних операцій, так і на якість управлінських рішень в аграрних підприємствах. Доведено, що системи точного землеробства здатні компенсувати кадрові обмеження за рахунок автономізації процесів, алгоритмізації управління та стандартизації агротехнологічних рішень. Виявлено основні проблеми їх адаптації, пов’язані з інерційністю управлінських моделей, кадровою невідповідністю, фрагментарністю цифрових рішень і складністю економічного обґрунтування інвестицій. **Висновки**. Обґрунтовано, що ефективне використання систем точного землеробства в умовах кадрового дефіциту можливе лише за умови поєднання технологічної автономності з організаційною трансформацією агровиробництва та чіткого розмежування функцій між людиною і технологічними системами. Доведено доцільність переходу від

фрагментарного впровадження цифрових рішень до системної адаптації агротехнологій. Перспективи подальших досліджень пов'язані з розробленням кількісних моделей оцінювання впливу автономних агротехнологій на продуктивність праці, економічну стійкість аграрних підприємств і формування нових організаційних моделей управління в умовах цифрової трансформації аграрного сектору.

**Ключові слова:** цифровізація агровиробництва, автоматизація технологічних процесів, агротехнологічна автономність, управління виробничими процесами, продуктивність праці, організаційна трансформація, кадрові обмеження, стійкість аграрних підприємств.

**Problem statement.** The modern agricultural sector operates in conditions of growing human resource shortages, caused by demographic changes, migration, the aging of the rural population, and increasing worker qualification requirements. Under these circumstances, traditional models of agricultural production organization lose their effectiveness, as they largely depend on labor-intensive operations and human control at all stages of the technological cycle. It necessitates rethinking approaches to agricultural production management and the search for tools capable of ensuring the stability, productivity, and competitiveness of agricultural enterprises in conditions of limited human resources. In this context, precision agriculture systems are gaining strategic importance as a scientifically substantiated approach to intensifying agricultural production, based on the use of digital technologies, sensor networks, satellite navigation, automated machinery, and analytical algorithms for decision-making. Their adaptation to the conditions of human resource shortage goes beyond a purely technological task. It is associated with solving complex scientific problems, in particular, optimizing human-machine interaction, increasing the autonomy of agrotechnological systems, formalizing agronomic knowledge as algorithms and models, and ensuring the reliability and stability of production processes with minimal personnel involvement.

The practical significance of this problem lies in the need to ensure the continuity and quality of agricultural production in conditions of personnel restrictions, reducing the dependence of economic activity results on the human factor and minimizing the risks associated with the lack of qualified specialists. The adaptation of precision agriculture systems to such conditions is directly related to solving significant applied problems of increasing labour productivity, reducing operating costs, rational use of land and resource potential, as well as the formation of new models of organizing agricultural production, focused on automation, digital support of management decisions and sustainable development of the agricultural sector.

**Analysis of recent research and publications**. A review of scientific literature indicates the emergence of several complementary research areas, within which the problem is considered from economic, ecological-resource, technological, and social-human resource perspectives. In several works, the labor shortage is examined through the lens of economic challenges and structural changes in the agricultural sector. In the study by Yu. A. Perehuda, a methodology for assessing the competitiveness of livestock products is proposed, in which increasing technological efficiency is considered a key condition for maintaining production positions amid limited labor availability [1]. Further work by Yu. A. Perehuda, focused on the economic efficiency of organic fertilizer production technologies, demonstrates the potential of technological innovations to reduce the labor intensity of production processes in small- and medium-sized agricultural enterprises [2]. O. Pohrishchuk analyzes the impact of global climatic, demographic and technological transformations on the development of the agricultural sector, emphasizing that the personnel shortage is becoming a systemic factor that stimulates the implementation of digital and automated solutions [3]. D. Krasovskyi complements this approach by considering the technological transformation of the agricultural sector of Ukraine in the context of economic and post-war challenges,

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where the shortage of labor resources is identified as one of the key drivers of the transition to precision farming systems [4].

Another group of studies focuses on ecological, economic, and resource aspects, in which precision farming systems are considered a tool for increasing the manageability of agroecosystems with minimal personnel involvement. I. V. Honcharuk and co-authors prove that the introduction of precision farming technologies contributes to the optimization of the use of natural and material resources, which indirectly reduces the need for labor-intensive operations [5]. The work of V. Skliar and co-authors demonstrates the importance of systematic spatial monitoring of natural processes, which, in modern conditions, is implemented primarily through digital, automated data-collection tools [6]. I. Zubtsova and co-authors emphasize the need for accurate quantitative analysis of the state of plant communities, underscoring the role of precise measurement technologies as an alternative to labor-intensive field observation methods [7].

A significant part of scientific publications focuses on the analysis of precision farming technologies themselves as a means of compensating for the shortage of human resources through automation and the digitalization of production processes. B. Erickson et al. substantiate the role of precision agriculture in ensuring food security, emphasizing the reduction of the dependence of agricultural production on the human factor [8]. M. J. M. Cheema et al. systematize the current state of implementation of precision agriculture technologies and determine strategies for their further development, focusing on sensor networks, remote management and data analytics as tools to reduce the need for labor [9]. A. Afzal et al. consider precision agriculture as the basis of sustainable agricultural production, emphasizing its ability to reduce the labor intensity of key agrotechnological operations [10]. G. Gyarmati et al. analyze the current and future state of precision agriculture, noting the growing role of autonomous and semi-autonomous systems in the context of a global shortage of agricultural personnel [11].


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A separate group consists of studies that examine the agricultural sector's adaptation to labor shortages through the lens of human capital management, robotization, and the use of artificial intelligence. R. Gherman and co-authors analyze the shortage of human resources in agriculture and justify the feasibility of using digital and automated solutions as basic adaptation mechanisms [12]. R. Bogue considers agricultural robots as an effective tool for replacing manual labor and reducing the labor intensity of production processes [13]. A. O. Adewusi and co-authors summarize approaches to the use of artificial intelligence in precision agriculture, emphasizing its role in automating management decision-making and reducing the burden on personnel [14]. M. Eissa analyzes the integration of artificial intelligence and robotics into precision agriculture systems as the basis for the long-term sustainability of agricultural production in conditions of chronic shortage of human resources [15].

**Identification of previously unresolved parts of the general problem**. Despite active research into the digitalization of agricultural production, the issue of human resource shortage is mainly considered in isolation, without a systematic connection to the organization and outcomes of agricultural production. The limits of effective autonomization of precision agriculture systems, their adaptation to the real human resource potential of enterprises, and the organizational and managerial barriers to implementation under conditions of limited personnel participation remain insufficiently studied. The study focuses on a systematic analysis of the relationships among personnel limitations, the level of technological autonomy, and the organizational mechanisms governing the functioning of agricultural production systems. The obtained generalizations provide a theoretical basis for further understanding of the role of precision agriculture systems in transforming agricultural production management models under conditions of limited personnel participation.

**Formulation of the objectives of the article (task statement).** The article aims to substantiate directions and tools for adapting precision farming systems to the conditions of human resource shortage in agriculture, thereby increasing the efficiency, autonomy, and sustainability of agricultural production processes.

To achieve the set goal, the article envisages solving the following tasks:

1. To analyze the prerequisites for the formation of a human resource shortage in agriculture and determine its impact on the organization, management and results of agricultural production.

2. To generalize the potential and approaches to adapting precision farming systems and digital agricultural technologies in the context of reducing labor intensity and minimizing the dependence of production processes on the human factor.

3. To identify the main scientific and practical problems of implementing precision farming systems under conditions of personnel limitations and to substantiate recommendations for increasing the efficiency of their use in agricultural enterprises.

**Presentation of the main research material**. The formation of a shortage of human resources in agriculture is a multifactorial process that reflects structural transformations of the economy, demographic shifts and changes in the social and labor priorities of the population. The long-term decline in the rural population, the aging of the workforce, the intensification of labor migration to cities and abroad, and the decrease in the attractiveness of agricultural labor for young people create an imbalance between the needs of agricultural production and the actual labor opportunities on farms. Under these conditions, the shortage of personnel manifests not only quantitatively but also qualitatively, as modern agriculture requires workers with digital, technical, and managerial competencies, which significantly complicates staffing production processes. The impact of a shortage of human resources on agricultural production is systemic. It covers all levels of management – from the implementation of technological operations to strategic planning. An insufficient number of personnel leads to violations of technological deadlines, simplification or formalization of agrotechnical solutions, increased production risks and the dependence of results on the subjective experience of individual workers. It directly affects labor productivity, yield stability, and economic indicators of agricultural enterprises, underscoring the need to develop alternative mechanisms to compensate for staffing limitations (table 1).

**Table 1**

Key prerequisites for the shortage of human resources in agriculture and their impact on agricultural production

| Preliminary | Character of manifestation | Impact on the organization and results of agricultural production |
|---|---|---|
| Demographic decline of the rural population | Decrease in the number of non-disabled people in rural areas | Limitations in the staffing of production processes |
| Aging of the labor force | Predominance of workers of older age groups | Decrease in adaptability to new technologies, increase in operational risks |
| Labor migration | Outflow of qualified personnel to cities and abroad | Deficit of specialists, increase in training and replacement costs |
| Change in employment structure | Orientation of youth to non-agricultural areas | Deterioration of personnel reproduction in the agricultural sector |
| Increasing requirements for competencies | Need for digital and technical skills | The gap between production requirements and available personnel potential |

Source: formed by the author based on [1, p. 11; 3, p. 356; 4, p. 130; 12, p. 74–75]

In modern agricultural enterprises, the above-mentioned human resource shortages give rise to specific organizational and technological consequences that directly affect agricultural production outcomes. Thus, the reduction in the number of non-disabled rural residents' forces farms to operate with minimal staffing, with one operator responsible for several production processes that were previously performed by individual employees [12, p. 75]. It increases personnel workload and the risk of errors in operational agronomic decisions, particularly when determining sowing dates, fertilizer application rates, or protective measures. In practice, the aging of labor resources limits the speed of implementation of new technologies, since a significant part of the personnel is focused on traditional farming methods and requires additional training to work with digital monitoring, navigation, and data

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analysis systems. In such conditions, agricultural enterprises are often forced to simplify technological schemes or abandon potentially effective solutions due to the impossibility of fully exploiting them by the existing staff. Labor migration and the outflow of qualified specialists create a situation in which agricultural production processes become overly dependent on a limited number of specialists focused on key managerial and technical functions. In practice, this means that the absence of one agronomist or engineer can lead to delays in the performance of critical operations, disruption of technological discipline and a decrease in yield [1, p. 11]. At the same time, the growing demand for digital and technical competencies widens the gap between staffing's actual capabilities and the complexity of modern agricultural technologies.

The potential of precision farming systems to reduce the labor intensity of agricultural production and minimize the dependence of their results on the human factor lies in their ability to automate key technological operations and translate a significant part of management decisions into algorithmic data processing. The use of digital monitoring and management tools reduces the need for constant field personnel presence, reduces manual labor, and ensures operational stability regardless of individual experience or subjective decisions (table 2).

**Table 2**

The potential of precision farming systems in reducing labor intensity and dependence of production processes on the human factor

| Element of the precision farming system | Functional purpose | Impact on labor intensity and the role of the human factor |
|---|---|---|
| Automated machinery control systems | Performing technological operations with high accuracy | Reducing the need for operator control |
| Crop and soil monitoring systems | Collecting data on the state of the agroecosystem | Reducing manual surveys and visual assessments |
| Variable rate technologies | Algorithmic dosing of resources | Eliminating the subjectivity of agronomic decisions |
| Digital management platforms | Data integration and decision support | Centralization of management with a minimum number of personnel |


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| Element of the precision farming system | Functional purpose | Impact on labor intensity and the role of the human factor |
|---|---|---|
| Analytical models and forecasts | Planning and optimization of production | Reducing dependence on the individual experience of specialists |

Source: formed by the author based on [5, p. 112; 8, p. 4459; 9, p. 236–237; 10, p. 195; 11, p. 595]

Thus, the use of self-piloted equipment allows one operator to service much larger areas than in traditional conditions, while ensuring stable operational quality regardless of the driver's level of fatigue or qualifications. It is essential during peak load periods, when staff shortages are combined with tight agrotechnical deadlines. Remote monitoring systems based on satellite images and sensors eliminate the need for regular field trips to assess crop condition, replacing them with the analysis of digital indicators of vegetation, moisture, and soil condition. In practice, this means the agronomist can make informed decisions on fertilizing or protecting plants while away from the farm, significantly reducing the need for numerous field personnel. Technologies for variable-rate resource application, combined with analytical models, allow for standardizing agronomic decisions that previously largely depended on the individual experience of a specialist [11, p. 595]. In modern conditions, this manifests as algorithms automatically adjusting technological parameters across different sections of the field, reducing the risk of errors and ensuring the reproducibility of results even with limited personnel. Taken together, such practical solutions indicate that precision farming systems not only reduce the labor intensity of individual operations but also form a fundamentally new level of autonomy of agricultural production processes, adapted to the conditions of a long-term shortage of human resources. In modern research and practice of implementing digital and automated agricultural technologies, adaptation to conditions of limited personnel participation is considered as a process of purposeful rethinking of the logic of managing agricultural production systems, in which the key functions of planning, control and regulation are performed by technological means [8, p. 4459]. The focus is not so much on increasing the automation of individual operations, but on developing holistic technological solutions that ensure stable production with minimal personnel involvement and limited management intervention (table 3).

**Table 3**

Approaches to the adaptation of digital and automated agricultural technologies to the conditions of limited personnel participation

| Approach | Contentual characteristics | Practical orientation |
|---|---|---|
| Automation of technological processes | Transfer of execution and control functions to automated systems | Reducing the need for the constant presence of personnel |
| Algorithmization of management decisions | Formalization of agrotechnological decisions in the form of algorithms | Reducing the subjectivity of management |
| Modular construction of digital systems | Use of independent functional blocks | Flexible scaling under staffing constraints |
| Simplification of human-machine interaction | Focus on intuitive interfaces and scenarios | Reducing requirements for personnel qualifications |
| Integration of management circuits | Combining technological and analytical functions | Reducing the management workload |

Source: formed by the author based on [9, p. 239; 11, p. 596; 13, p. 3; 14, p. 2280; 15]

The implementation of the above approach's manifests in the transformation of the traditional organization of agricultural production, in which most operations are performed in a semi-autonomous mode, with human participation focused on controlling key parameters and making strategic decisions. For example, the automation of technological processes allows organizing the performance of production operations according to predetermined scenarios, in which personnel intervention is required only in the event of deviations or emergencies. It allows one specialist to support a much larger volume of production than in traditional conditions. Algorithmizing management decisions in practice means that the choice of technological operating modes is based on formalized rules and models, reducing the dependence of results on individual specialists' experience. In modern agricultural farms, this is manifested in the use of systems that automatically offer optimal technological scenarios, with personnel confirming or adjusting them [9, p. 239]. The modular construction of digital systems enables the gradual implementation of technologies without a sharp increase in organizational complexity, which is critically essential in conditions of limited staff. Simplifying human-machine interaction and integrating management circuits reduces personnel's cognitive load and concentrates management functions within a single digital environment. Taken together, this forms a practical model of agricultural production, in which the efficiency and stability of processes are achieved not through the number of personnel but through the structural organization and functional maturity of digital and automated agricultural technologies.

The adaptation and implementation of precision agriculture systems in conditions of human resource shortage are accompanied by a complex of scientific and practical problems of technological, organizational, personnel, and economic nature, which manifest themselves at all stages of the functioning of agricultural production systems. One of the key problems is the limited readiness of agricultural enterprises to transition from traditional human-oriented management models to system-oriented solutions, in which a significant part of the functions is transferred to automated and digital technologies [15]. It creates inertia in decision-making and hinders the full potential of precision agriculture systems. A significant problem remains the mismatch between the complexity of digital agricultural technologies and the fundamental competencies of the available personnel. In conditions of worker shortage, agricultural enterprises are often forced to combine the functions of an agronomist, engineer, and operator into a single position, which increases the risk of errors, staff overload, and the formal use of technologies without deep integration into production processes [14, p. 2280]. It complicates the adaptation of precision agriculture systems precisely as tools for reducing personnel dependence. Technological problems manifest in the fragmentation of the implementation of digital solutions, insufficient compatibility between equipment and software, and limited reliability of automated systems under variable natural and climatic conditions. In conditions of personnel shortages, even minor technical failures can lead to a halt or simplification of production processes, reducing trust in technology and increasing dependence on manual control.

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An additional limitation is the complexity of maintaining and configuring precision farming systems in conditions of reduced staffing of technical specialists. Economic problems are associated with high initial costs for implementing digital and automated solutions and the delayed economic effects, which are not always apparent to farms with limited resources. In conditions of personnel shortage, assessing the effectiveness of such investments is complicated, as there are insufficient analytical capabilities for quantitative substantiation of results and for the correct adjustment of systems to specific production conditions. Organizational problems stem from insufficient coordination between technological changes and the management structures of agricultural enterprises. The implementation of precision farming systems is often not accompanied by a review of the distribution of responsibilities, decision-making procedures and control models, which, in conditions of human resource shortage, leads to duplication of functions or, conversely, to management gaps.

Increasing the efficiency of precision farming systems in agricultural enterprises under staffing constraints should be achieved through a targeted orientation of technological and organizational solutions to reduce the need for constant personnel involvement and the complexity of managing production processes. First of all, it is recommended to implement precision farming system configurations that provide maximum autonomy for performing basic technological operations and allow human participation to focus on controlling key parameters and strategic planning, rather than on manual operational management.

An important direction is the adaptation of digital solutions to the enterprise's real personnel potential through the use of modular, scalable systems, which allows for a gradual increase in automation without overloading personnel and the management structure. It is advisable to prioritize technologies with simplified interfaces, automated response scenarios, and minimal specialized user training requirements, which reduce the risk of errors and shorten employee adaptation time.

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To compensate for the shortage of qualified personnel, it is recommended to integrate precision agriculture systems into a single digital management environment that provides centralized access to data, automated recommendation generation, and standardized management decisions. It allows one specialist to coordinate a much larger volume of production processes effectively and reduces the dependence of results on individual workers' experience.

It is advisable to pay special attention to the organizational aspects of implementation, particularly the distribution of functions and responsibilities between personnel and technological systems. It is recommended to clearly formalize the zones of automated and human control, which, under conditions of personnel limitations, help reduce management gaps and increase the stability of production processes. In total, implementing these recommendations lays the groundwork for transforming precision agriculture systems from a tool for individual technological improvements into an effective mechanism for adapting agricultural enterprises to a long-term shortage of human resources.

**Conclusions**. The study found that the shortage of human resources in agriculture has a stable systemic nature and determines the need to transform traditional models of organizing agricultural production. It is proven that personnel limitations affect not only the volume of technological operations but also the quality of management decisions, increasing the dependence of production results on individual personnel experience and increasing production risks. It is substantiated that precision farming systems are an effective tool for compensating for personnel shortages by reducing labor intensity, standardizing technological operations, and increasing the autonomy of agricultural production processes.

It is revealed that the key problems of adapting and implementing precision farming systems in conditions of personnel limitations are the inertia of management models, the mismatch between the complexity of digital technologies and personnel competencies, the fragmentation of technological solutions, the limited reliability of automated systems, and the complexity of the economic justification of investments.

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It is proven that without simultaneous organizational transformation and a clear redistribution of functions between people and technologies, the potential of precision farming is not fully realized.

Based on the results, recommendations are proposed to increase the efficiency of precision farming systems, prioritizing autonomous and modular solutions, integrating management circuits into a single digital environment, and standardizing management decisions with minimal personnel involvement. Prospects for further research include developing quantitative models to assess the effectiveness of autonomous agricultural technologies, determine the optimal level of their integration, and analyze the long-term organizational consequences of the digital transformation of agricultural production.

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