MANAGEMENT OF AGRICULTURAL MACHINERY AND ACTIVITIES USING GPS AND GIS TECHNOLOGIES

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ABSTRACT: This paper examines the contribution of Global Positioning System (GPS) and Geographic Information System (GIS) technologies to the management of agricultural machinery and field operations within the broader framework of precision agriculture. The study synthesizes the technical principles of satellite positioning and geospatial data processing, then discusses their operational relevance in soil sampling, machinery guidance, crop monitoring, site-specific pest control, yield assessment, agricultural risk evaluation, and water resource management. Particular attention is given to the integration of GPS, GIS, sensors, and decision-support systems as a basis for data-driven farm management. The analysis indicates that geospatial technologies improve operational accuracy, reduce unnecessary input use, strengthen traceability, and support more sustainable exploitation of agricultural resources. At the same time, their successful adoption depends on access to equipment, software, digital skills, and the capacity to translate spatial data into practical management decisions.

KEYWORDS: precision agriculture, GPS, GIS, agricultural management, geospatial monitoring, decision support, sustainability.

1. INTRODUCTION

Agriculture remains a strategic sector for every national economy because it provides food, raw materials, employment, and an essential foundation for social stability. In recent decades, however, the sector has been subjected to increasing pressure generated by population growth, market volatility, climate uncertainty, and the need to ensure both competitiveness and environmental responsibility.

At the same time, agricultural production systems are confronted with soil degradation, uneven field productivity, pest pressure, higher costs for seeds, fertilizers, plant protection products, and fuel, as well as growing regulatory and societal expectations regarding the sustainable use of natural resources. Under these conditions, conventional uniform management of fields is progressively being replaced by approaches that account for local variability and support more precise interventions.

Within this context, GPS and GIS technologies have become central instruments in the digital transformation of agriculture. GPS enables the accurate positioning of machinery, samples, and field observations, while GIS provides the framework for storing, integrating, analysing, and visualising georeferenced information. Used together, these technologies support more rigorous planning, execution, monitoring, and evaluation of agricultural activities. The purpose of this paper is to analyse the role of GPS and GIS in the management of agricultural machinery and operations and to highlight their contribution to efficiency, profitability, and sustainability [1.2,3].

2. TECHNICAL FOUNDATIONS OF GPS AND GIS IN PRECISION AGRICULTURE

Precision agriculture [4] may be defined as a management approach based on the collection and use of spatially explicit information in order to adapt agricultural interventions to the variability of the field. Instead of treating a parcel as a homogeneous production unit, precision agriculture seeks to apply the appropriate treatment, in the appropriate quantity, at the appropriate place, and at the appropriate time.

From a technological perspective, this approach relies on the integration of satellite navigation, geospatial databases, remote sensing, onboard electronics, automated guidance systems, and decision-support tools. Its major objectives are the stabilisation of yields, the optimisation of production costs, the rational use of inputs, and the reduction of negative environmental externalities.

GPS and GIS constitute two of the most important pillars of this paradigm. GPS provides accurate spatial referencing in the field, whereas GIS transforms georeferenced observations into structured information that can support planning and intervention. Their combined use allows farm managers to move from intuition-based decisions to evidence-based operational control.

2.1. GPS System

The Global Positioning System is a satellite-based navigation system that determines the position of a receiver on the Earth's surface by processing signals transmitted by multiple satellites. Operationally, the system comprises the space segment, the control segment, and the user segment. Positioning is obtained through trilateration, based on the travel time of signals between satellites and the receiver. [5]

In agriculture, GPS is valuable because it enables the precise localisation of machinery trajectories, sampling points, treated areas, obstacles, and field anomalies. This precision underpins guidance and auto-guidance systems, repeatable routes, activity logs, and improved control of machine operations.

2.2. GIS System

A Geographic Information System is a computer-based framework for the acquisition, storage, organisation, processing, analysis, and representation of georeferenced data. In contrast to GPS, which primarily indicates location, GIS makes it possible to connect spatial position with agronomic, climatic, pedological, technical, and economic information.

A GIS architecture typically includes hardware, specialised software, spatial databases, analytical procedures, and trained users. Its main strength lies in the capacity to overlay multiple thematic layers and to derive patterns, correlations, and management zones that are not immediately visible through isolated data sources. For agricultural holdings, GIS becomes the informational infrastructure that supports diagnosis, planning, and operational decision-making.

3. APPLICATIONS OF GPS AND GIS IN AGRICULTURAL MANAGEMENT

3.1. Mapping and Soil Sampling

Soil sampling represents one of the foundational applications of GPS and GIS technologies in precision agriculture, as it provides the empirical basis for understanding spatial variability within agricultural fields. Traditional soil sampling methods often rely on generalized field-level assessments, which may obscure significant intra-field differences in soil properties. By contrast, GPS-assisted soil sampling enables the accurate georeferencing of every sampling point, ensuring that each observation is precisely linked to its spatial position within the field. This geospatial accuracy improves both the reliability and reproducibility of soil surveys, especially when repeated measurements are required over multiple growing seasons. [6]

Once collected, soil samples are subjected to laboratory analysis in order to determine key physical and chemical parameters, such as pH, organic matter content, salinity, moisture, texture, and macro- and micronutrient concentrations. These analytical results can then be integrated into a GIS environment, where they are transformed into thematic maps that visually represent the spatial distribution of soil characteristics. Such maps provide a much more detailed representation of field heterogeneity than conventional tabular data, allowing farmers and agronomists to identify high- and low-productivity zones, nutrient-deficient areas, or sectors affected by salinization and poor water retention (fig.1). [7]

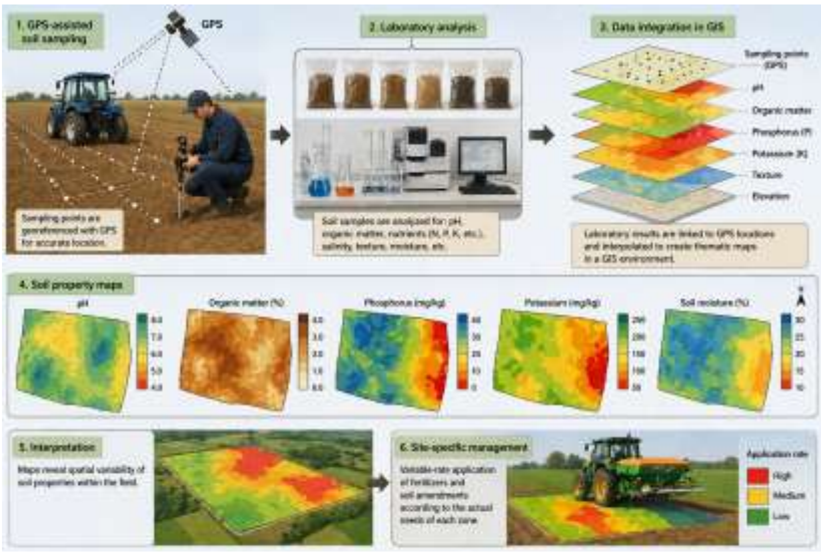

Fig.1. GPS-assisted soil sampling and soil mapping workflow

An important advantage of GIS-based soil mapping is its capacity to support site-specific crop management. Rather than applying uniform quantities of fertilizers, lime, or other soil amendments across the entire field, producers can adapt inputs according to the actual needs of each management zone. This differentiated approach improves nutrient-use efficiency and enhances the agronomic effectiveness of interventions. For example, areas with low phosphorus availability can receive localized fertilization, while sectors with unfavorable pH levels can be selectively amended to restore soil balance. In this way, resource allocation becomes more rational and better aligned with actual field conditions.

Moreover, soil mapping contributes to more informed long-term planning. Repeated georeferenced sampling over time allows the monitoring of changes in soil fertility and the evaluation of the cumulative effects of agricultural practices. As a result, farmers can assess whether management strategies are improving soil quality, maintaining productivity, or generating degradation risks. This temporal dimension is especially important for sustainable agriculture, where the objective is not only to maximize short-term yields but also to preserve soil health over the long term.

From an economic perspective, GPS- and GIS-based soil sampling reduces unnecessary expenditures by limiting interventions to areas where they are agronomically justified. It also reduces the waste of fertilizers and amendments, lowers fuel and labor costs associated with excessive applications, and minimizes the environmental risks linked to nutrient leaching or chemical accumulation in the soil. Therefore, mapping and soil sampling should be regarded not merely as technical procedures, but as essential decision-support instruments that improve the efficiency, sustainability, and scientific basis of agricultural management.

3.2. Machinery Guidance and Auto-Guidance

One of the most widespread and practically significant applications of GPS technology in agriculture is the guidance and auto-guidance of tractors and self-propelled machines during essential field operations such as tillage, sowing, fertilisation, spraying, and harvesting. In conventional fieldwork, machine trajectories are often influenced by operator experience, field visibility, and environmental conditions, which can result in overlaps, missed strips, and deviations from the intended path. GPS-based guidance systems substantially reduce these inefficiencies by enabling the machine to follow predefined routes with a high degree of positional accuracy, regardless of field shape or visibility constraints. A major advantage of this technology lies in the possibility of recording and repeating routes across multiple operations. Once an optimal path has been established for a specific field, it can be reused for subsequent interventions, ensuring consistency in the spatial execution of agricultural tasks. This repeatability is especially valuable in precision agriculture, where the alignment between sowing rows, fertiliser applications, and crop protection treatments can directly affect crop performance and operational efficiency. By maintaining parallel trajectories and reducing steering errors, GPS-guided machinery improves the uniformity of field operations and contributes to a more orderly and controlled production process. [8]

The reduction of overlaps and untreated areas has important economic implications. Overlapping during sowing, spraying, or fertiliser application leads to excessive use of inputs, while missed strips may result in lower yields, weed infestation, or uneven crop development. GPS guidance helps avoid both problems by ensuring a more accurate distribution of seeds, nutrients, and plant protection products across the field. Consequently, farms can reduce unnecessary expenditure on costly inputs and improve the technical quality of field interventions.

In addition to input savings, GPS-based machine guidance also contributes to lower fuel consumption and reduced labour requirements. More precise routing shortens working time, minimizes repeated passes, and enables operators to cover the field more efficiently. This becomes particularly important in large-scale farming systems, where even small gains in operational efficiency can generate substantial cumulative savings. Furthermore, by reducing operator fatigue and the need for constant manual steering corrections, guidance systems improve working conditions and can support longer and more consistent working periods during critical agricultural windows.

Another important benefit concerns the functioning of agricultural machinery under low-visibility conditions, such as during nighttime operations, fog, or dust.

GPS guidance allows the continuity of work with minimal loss of precision, thereby increasing farm flexibility and allowing time-sensitive interventions to be carried out when agronomically required. This capability is especially relevant in periods when delays in sowing, spraying, or harvesting may negatively affect crop productivity and quality. [9]

Overall, the use of GPS for the guidance of agricultural machinery represents a key element of modern farm management. It enhances the precision, consistency, and efficiency of field operations, while simultaneously reducing production costs, limiting resource waste, and supporting a more sustainable use of agricultural inputs. For these reasons, machine guidance systems are widely regarded as one of the most accessible and impactful entry points into precision agriculture.

3.3. Crop Monitoring and Site-Specific Pest Control

Geospatial technologies also play a major role in the monitoring of crop condition and in the early identification of spatially distributed agronomic problems, such as pest infestations, disease outbreaks, nutrient deficiencies, and water stress. In conventional crop management, such problems are often detected through visual inspection and are frequently addressed at the scale of the entire field. However, agricultural fields are rarely homogeneous, and biotic or abiotic stress factors tend to occur unevenly across space. By integrating GPS, GIS, field observations, proximal sensors, and remote sensing data, precision agriculture makes it possible to detect, map, and interpret this variability with far greater accuracy.

A key advantage of geospatial monitoring is that every observation can be linked to a precise location in the field. Whether the information is collected manually by field operators, automatically by in-field sensors, or remotely through satellite or drone imagery, georeferencing allows each data point to be positioned within a broader spatial framework. Once incorporated into a GIS environment, these data can be processed and visualized as thematic maps that show the distribution, extent, and severity of specific crop problems. For example, areas affected by pest pressure, disease symptoms, chlorosis, or moisture deficit can be clearly distinguished from unaffected zones, providing a much more nuanced understanding of field conditions than generalized field-level assessments. (Fig.2)

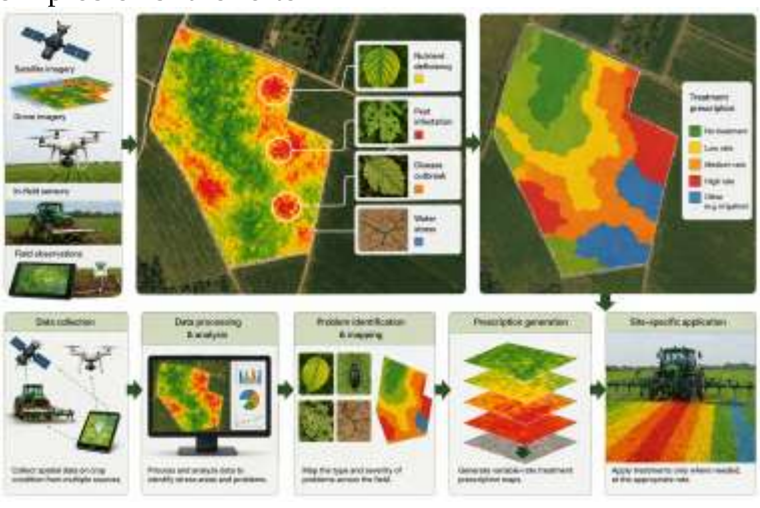

Fig.2. Integration of geospatial data for crop condition monitoring and targeted pest management

This spatially explicit approach significantly improves decision-making in crop protection and agronomic intervention. Instead of relying on blanket applications of pesticides, fungicides, fertilizers, or irrigation across the entire field, farmers can adopt site-specific treatments targeted only to the areas where problems are actually present. Such an approach increases the technical efficiency of interventions and helps ensure that inputs are applied where they are most likely to generate agronomic value. In pest and disease management, for instance, localized treatments can limit the spread of infestation while avoiding unnecessary chemical applications in healthy parts of the field. Similarly, nutrient-deficient zones can be corrected with variable-rate fertilisation rather than through uniform applications that may lead to overuse in unaffected areas. [10]

The economic benefits of this strategy are substantial. By limiting interventions to agronomically justified zones, farms can reduce expenditure on plant protection products, fertilizers, water, fuel, and labor. At the same time, site-specific crop monitoring may help prevent yield losses by allowing earlier and more accurate responses to emerging stress factors. The ability to intervene promptly in localized areas can be especially important in intensive farming systems, where the rapid development of pests or diseases may compromise productivity if not addressed in time.

From an environmental perspective, geospatially guided interventions are equally important. Blanket treatments often result in excessive use of chemicals and water, increasing the risk of soil contamination, nutrient leaching, pesticide drift, and negative effects on non-target organisms. By contrast, spatially targeted management reduces unnecessary input application and supports a more sustainable balance between productivity and environmental protection. In this sense, geospatial technologies contribute not only to operational efficiency but also to the ecological modernization of agriculture.

Furthermore, the repeated collection and mapping of crop condition data over time enables dynamic monitoring and temporal analysis. GIS can be used not only to locate current problem areas but also to compare seasonal patterns, identify recurring stress zones, and evaluate the effectiveness of previous interventions. This adds a strategic dimension to farm management, as crop monitoring evolves from a reactive activity into a knowledge-based system of continuous observation, diagnosis, and adjustment.

Overall, the integration of geospatial technologies into crop monitoring provides farmers with a powerful framework for understanding spatial variability in crop health and for implementing more precise, timely, and sustainable agronomic responses. It transforms isolated observations into actionable spatial intelligence and strengthens the capacity of agricultural management to respond effectively to both routine and unexpected field conditions.

3.4. Water Resource Management and Risk Assessment

GIS is increasingly used in the management of agricultural water resources, particularly in irrigation planning, drainage analysis, and the identification of areas affected by excessive water loss or insufficient water supply. Water availability is one of the most critical determinants of agricultural productivity, especially under conditions of climatic variability and increasing pressure on natural resources. In this context, GIS provides a spatial decision-support framework through which farmers, planners, and agricultural institutions can better understand the distribution of water-related constraints within and across cultivated areas.

In irrigation planning, GIS enables the integration of multiple categories of spatial data, including topography, soil texture, infiltration capacity, crop type, evapotranspiration rates, and the location of water infrastructure. By combining these variables, it becomes possible to identify zones with different irrigation requirements and to establish priorities for water allocation according to agronomic need and resource availability. This is particularly important in regions where irrigation water is limited and must be distributed efficiently in order to maximize crop performance while minimizing waste. GIS-based analysis can therefore support both operational decisions, such as where and when to irrigate, and strategic decisions concerning the modernization or extension of irrigation systems.

Drainage management is another important field of application. Excess water, poor drainage, or uneven water distribution can negatively affect root development, soil aeration, nutrient uptake, and overall crop productivity. GIS allows the mapping of depressions, poorly drained soils, and runoff accumulation zones, helping decision-makers identify areas vulnerable to waterlogging or erosion. In addition, it can support the design and prioritization of drainage infrastructure by indicating where interventions such as drainage channels, subsurface systems, or land leveling measures are most needed. Through this capability, GIS contributes not only to increased production efficiency but also to the prevention of long-term soil degradation.

Another relevant use of GIS concerns the identification of areas affected by water loss. Spatial analysis can reveal sectors where irrigation inefficiencies, seepage, evaporation, or conveyance losses reduce the effectiveness of water delivery. When combined with field observations, hydrological data, or remote sensing information, GIS can help determine whether such losses are associated with damaged infrastructure, unsuitable soil conditions, or inappropriate irrigation practices. This diagnostic role is particularly valuable in improving system performance and reducing the economic and environmental costs associated with water misuse.

This functionality is highly relevant not only for farm managers, but also for insurance companies and public authorities. For farm managers, spatial risk assessment supports better planning decisions regarding crop selection, irrigation investment, planting schedules, or protective measures. For agricultural insurers, geospatial analysis improves the evaluation of insured parcels by linking environmental conditions and management history with the probability and potential severity of losses. This can contribute to more accurate premium calculation, better verification of claims, and more transparent risk classification. Public authorities may also use GIS-based assessments in the development of agricultural policies, disaster response plans, climate adaptation strategies, and regional investment programs.

From a broader perspective, the integration of GIS into water management and risk assessment reflects the transition from reactive to anticipatory agricultural management. Instead of responding only after water shortages, drainage failures, or climatic hazards have already generated losses, stakeholders can use spatial analysis to identify vulnerabilities in advance and implement targeted preventive measures. In this way, GIS supports not only the efficient use of water resources, but also the strengthening of resilience in agricultural systems increasingly affected by environmental uncertainty.

Overall, the application of GIS in irrigation planning, drainage analysis, and agricultural risk assessment demonstrates the strategic value of geospatial technologies for sustainable farm management. By transforming spatially distributed data into actionable knowledge, GIS helps optimize resource allocation, improve infrastructure planning, reduce exposure to hazards, and support more informed decision-making at both farm and institutional levels.

4. SENSORS, DECISION SUPPORT, AND IMPLEMENTATION CONSTRAINTS

The effectiveness of precision agriculture depends not only on spatial positioning and cartographic processing, but also on the capacity to collect reliable data regarding soil, crops, and environmental conditions. For this reason, GPS and GIS are increasingly combined with sensors capable of measuring soil conductivity, compaction, moisture, nutrient status, chlorophyll content, canopy reflectance, or other parameters relevant to agricultural diagnosis.

Electromagnetic sensors can provide information on soil texture, salinity, moisture, or organic matter; optical sensors are used to assess vegetation status and crop vigour; mechanical sensors can help evaluate compaction; and electrochemical sensors can support nutrient and pH analysis. When integrated into a GIS environment and linked to decision-support systems, these measurements can be translated into concrete recommendations for variable-rate fertilisation, crop protection, irrigation scheduling, or machinery deployment.

The benefits associated with these technologies are substantial. Economically, they contribute to lower input consumption, better use of working time, and improved productivity. Technically, they increase the precision, repeatability, and traceability of operations. Environmentally, they help limit the excessive application of chemicals and support a more rational use of soil and water resources.

Nevertheless, the widespread implementation of GPS- and GIS-based systems also faces important constraints. Initial investments can be significant, the use of software and equipment requires trained personnel, and the interpretation of spatial data remains a challenge in farms with limited digital capacity. Therefore, the performance of these technologies depends not only on their technical accuracy, but also on the organisational ability to incorporate them into coherent farm management practices.

5. CONCLUSION

The analysis confirms that GPS and GIS technologies are essential instruments for the modernisation of agricultural management and for the development of precision agriculture. By enabling accurate positioning, geospatial analysis, and data-driven decision support, these systems improve the planning and execution of field operations and contribute to more efficient management of agricultural machinery and resources.

Their practical relevance is evident in soil sampling, machinery guidance, crop monitoring, localised pest control, yield analysis, irrigation planning, and agricultural risk assessment. Beyond the operational gains, these technologies also support broader strategic objectives such as farm sustainability, resource efficiency, and environmental protection.

In the medium and long term, the integration of GPS and GIS with advanced sensors, remote sensing platforms, mobile communications, and data analytics will accelerate the transition towards digital agriculture. Farms capable of using these tools effectively will be better positioned to respond to the growing demands for productivity, traceability, resilience, and sustainable development.

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