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Aerial visual monitoring of potato globoderosis

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Abstract. The relevance of the problem under study lies in the need for timely detection of potato globoderosis foci in order to localise, eliminate and prevent further spread of the quarantine organism. The main task of the work was to improve the system of nematological monitoring of phytocenoses by combining the latest and traditional diagnostic methods. To detect focal lesions of solanaceous crops by globoderosis, the use of unmanned aerial vehicles (UAVs) was tested. The golden potato nematode *Globodera rostochiensis* (Wollenweber, 1923) Behrens remains one of the most dangerous quarantine organisms in Ukraine. The spread of monoculture of solanaceous crops in small households contributes to the mass accumulation of this phytoparasite and an increase in its harmfulness. It has been found that damage to crops not only leads to significant yield losses, but also complicates the sale of products due to the need to comply with quarantine restrictions. The results obtained confirm the need to improve traditional approaches and introduce new approaches to phytonematological monitoring. It has been determined that the optimal time for nematological monitoring of potatoes is the end of June to the first half of July, when visual symptoms of globoderosis appear and female

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nematodes are found on the roots. Analysis of aerial photographs made it possible to refine survey routes and selectively collect plant samples from affected areas, which significantly reduced costs compared to traditional methods. If it was impossible to monitor during the growing season, the quarantine status of the fields was determined after harvesting by analysing the soil for the presence of nematode cysts. Establishing the spatial distribution, total area of detected foci, and level of potato globoderosis infestation allows for the differentiation and local application of phytosanitary measures, which significantly reduces plant protection costs. It should be noted that the developed methodology for aerial visual inspection of phytocenoses using modern UAVs equipped with high-resolution cameras can also be used to detect foci of damage to agricultural crops by other types of cyst-forming nematodes. The developed methodology for aerial visual monitoring should primarily be used by specialists in phytosanitary inspections for plant quarantine, as well as by specialists in large farms and agricultural holdings

Keywords: golden potato cyst nematode; nematodoses; advanced nematological diagnostic methods; phytocenoses; unmanned aerial vehicles

INTRODUCTION

Significant changes that have taken place in the structure of Ukraine's sown areas have led to a shift towards cultivating agricultural crops in short-rotation crop rotations, and potatoes are, in fact, grown as a monoculture in the household sector. Under such conditions, there is a massive accumulation of highly specialised harmful organisms, among which cyst-forming nematodes are one of the most problematic.

According to studies by Y. He *et al*. (2022), J.A. Price *et al*. (2022), M. Esquibet *et al*. (2024), the golden potato cyst nematode (GPCN) *Globodera rostochiensis* (Wollenweber, 1923) Behrens, 1975 and the pale potato cyst nematode (PPCN) – *Globodera pallidae* (Stone, 1973) Behrens, 1975 represent a significant threat to potato production. Their parasitism in potato roots causes plant damage, which is called globoderosis. In addition to potatoes, a number of other crops of the Solanaceae family, in particular tomatoes and eggplants, are host plants for these nematode species. In the absence of susceptible cultivated plants for reproduction, they are able to complete their full development cycle and, accordingly, survive on weeds such as nightshade, henbane and some others.

C.M. Holguin *et al*. (2023) and R. Jiang *et al*. (2022) believe that since the potato originated in South America – the highlands of the Andes, where tuberous forms of Solanum still occur – the centre of origin of potato cyst nematodes is also the Central Andes, from where they were most likely brought to Europe along with planting material. The golden potato cyst nematode, *Globodera rostochiensis* (Wollenweber, 1923) Behrens, 1975, was first discovered in Germany at the end of the 19th century. However, until the beginning of the 20th century, it was mistakenly considered a biological race of the beet nematode (Kuhn, 1874), which was widespread in many countries at that time. Only with time was their belonging to different biological species scientifically proven.

A. Babich *et al*. (2018) noted that the first mention in scientific literature of the discovery in Ukraine of the golden potato nematode – *Globodera rostochiensis* (Wollenweber, 1923) Behrens, 1975 – dates back to 1963. It is believed that the golden potato nematode most likely entered the Potato Wart Research Station in Chernivtsi region along with seed tubers. However, despite the introduction of quarantine measures, it was not possible to prevent the spread of the phytoparasite. In 2025, the golden potato nematode is found sporadically in most areas of modern potato cultivation in Ukraine. L.A. Pylypenko *et al*. (2008) at the beginning of the 21st century, from soil samples collected in the Zakarpattia region, the pale potato nematode *Globodera pallida* (Stone, 1973) Behrens, 1975, which is subject to external plant quarantine, was also isolated and identified for the first time. However, despite a number of scientific publications, there is no official registration of this species in Ukraine as of 2025 (Subbotin, 2025). One of the main obstacles to the effective detection of *Globodera pallida* is its low abundance in mixed populations with *Globodera rostochiensis*, where the proportion of the former usually does not exceed 2-5%.

The golden potato nematode in Ukraine is subject to internal plant quarantine, while the pale potato nematode is subject to external plant quarantine. A biological feature of the pale potato nematode is that, unlike the golden potato nematode, females form brown cysts without an intermediate yellow phase. The authors O.I. Borzykh *et al*. (2021) pointed out that the pale nematode is more aggressive because it is capable of infecting potato varieties that are resistant to the golden potato nematode. The ontogenesis of the golden potato nematode includes the following stages: egg, larvae (invasive second instar, parasitic third and fourth instars), adults: male and female, and cyst (dead female filled with eggs). Its microscopic size makes it difficult to detect its foci in a timely manner, especially in the early stages of colonisation of the land, and the cyst stage is a factor in protecting the offspring under conditions unfavourable for reproduction. J.M. Mwangi *et al.* (2021) noted that the cyst is also a source of passive dispersal of the quarantine organism along with contaminated planting material, soil cultivation tools, wind erosion of the soil, etc. Considering that traditional nematological monitoring of agrocenoses requires considerable physical effort and time, the aim of the study was to develop new methods for remote detection of globoderosis foci.

MATERIALS AND METHODS

The study was conducted over four growing seasons in 2021, 2022, 2023 and 2024 (repeated annually) using modern UAV models (DJI Phantom and DJI Spark) at the Voykov private lease enterprise (Chernihiv district, Chernihiv region), as well as on private plots in the village of Mykhailo-Kotsyubynske, Chernihiv district, Chernihiv region, on sod-podzolic soils typical for this region. The optimal periods for aerial visual diagnosis of potato plant damage by globoderosis were determined to be the third decade of June and the first and second decades of July. The research materials were potatoes susceptible to the golden potato nematode ('Lugovska', 'Svitanok Kyivskyi') and nematode-resistant varieties ('Dnipryanka', 'Zabava', 'Slovianka'), root systems, soil samples, cysts, eggs, larvae and adult golden potato nematodes.

Soil samples were collected with a soil auger before planting and after harvesting the tubers. At the same time, on land where seed potatoes were to be grown, as well as to determine the effectiveness of phytosanitary measures, 300 primary samples of 5 cm^3 each with a total volume of 1,500 cm^3 of soil or 6 average samples of 250 cm^3 of soil were collected from 1 ha. On fields intended for growing food potatoes, 100 primary samples were collected from 1 hectare, from which an average sample of at least 400 cm^3 of soil or 2 average samples of 200 cm^3 of soil were formed. From each household plot, 50 primary samples of 5 cm^3 of soil were collected from a uniform grid, with a total volume of at least 200 cm^3 of soil. To determine the potential harmfulness based on actual crop losses, the sizes of the survey areas ranged from 1-5 m^2 to 100 m^2. Control measurements of typical foci for this phytocenosis, repeated four times, made it possible to determine their average sizes, and counting the number of similar foci for each group made it possible to determine the total area of damage.

For flotation analysis, an average sample of 100 cm^3 of air-dry soil was poured into a 1-litre glass, filled with water and thoroughly mixed. The contents of the glass were left to settle until a sediment appeared. Since cysts are lighter than water, they float to the surface. The resulting mixture was poured into a funnel with a paper filter inserted beforehand. Each sample was stirred and drained twice. After the water had completely drained, the presence of cysts was determined, which were mostly distributed across the upper water level on the cone filter. The accuracy of the method was achieved by visually counting the number of eggs and larvae in the cysts using optical instruments (binoculars), isolated by flotation from the selected soil samples. In total, over 800 plant and soil samples were collected and analysed during the research period.

Aerial monitoring of agrocenoses was carried out using modern UAVs (DJI Phantom and DJI Spark) during the daytime in order to obtain high-resolution images. The percentage of affected plants and the average damage score were calculated using generally accepted formulas (1, 2), taking into account the specifics of nematological research.

$$P = \frac{100 * \mathrm{n}}{\mathrm{N}}, \tag{1}$$

where P – the nematological damage index, %; n – the number of plants with signs of damage; N – the total number of plants recorded, in pieces.

$$B = \frac{\sum n*b}{N}, \tag{2}$$

where B – the average damage index; $\sum n*b$ – the total index obtained by multiplying the number of damaged plants by the corresponding damage scores; N – the number of plants surveyed during the study, in pieces.

The level of plant damage, % (on the reference plot), was determined using the following formula (3):

$$Da = \frac{100*(M*n)}{P}, \tag{3}$$

where Da – degree of plant damage, %; M – average size of nematode foci, m^2; n – number of detected foci, pcs.; P – size of the area subject to accounting, m^2.

Experimental studies of plants, including the collection of plant material, complied with institutional, national and international guidelines. The authors adhered to the standards of the Convention on Biological Diversity (1992). Statistical processing of the experimental data obtained was performed using Microsoft Office Excel 2007, Statgrafics and Statistica 5.0 computer programs.

RESULTS AND DISCUSSION

With modern potato cultivation in Ukraine, which is essentially a monoculture of small households, it is quite difficult to comply with phytosanitary measures to control the golden potato cyst nematode, which causes its mass accumulation and leads to significant crop losses. In order to detect foci of this limited-spread quarantine organism in a timely manner and prevent its further spread to new areas, it is necessary to develop both new diagnostic methods and improve generally accepted monitoring methods. For commercial plantings, and in recent years for many household plots, a banded arrangement of potato bushes is typical when using a mechanised planting method. This is clearly visible when the surveyed area has uniform plant cover. At a low level of infestation, the banded structure of the cover is preserved, but unevenness may appear locally, and chlorotic or stunted plants may be found sporadically (Fig. 1).

Figure 1. Photo of potato globoderosis foci detected using UAV
Source: provided by the authors

In Ukraine, over 90% of potatoes are grown on private household plots, essentially within settlements. Under these conditions, the most effective method for aerial visual inspection of plantings for globoderosis infestation is the use of unmanned aerial vehicles (UAVs). Using a pre-planned flight route within a geographical information system (GIS) and flying at a height of 50 metres in a shuttle pattern, it's possible to survey dozens of hectares of potato plantings in just a few hours, whereas traditional ground inspections would take several days. An important advantage of using UAVs is the non-contact nature of the survey, which reduces the risk of spreading the quarantine nematode species to neighbouring plots – a risk that exists when people or equipment work in the field. If local irregularities are detected in the plant cover, a UAV can perform a repeat inspection of the designated areas from a height of 2-10 metres, providing detailed images for further analysis (Fig. 2).

At a moderate degree of damage, the row structure of potato plantings is generally preserved; however, localised foci with clearly pronounced plant suppression are diagnosed. These foci are visually distinguishable against the background of unaffected plants by such features as delayed growth and development, and mottled leaf colour ranging from pale green to yellowish or brown desiccated leaves. At the same time, it should be noted that under conditions of high crop density, due to row closure, the distinct strip structure of the crop may not be visible. However, in this case, a focal infestation of globoderosis can still be diagnosed visually. In cases of severe or very severe damage, globoderosis foci can extend for several dozen metres, with significant plant thinning, especially in the central part, and stunting at the edges of such foci. At the same time, small micro-foci of less affected, chlorotic plants may also appear in different parts of the field. This is due to the different times of initial infestation of the plots by the golden potato nematode.

Figure 2. Photo of potato globoderosis foci detected using UAV
Source: provided by the authors

According to studies by D. Sigareva *et al.* (2024) and A. Babich *et al.* (2018), nematodes parasitising the roots of susceptible crops cause morphological, physiological, and pathological changes in plant cells. The visual signs of plant damage (stunted growth, chlorosis, yellowing and dieback of lower leaves, wilting, and – in cases of severe infestation – localised plant death) become visually apparent and mostly coincide with the beginning of potato flowering. The root system of such affected plants often has a huge number of small rootlets. However, in cases of very severe infestation, the roots turn brown and die prematurely, which leads to the death of globoderosis-affected plants and the formation of "bald spots." The presence of bald spots indicates that these areas have been infested by the golden potato nematode for a long time, provided that females are found on the roots of the plants during selective route surveys. This also indicates a high probability of infestation of adjacent plots, even in the absence of typical visual signs of globoderosis. Specifically, it was found that the use of technical equipment during plowing or mechanical potato diggers during harvesting – with constant movement from one owner to another without thorough cleaning of the equipment – was one of the reasons for the passive dispersal of golden potato nematode cysts within the settlement. The optimal periods for aerial visual diagnosis of globoderosis damage in potato plantings are the third decade of June and the first and second decades of July. These calendar dates mostly coincide with the potato flowering phase. This is because during the period of mass appearance of females on the root system, plants suffer the most from the negative effects of both the parasitism of the females and unfavourable environmental factors, especially prolonged drought. Plants, even with a moderate level of infestation, wilt during the daytime, and at a high level, they dry out prematurely, which leads to the localised formation of bald spots. Table 1 provides the criteria for the remote visual assessment of globoderosis infestation in potato plantings, which are based on visual signs detected using a UAV.

Table 1. Criteria for remote visual assessment of potato plant damage caused by globoderosis

Score	Degree of damage	Visual manifestations of damage to plants	Proportion of affected area out of total, %	Predicted yield reduction, %
0	None	The plant cover is uniform. No signs of plant damage	0	0
1	Absent or mild	Slight chlorosis of individual plants or small foci	<10	<5
2-3	Mild	The plant cover is locally uneven. Chlorotic and sporadic patches of stunted plants	11-25	6-10
4-5	Moderate	Significant unevenness of the plant cover. Small and moderate foci with wilted leaves and localised plant death	26-50	11-30

Table 1. Continued

Score	Degree of damage	Visual manifestations of damage to plants	Proportion of affected area out of total, %	Predicted yield reduction, %
6-7	Severe	The plant cover is patchy. Significant depression and local plant death. Clearly visible areas of damage, so-called "bald spots"	51-75	31-50
8-9	Very severe	Very significant thinning of potato plantings. Large, often continuous areas with significant thinning of plants and the formation of "bald spots"	>75	>50

Note: formulas 1, 2, and 3 were used to calculate the degree of plant damage and the proportion of the surveyed area affected
Source: developed on the basis of authorial research

Globoderosis disrupts plant metabolism, suppresses photosynthesis, and impairs the uptake of water and nutrients, which manifests itself in symptoms that can be clearly diagnosed visually. The developed criteria represent a systematised approach to nematological assessment of potato plantings. It should also be noted that aerial visual monitoring enables the inspection of large areas of solanaceous crops for potato globoderosis at the most appropriate phenological stages.

For diagnosis, the degree of host plant infestation was assessed depending on the level of root invasion by females of Heteroderidae. The evaluation scale (0-9 points) takes into account visual manifestations, the proportion of affected area, and predicted yield losses. This approach combines qualitative observations with quantitative outcomes, forming the basis for management decisions in agricultural production. These criteria were developed in the course of the present study. For instance, at the first score, symptoms of infestation were weakly expressed, and chlorotic plants were mainly found in marginal field strips, with the proportion of affected area not exceeding 10%. At the 2-3 score, chlorotic and locally yellowed plants were diagnosed on up to 25% of the surveyed area. At a moderate damage level (scores 4-5), pronounced heterogeneity of plant cover encompassed up to 50% of the surveyed area, with locally diagnosed foci of severe suppression and plant death. Severe (scores 6-7) and very severe (scores 8-9) infestation indicate the long-term persistence of golden potato cyst nematode foci in certain agrocenoses. Marked thinning of stands and the formation of so-called "bald patches" over extensive areas resulted in yield losses ranging from 31-50% or even higher.

The developed criteria can be integrated into UAV software, satellite monitoring systems, or mobile applications for agro-scouting, aligning with modern trends in precision agriculture, and providing a foundation for economic and biological modelling of the feasibility of applying plant protection products (PPPs) or implementing crop rotation. In addition, the visual assessment scale may be used in agronomic expertise and in state monitoring of the phytosanitary condition of agricultural lands. It should be emphasised that conducting aerial visual monitoring at later stages may be complicated by potato late blight epiphytotics, particularly under prolonged humid conditions. However, during epiphytotic disease development, plant death is observed over large contiguous areas, in contrast to the predominantly focal damage caused by potato globoderosis. It has been established that globoderosis symptoms are more clearly expressed at daytime temperatures above 25°C. Therefore, the first trial flights are best carried out between 12:00 and 18:00, when affected plants, in addition to the above-mentioned diagnostic features, show the greatest wilting, especially if no precipitation has occurred for several days prior to the inspection.

Aerial visual detection of localised areas of heterogeneous plant cover subsequently narrowed down the survey area of suspected agrocenoses for examination by standard methods. To confirm that potato plants were affected specifically by globoderosis, it was appropriate to analyse samples of infested plants collected during selective route surveys. The detection of white females on the root system of suppressed plants served as confirmation that agrocenoses were colonised by the quarantine organism – the golden potato cyst nematode.

The use of UAVs in quarantine inspections of household plots provides significant advantages. Route surveys of plots were first conducted to clarify the phytosanitary status of households where aerial visual monitoring had diagnosed potato infestation by globoderosis. If the infestation was confirmed by conventional methods, adjacent plots in the settlement were also examined. Where it was not possible to survey all problem plots during the vegetation period of host plants, the nematological status of such land was determined after harvest by sampling and analysing soil for the presence of cysts containing viable offspring. Based on the remotely detected foci of plant suppression or local plant death, it was possible to plan the inspection routes of problem plots more precisely and collect nematological samples to confirm or refute the colonisation of a particular plot by the golden potato cyst nematode. Priority attention was paid to heterogeneity and patchiness of the plant cover, as well as differences in plant colouration (chlorosis, yellowing, browning, leaf desiccation). Technical errors in farming operations were mostly distinguished by sharper rectangular contours. By contrast, foci of locally suppressed plants usually had an elongated-elliptical shape in the predominant direction of soil cultivation operations, which is attributable to passive dispersal of cysts by machinery.

Aerial visual diagnosis substantially reduced the time and costs associated with sampling large numbers of soil specimens by the route method, their preparation for flotation analysis, cyst extraction from air-dried soil, and counting of eggs and larvae in each sample. Given that, at the initial stages of agrocenosis colonisation by cyst-forming nematodes, foci may be smaller than 1 m^2, whereas after long-term infestation they may extend over several hundred square metres, the dimensions of accounting plots ranged from 1-5 m^2 to 100 m^2, depending on the actual yield losses observed. Control measurements of typical foci for the given phytocoenosis, conducted in quadruplicate, enabled determination of their average size, while counting the number of similar foci in each group yielded the total affected area. The long-term persistence of foci within defined spatial boundaries and the slow course of the pathological process are the main advantages of diagnosing potato globoderosis compared with actively migrating phytophagous species or the spread of mycological diseases capable of epiphytotics.

Thus, the use of UAVs makes it possible to establish the spatial distribution of cyst-forming nematode foci across surveyed areas within a short timeframe while significantly reducing the costs compared to conventional route methods. Digital mapping of phytoparasitic nematode spread offers great prospects for the practical application of research results. Integrating nematological monitoring results into electronic databases with GPS-based spatial referencing enables reproduction of inspection routes and localisation of detected microfoci of cyst-forming nematodes in subsequent surveys. This in turn provides opportunities to track and, if necessary, adjust both the boundaries of their spread and the level of soil infestation, which is critically important for decision-making regarding the removal of quarantine restrictions from certain territories. Research demonstrates the effectiveness of UAVs equipped with thermal and multispectral sensors, as well as the use of machine learning and metabarcoding techniques, for the early detection of nematodes and assessment of plant condition in various crops.

According to J. Wainer & Q. Dinh (2021) and X. Wang *et al.* (2022), under modern classification the genus *Globodera* includes, besides the golden potato cyst nematode (*Globodera rostochiensis* (Wollenweber, 1923) Behrens, 1975), also the pale potato cyst nematode (*Globodera pallida* (Stone, 1973) Behrens, 1975), which is more aggressive as it can infest potato varieties that are resistant to the golden potato nematode. Data from V.P. Fedorenko *et al*. (2012) and A. Pulavarty *et al*. (2022) indicate that traditional nematological monitoring includes visual diagnosis of potato plantings; sampling and analysis of plants and soil; flotation-based cyst extraction; counting of eggs and larvae contained in cysts; species identification of nematodes; and compilation of nematological cartograms. Priority nematological surveys should be conducted in household sector plots, since under monoculture or with minimal intervals between repeated cultivation of host plants, populations of the golden potato cyst nematode accumulate much more rapidly than in crop rotation fields. As R.A. Sikora *et al*. (2023) note, confirmation of infestation specifically by globoderosis requires the examination of the root system of visually suppressed potato plants for the presence of spherical white females.

Given the labour intensity and significant time costs, particularly for soil sampling, flotation analysis, and counting the number of eggs and larvae in each sample, the search for alternative monitoring methods of PCN (potato cyst nematodes) has become essential. At the end of the 20th century, small aircraft were first used to detect foci of *Globodera* infestation. However, according to A.G. Babych *et al*. (2024), due to the high costs of such aerial visual surveys, as well as the difficulty of clearly delineating the distribution boundaries of infestation foci when interpreting aerial photographs, this method did not become widely implemented. The main advantage of developing nematological maps, including those produced with modern technical tools, compared with actively migrating phytophagous species, lies in the long-term persistence of foci within defined spatial boundaries, which is due to the ability of progeny to remain viable in the cyst stage for 10 years or more in a state of anabiosis.

The study by K. Jindo *et al*. (2023) demonstrated the effectiveness of UAV-derived data, particularly thermal sensors and vegetation indices, for early detection of potato infection with the pale cyst nematode *G. pallida*. A correlation was found between canopy temperature and infection density, linked to the physiological response of the plants. The chlorophyll content index proved most reliable for predicting yield losses. The results indicate the potential for integrating such methods into modern agromonitoring systems, with further refinement through multifactorial studies. In the research by M.P. Tangvik *et al*. (2025), metabarcoding (for nematodes, bacteria, fungi, and oomycetes), UAV-based multispectral imaging, and traditional nematode extraction from soil were combined to diagnose potato crop infestation in Norway. NDVI analysis identified areas of optimal and suppressed plant growth. Evidence pointed to phytonematodes as the likely cause, given their presence and the low alpha-diversity in affected zones. Metabarcoding showed high accuracy compared with traditional diagnostic methods. The combined approach proved promising for detecting growth differences across entire fields. However, no statistically significant correlation was found between the relative abundance of *Globodera* spp. and NDVI. Nonetheless, the dominance of this genus in metabarcoding results suggests its potential role in plant growth suppression. The absence of a direct link may be explained by the fact that after a certain threshold density of the phytoparasite is reached, further accumulation does not cause a proportional increase in damage.

In the study by V.P. Cavalcanti *et al*. (2023), the potential of UAV imagery was assessed for monitoring the impact of root-knot nematodes on lettuce (*Lactuca sativa*). The experiment determined the optimal flight altitude for mapping infestation and calculated vegetation indices and canopy parameters. It was established that UAV imagery, even from low-cost equipment, can be reliably used to detect plant stress and predict yield, despite some limitations related to lighting. In the study by B.H.T. Arantes *et al*. (2023), the effectiveness of UAV-based multispectral imaging was examined for detecting *Heterodera glycines* and *Pratylenchus brachyurus* during the soybean flowering stage (R1). Data from Sequoia, Sentera, and Phantom 4 Advanced cameras were used to analyse the relationship between spectral reflectance and nematode density in soil and roots. It was found that the red spectrum best indicated the presence of *H. glycines*, whereas for *P. brachyurus* the most informative were the RedEdge and NIR spectra. The results confirm the feasibility of early diagnosis of infestation using readily available sensors. In the context of aerial monitoring of potato *Globodera* infestations, the study by D. Komarchuk *et al*. (2020) is also relevant, as the authors developed algorithms and software for UAV flight planning aimed at monitoring plant stress. This aligns with the present study, in which aerial photographs were used to detect potato infestation foci caused by the golden nematode, refine survey routes, and enable targeted sampling. The application of the solutions described by D. Komarchuk *et al*. may improve the accuracy, efficiency, and timeliness of phytosanitary monitoring using UAVs.

The study by F.V. Pereira *et al*. (2022) focused on the application of machine learning and remote sensing for monitoring coffee plantations infested with nematodes. Using UAV and Planet satellite imagery, the authors assessed physiological plant parameters with the help of Random Forest and SVM algorithms. The results demonstrated high accuracy in predicting such indicators as chlorophyll content, plant height, branch length, and branch number. This approach enables spatial analysis of crop condition and, accordingly, the adoption of management decisions regarding protection against harmful organisms. S. Joalland *et al*. (2018) evaluated the effectiveness of imagery obtained from UAV-mounted sensors and handheld devices for phenotyping sugar beet cultivars infected with beet cyst nematode (BCN). The analysis included spectral, hyperspectral, thermal, and height-related parameters of crop canopies. It was established that spectral indices related to chlorophyll, nitrogen, and water content reliably distinguish nematode-resistant cultivars from susceptible ones, particularly in the later stages of vegetation. UAVs proved advantageous compared with traditional methods. The findings highlight the potential of integrating multiple sensor datasets for yield prediction and improvement of breeding processes.

A.J. Oliveira *et al*. (2019) presented a methodology for detecting nematodes in coffee plantations using RGB imagery acquired from UAVs and machine learning techniques. Visual plant features were employed to classify plots as infested or non-infested. Several approaches were tested, including segmentation. The best performance was achieved by the U-net model with manual segmentation, yielding an F-measure of 63%. The article by R. Sathya Priya *et al*. (2025) reviewed modern and traditional remote sensing technologies used for monitoring pests, plant diseases, parasitic nematodes, weeds, soil microorganisms, and environmental threats. The technology enables detection of infestation foci, localised pesticide application, and effective agronomic decision-making. Special attention was given to the integration of remote sensing with site-specific weed management (SSWM) and field survey data. In the context of Agriculture 4.0, such approaches enhance crop productivity, reduce costs, and contribute to the sustainable development of the agricultural sector.

In summary, these studies indicate the existence of correlations between spectral indices, canopy temperature, and infestation levels, which make it possible to predict yield losses and identify problem areas. New approaches that combine traditional and modern methods increase the accuracy of monitoring and contribute to the implementation of precision farming systems, which ensures effective control of harmful organisms and the sustainable development of agricultural production.

CONCLUSIONS

Considering the labour-intensive nature of traditional route-based nematological surveys of phytocenoses, the use of an effective and economically accessible method of remote diagnostics allows for the monitoring of large areas for globoderosis infestation in a short time. This enables the local and differentiated application of phytosanitary measures, thereby significantly reducing the material costs of plant protection.

The optimal times for aerial visual diagnosis of globoderosis damage in potato plantings are the last ten days of June and the first and second ten days of July. This period coincides with the mass appearance of females on the root system, which mostly overlaps with the flowering phase when plants suffer most from the negative effects of both phytoparasites and adverse environmental factors, especially prolonged drought. The use of a traditional monitoring system remains necessary to confirm or refute the suspicion of globoderosis in certain potato agrocoenoses that has been diagnosed by the aerial visual method. Since invasive larvae have minimal active migration, the centres of spread for the golden potato nematode remain within defined spatial boundaries for many years. This is a significant advantage for the development and practical use of nematological maps compared to actively migrating species of phytophages.

The research results also confirm the feasibility of applying the developed method of aerial visual monitoring to detect local damage to plants by other species of cyst-forming nematodes. It is promising to create internal farm maps (plans) with a detailed determination of the location of cyst-forming nematode foci on cartograms, their area, and soil infestation density to optimise the structure of sown areas and crop rotation. This will also aid in the organisation and implementation of effective and environmentally friendly control measures. New approaches that combine traditional and modern methods increase the effectiveness and accuracy of monitoring phytoparasitic nematodes, contribute to the implementation of precision farming systems, and ensure the differentiation of pest control measures. Prospects for further research include using the rapid development of UAV technologies and the implementation of artificial intelligence to improve methods of phytosanitary monitoring, which opens up new opportunities in the detection and control of quarantine organisms.

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Аеровізуальний моніторинг глободерозу картоплі

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Анотація. Актуальність досліджуваної проблеми полягає в необхідності своєчасного виявлення осередків глободерозу картоплі з метою їх локалізації, ліквідації і запобіганню подальшому розселенню карантинного організму. Основним завданням роботи було вдосконалення системи нематологічного моніторингу фітоценозів за поєднання новітніх і традиційних методів діагностування. Для виявлення осередкового ураження пасльонових культур глободерозом було апробовано використання безпілотних літальних апаратів (БПЛА). Золотиста картопляна нематода *Globodera rostochiensis* (Wollenweber, 1923) Behrens залишається одним із найбільш небезпечних карантинних організмів в Україні. Поширення монокультури пасльонових культур у дрібних домогосподарствах сприяє масовому накопиченню цього фітопаразита та зростанню його шкідливості. Виявлено, що ураження посівів призводить не лише до значних втрат урожаю, а й ускладнює реалізацію продукції через необхідність дотримання карантинних обмежень. Отримані результати підтверджують необхідність удосконалення традиційних та впровадження новітніх підходів до фітонематологічного моніторингу. Визначено, що оптимальними строками нематологічного моніторингу картоплі є кінець червня – перша половина липня, коли проявляються візуальні симптоми глободерозу та виявляються самиці нематоди на коренях. Аналіз аерофотознімків дозволяв уточнювати маршрути обстеження та цільово відбирати рослинні зразки з уражених ділянок, що значно знижувало витрати порівняно з традиційними методами. У разі неможливості контролю під час вегетації карантинний статус полів визначали після збирання врожаю за аналізом ґрунту на наявність цист нематоди. Встановлення особливостей просторового поширення, загальної площі виявлених осередків та рівня ураженості картоплі глободерозом, дає змогу диференціювати та локально застосовувати фітосанітарні заходи, що суттєво скорочує витрати на захист рослин. Варто зазначити, що розроблена методологія аеровізуального обстеження фітоценозів сучасними БПЛА, обладнаних камерами з високою роздільною здатністю,

також може бути використана для виявлення осередків ураження сільськогосподарських культур іншими видами цистоутворюючих нематод. Розроблену методологію аеровізуального моніторингу доцільно першочергово використовувати спеціалістами фітосанітаних інспекцій з карантину рослин, а також фахівцями великих господарств та агрохолдингів

Ключові слова: золотиста картопляна цистоутворююча нематода; нематодози; новітні методи нематологічного діагностування; фітоценози; безпілотні літальні апарати