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Soil monitoring in precision farming technologies

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SUMMARY

One of the key stages in implementing precision farming is agrochemical surveying, which provides scientifically grounded recommendations for fertilizer application, seed sowing, and plant protection measures, to reduce the pesticide load on the natural environment. A comprehensive analysis includes all major stages, from preparatory work and laboratory testing to the creation of agrochemical maps, fertilizer requirement maps, and task maps for agricultural machinery. Additionally, the use of automated monitoring systems enables real-time control of soil agro-physical parameters, such as moisture levels, temperature, and the detection of pests and diseases, allowing for timely responses to changes. Data from remote sensing technologies and geographic information systems facilitate the collection, processing, and visualization of information.

The frequency of soil sampling for agrochemical analysis depends on the type of land and the intensity of its use. According to the recommendations of the Institute of Soil Protection of Ukraine, agrochemical surveys of peat and peat-bog soils are conducted every five years. Additionally, sampling is carried out as needed – in case of changes in agricultural technologies, signs of soil degradation, decreased yields, or after the application of large doses of fertilizers.

The integration of these technologies into agricultural production enhances productivity, economic efficiency, and the environmental sustainability of the agricultural sector.

Keywords: precision farming, soil agrochemical analysis, sampling scheme, geoinformation technologies (GIS), remote sensing (RS), Internet of Things (IoT), variable-rate technology (VRT), global navigation satellite system (GNSS), agricultural automation, soil mapping, farm management systems (FMS).

Introduction

In the context of global climate change and increasing pressure on natural resources, the rational use of soils has become one of the key challenges in modern agricultural production and environmental protection. The degradation of agro-landscapes on a global scale highlights the task of preserving and enhancing agricultural productivity.

The yield potential of a field is determined by the condition of the soil cover and, naturally, by the presence of toxic components such as pesticide residues, heavy metals, and radionuclides. Precision farming is a modern approach to agricultural management that requires significant investments of time and resources. In Ukraine, the most active users of precision farming technologies are primarily large agricultural holdings, such as Ukrprominvest-Agro, HarvEast, Epicenter Agro, Astarta, Ukrlandfarming, Kernel, and others. These enterprises were among the first to implement sustainable development standards and allocate significant resources to achieving its goals (Aggrieve 2021, July 15).

Precision farming technologies are based on precise measurement of soil and crop conditions, enabling prompt responses to the identified issues. They also aim to reduce resource consumption (water, fuel, electricity, fertilizers, herbicides, etc.). For instance, the number of machineries passes over a field is minimized through precise trajectory planning, which directly reduces fuel combustion and the associated CO_2 emissions.

Thus, the issue of soil monitoring extends beyond economic feasibility to environmental responsibility, becoming an essential tool in this process by providing objective information on soil fertility, moisture availability, contamination levels, and other parameters.

Theory

Precision farming is a comprehensive approach that involves the use of advanced digital technologies. Remote monitoring systems utilizing satellite data and unmanned aerial vehicles (UAVs) provide real-time assessment of soil moisture, texture, organic matter content, and processes related to gully formation, landslides, and other environmental changes (Phang et al., 2023).

The implementation of precision farming requires a holistic approach to soil productivity management using global positioning system (GPS) technologies, yield-monitoring technologies (YMT), geographic information systems (GIS), remote sensing (RS), and variable rate technology (VRT). These technologies enable resource optimization by facilitating precise and differentiated application of fertilizers, soil amendments, and crop protection products (Zatserkovnyi et al., 2019).

The Internet of Things (IoT) plays a crucial role in modern agriculture by integrating sensor networks and devices that collect and transmit real-time data on field conditions, soil parameters, and climatic factors. These technologies allow farmers to monitor soil moisture, temperature, nutrient content, and phytosanitary risks. For instance, electrical conductivity sensors help identify variations in soil texture and moisture, while pH probes detect areas with increased acidity or alkalinity. This capability enables rapid and localized field assessments without the need for continuous laboratory testing.

Modern agricultural machinery is typically equipped with GNSS systems featuring autopilot functionality and real-time kinematic (RTK) signal correction, reducing navigation errors from several meters to approximately 2.5 cm. This precision minimizes row overlap during field operations, thereby reducing fuel consumption, operational time, and errors related to human factors.

Advanced precision irrigation technologies are evolving through the integration of soil moisture monitoring, weather data, and variable rate irrigation (VRT) systems, significantly improving water resource efficiency (Villa-Henriksen et al., 2020).

Traditional soil assessment methods rely on sampling from predetermined field points for subsequent laboratory analysis of macro- and micronutrient content, pH levels, organic matter, and potential contaminants such as pesticides and heavy metals. Agrochemical properties of soil can vary significantly even within small field sections, necessitating careful planning of sampling schemes. The configuration and density of the sampling grid directly affect the accuracy of nutrient content assessments. Notably, Ukrainian legislation mandates periodic agrochemical soil surveys for agricultural lands, requiring documentation in the form of an agrochemical passport, which records baseline and current nutrient levels as well as contamination by toxic substances and radionuclides (Law of Ukraine, 2003).

The integration of soil sample analyses, sensor measurements, and remote sensing imagery is facilitated by geographic information systems (GIS), which process spatial data within field coordinates (Aniskevych, 2021). GPS mapping enables precise sample location tracking and optimized machinery trajectories. Based on this data, digital fertility maps are generated, serving as the foundation for variable rate fertilizer application, irrigation planning, and long-term soil condition monitoring.

A key component of precision farming is the incorporation of soil monitoring results into specialized farm management systems (FMS) (Giua et al., 2021). Data on soil moisture, fertility, acidity, and nutrient content are fed into software platforms, enabling the creation of electronic land databases and field maps that delineate zones with varying nutrient levels. This information is used to generate "prescription maps" for variable rate fertilization, irrigation, and even tillage depth adjustments. This approach offers multiple advantages, including optimized fertilizer and water application, reduced fuel consumption, lower CO_2 emissions, and minimized environmental impact due to decreased water pollution and toxic residue accumulation.

A 2021 survey of 500 Ukrainian farmers of various sizes and from different regions revealed that digital field mapping is widely adopted by medium and large agricultural enterprises, with digital coverage reaching up to 95%. Route indicators, autopilot systems, and GPS monitoring are extensively used, with higher adoption rates among larger enterprises. Satellite imagery is less common, utilized by only 16% of small-scale farmers compared to 71% of large agricultural holdings. Agrochemical soil analysis is of interest to farmers of all sizes. Soil moisture sensors are used by 39% of the respondents, while meteorological data from weather stations remain a focal point. Drone usage is significantly higher among large agricultural enterprises (86%) compared to smaller farms (10%). Pest and disease forecasting software has the lowest adoption rate, with only 5% of small-scale farmers and 43% of the large enterprises utilizing such tools (The Netherlands Enterprise Agency, 2021).

Results

To determine the optimal rates of fertilizer and crop protection product application, agrochemical soil analysis remains one of the most effective tools. Research indicates that applying large doses of fertilizers and chemical treatments without considering the actual crop needs and soil characteristics can eventually lead to decreased soil fertility and undesirable changes in the soil adsorption complex. Specifically, this can result in increased acidity, accumulation of potentially harmful elements (such as fluorine and uranium), deterioration of the physical-chemical and microbiological properties of the arable layer, degradation of groundwater quality, and negative shifts in biocenoses (Chandini et al., 2019).

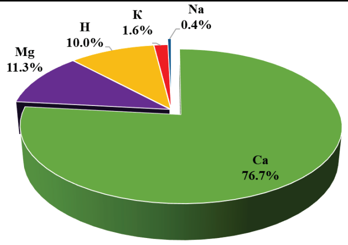
Soil monitoring was conducted on a 309.6-hectare plot located near the village of Berizka in the Varvynska Territorial Community of the Pryluky District, Chernihiv region, through agrochemical surveying and remote sensing data analysis. The laboratory results of soil samples from the arable layer for 2010-2020 provided by the agricultural company "Kernel" are presented in Table 1. The samples were collected using a grid-based method with a 10-hectare step, and the mean values were used for a comprehensive assessment of the field's characteristics.

Variable-rate application of fertilizers and crop protection products allows for a reduction in the use of these substances by an average of 10-20% without compromising yield. Reducing the number of fertilizers and pesticides entering water resources significantly lowers the risk of environmental pollution and the accumulation of toxic residues in agricultural products. Some fertilizers, particularly phosphate-based ones, may contain heavy metals, while excessive and frequent pesticide use leads to their accumulation in the soil. Variable-rate application helps regulate dosage according to localized needs, preventing the exceedance of environmentally safe levels (Wang et al., 2023).

Analysing the table 1 data while considering the applied agronomic practices, we can draw conclusions about the impact of fertilization and the cultivated crop. Between 2010 and 2020, NPK fertilizers were applied to the field, which likely influenced the changes in soil nutrient content. In particular, phosphorus (P) increased from 100 mg/kg in 2010 to 142.9 mg/kg in 2020, indicating its gradual accumulation, probably due to the application of phosphorus-containing fertilizers. A similar trend is observed for exchangeable potassium (K), which rose from 105.5 mg/kg to 121.2 mg/kg, likely as a result of potassium fertilizer use. Since corn for grain was cultivated on this field, this could also affect the nutrient balance. Corn actively consumes nitrogen (N), phosphorus (P), and potassium (K), which explains the need for

NPK fertilizers. At the same time, the gradual decline in soil pH may be associated with the prolonged use of nitrogen fertilizers, which contribute to soil acidification. The organic matter content also slightly decreased, possibly due to intensive farming and insufficient organic matter replenishment in the soil.

Table 1 *Agrochemical Survey of the Investigated Field in 2010-2020.*

Indicator	Method	Mean Value [number of soil samples]			
		2010	2013	2016	2020
pH (KCl), unit	DSTU ISO 10390:2019, IDT	6.25 [56]	-	5.84 [31]	5.7 [30]
Organic matter, %	DSTU 4289:2004	3.96 [11]	3.77 [28]	-	3.7 [30]
Phosphorus (P), mg/kg	laboratory methodology	100.0 [32]	111.0 [59]	146.2 [31]	142.9 [30]
Exchangeable Potassium (K), mg/kg	laboratory methodology at pH=7.0 (by Chirikov's method)	105.5 [32]	100.5 [59]	106.5 [31]	121.2 [30]
Cation Exchange Capacity (CEC) in 2020 – 19.4 meq/100 g (at pH=7.0)					
	**Degree of sodicity** DSTU 3866-99 $(K+Na)/(Ca+Mg+K+Na)$ **2.27%** non-saline				

Considering these indicators – together with the digital elevation model, crop conditions (monitored using vegetation indices), and production results (an average corn yield of 8.14 t/ha on the 2020 yield map, peaking at 14.4 t/ha in certain areas) – we determined the soil requirements for the 2021 planting season. The recommendations included up to 40 tons of ammonium phosphate and 5.3 tons of potassium fertilizer during primary tillage, as well as 19.1 tons of NPK(S) during pre-sowing preparation (Fig. 1), to reduce the pesticide load on the natural environment.

Variable-rate application is carried out according to the developed prescription maps (Zatserkovnyi et al., 2024).

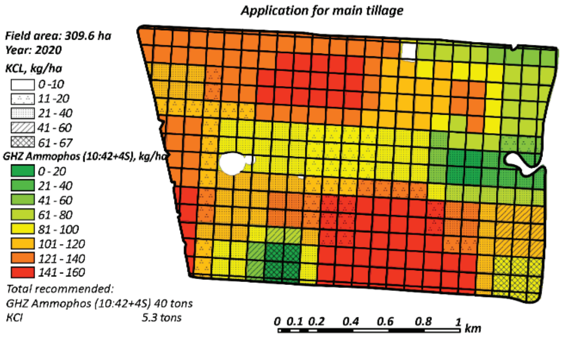


Figure 1 *Agricultural machinery task mapping for applying compound fertilizers.*

Considering the number of fertilizers applied and the needs of the upcoming crop, it can be concluded that the levels of nutrients introduced into the soil will remain within permissible limits and, therefore, will not have a negative impact on the environment.

Conclusions

Systematic soil monitoring and assessment of agricultural territories using precision farming technologies enable more efficient resource utilization, reduce anthropogenic pressure on the environment, and enhance farm sustainability.

The integration of geographic information systems, satellite and sensor technologies, along with agrochemical research, allows for rapid responses to changes in field conditions, cost optimization, and a simultaneous reduction in environmental impact. This approach improves yield performance, promotes agroecosystem stability, and can serve as a model for the broader adoption of precision farming technologies.

The conducted soil monitoring confirms the feasibility of integrating agrochemical studies with sensor-based methods and remote sensing data within the framework of precision farming. Based on laboratory analyses of the arable layer, consideration of the territory's physical and chemical characteristics, and production-economic indicators of the field, the levels of applied nutrients remained within environmentally safe limits.

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