

PRECISION AGRICULTURE: ANALYSING THE USE OF ADVANCED TECHNOLOGIES, DATA ANALYTICS AND REMOTE SENSING FOR SITE- SPECIFIC CROP MANAGEMENT AND RESOURCE OPTIMIZATION

Abstract

Precision agriculture has revolutionized modern farming by integrating cutting-edge technologies, data analytics, and remote sensing to optimize crop management and resource utilization. This study explores the multifaceted application of advanced technologies in agriculture, emphasizing their role in achieving site-specific precision. The adoption of precision agriculture practices has significantly improved crop yield, minimized resource wastage, and reduced environmental impact. The integration of global positioning systems (GPS), unmanned aerial vehicles (UAVs), and sensor technology has enabled precise mapping of field variability. Remote sensing techniques, such as satellite imagery and drones, provide valuable insights into crop health, soil conditions, and environmental factors, allowing farmers to make informed decisions. Data analytics is a cornerstone of precision agriculture, as it harnesses large volumes of data generated from various sources to drive actionable insights. Machine learning and artificial intelligence algorithms are increasingly employed to predict crop growth, disease outbreaks, and pest infestations. These insights empower farmers to apply fertilizers, pesticides, and irrigation with unprecedented accuracy, reducing costs and environmental impact. Resource optimization is another key aspect of precision agriculture. By precisely tailoring inputs, such as water, nutrients, and chemicals, to the specific needs of each part of a field, farmers can ensure more

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sustainable and efficient use of resources. This research delves into the successful implementation of advanced technologies, data analytics, and remote sensing in precision agriculture, highlighting their collective impact on enhancing crop yields, minimizing resource wastage, and promoting sustainable farming practices. It also examines the challenges and opportunities in scaling up these technologies for broader adoption in agriculture. Ultimately, precision agriculture represents a transformative approach that promises to meet the growing global demand for food while minimizing the ecological footprint of farming.

Keywords: Agriculture, Advanced Technologies, Crop Management,

I. INTRODUCTION

Precision agriculture has emerged as a transformative approach in modern farming, revolutionizing traditional agricultural practices. This concept involves the integration of advanced technologies, data analytics, and remote sensing techniques to enable site-specific crop management that implies application of precise quantity of inputs (fertilizers, water, pesticides etc) to the crop for resource optimization. By leveraging these tools, precision agriculture aims to enhance productivity, sustainability, and profitability while minimizing environmental impact. In this chapter, we will explore the significance of precision agriculture in modern farming and its potential to address the challenges faced by the agricultural sector.

Significance of Precision Agriculture in Modern Farming:

- 1. Increased Productivity:** Precision agriculture enables farmers to make informed decisions by providing accurate, real-time information about their fields. Data-driven insights into soil condition, crop health and nutrient requirements enable farmers to tailor management practices to their specific needs. By optimizing resource allocation and applying site-specific approaches, precision agriculture increases crop productivity and reduces yield variability.
- 2. Resource Efficiency and Sustainability:** One of the main benefits of precision agriculture is the ability to optimize resource usage. Precise application of inputs such as fertilizers, pesticides and water in response to in-field variability helps farmers minimize waste and reduce environmental impact. This approach makes efficient use of resources and reduces costs and potential negative environmental impacts. Precision agriculture also encourages sustainable practices such as conservation tillage, cover crops and crop rotation that contribute to soil health and long-term sustainability.
- 3. Improved Crop Quality and Yield Prediction:** Through the integration of advanced technologies and data analytics, precision agriculture enables better monitoring and management of crop health. Early detection of diseases, pests, or nutrient deficiencies allows for timely interventions, preventing yield losses. Additionally, by utilizing predictive models and historical data, farmers can forecast crop yields and plan their marketing and distribution strategies accordingly, leading to improved market competitiveness and profitability.
- 4. Mitigation of Environmental Impacts:** Conventional farming practices often result in the overuse of fertilizers, pesticides, and water resources, leading to environmental degradation and water pollution. Precision agriculture mitigates these impacts by encouraging targeted use of inputs. Precision agriculture reduces the risk of runoff, leaching and contamination by applying inputs only where and when they are needed. This approach contributes to the preservation of ecosystems, biodiversity, and water quality.
- 5. Enhanced Decision-Making and Risk Management:** Precision agriculture provides farmers with real-time data to make timely and accurate decisions. Using data analysis

techniques and decision support systems, farmers can evaluate the effectiveness of different management practices, assess risks and optimize their operational strategies. This enables proactive management of challenges such as extreme weather events, pests and market fluctuations, improving resilience and reducing potential losses.

II. SECTION 1: FUNDAMENTALS OF PRECISION AGRICULTURE

1. Definition and Principles of Precision Agriculture: Precision agriculture refers to a modern farming approach that integrates advanced technologies, data analytics, and remote sensing techniques to enable site-specific crop management and resource optimization. It aims to maximize productivity, minimize input wastage, reduce environmental impacts, and enhance overall agricultural efficiency. At its core, precision agriculture relies on the following underlying principles:

- **Site-Specific Management:** Precision agriculture recognizes that different areas within a field exhibit varying characteristics and requirements. By treating each area as a unique management unit, farmers can tailor their practices based on specific needs. This involves considering factors such as soil composition, nutrient levels, moisture content, and crop health, and applying appropriate inputs accordingly.
- **Accurate and Real-Time Data Collection:** Precision agriculture relies on the collection of accurate and timely data from various sources, including remote sensing technologies, sensors, and IoT devices. These data sources provide insights into crop health, soil conditions, weather patterns, and other crucial parameters. By continuously monitoring and analysing this data, farmers can make informed decisions and respond promptly to changing conditions.
- **Advanced Technologies:** Precision agriculture extensively utilizes advanced technologies to capture, store, and analyse data. These technologies include GPS, GIS, sensors, drones, robotics, and satellite imagery. They enable precise mapping, data collection, and automation of tasks, facilitating better decision-making and resource management.
- **Data Analytics and Decision Support Systems:** Precision agriculture relies on data analytics techniques and decision support systems to make sense of the vast amounts of data collected. Machine learning algorithms, predictive modelling, and big data analytics help process and interpret the data, providing valuable insights. Decision support systems offer recommendations and actionable information to farmers for efficient crop management.
- **Variable Rate Application:** Precision agriculture promotes the concept of variable rate application, where inputs such as fertilizers, pesticides, and irrigation are applied in precise quantities based on site-specific needs. By mapping the variability within a field and adjusting input rates accordingly, farmers can optimize resource allocation, reduce wastage, and minimize environmental impacts.

- **Sustainability and Environmental Stewardship:** Precision agriculture aims to enhance sustainability by minimizing the use of non-renewable resources and reducing negative environmental impacts. It promotes practices such as conservation tillage, cover cropping, precision irrigation, and integrated pest management to preserve soil health, biodiversity, and water quality.
 - **Continuous Monitoring and Evaluation:** Precision agriculture emphasizes the importance of continuous monitoring and evaluation of management practices. By regularly assessing the effectiveness of different strategies, farmers can make necessary adjustments, identify areas for improvement, and enhance overall performance.
2. **Technologies used in Precision Agriculture:** Precision agriculture revolutionizes traditional farming practices by integrating advanced technologies, data analytics, and remote sensing techniques. This integration enables site-specific crop management and optimal resource utilization, leading to improved productivity, efficiency, and sustainability. In this section, we will delve into the various components of precision agriculture and how they work together to transform farming practices.
- **Advanced Technologies:** Precision agriculture leverages a range of advanced technologies to collect data, monitor crops, and facilitate decision-making. Some key technologies include:
 - **Global Positioning System (GPS):** GPS is a satellite-based navigation system that provides accurate location information. In precision agriculture, GPS technology is used to precisely track and map fields. It allows farmers to determine the exact position of equipment, sensors, and crops. GPS data helps create detailed field maps, identify variability, and enables precise navigation during field operations.
 - **Geographic Information System (GIS):** GIS combines GPS data with spatial information to create detailed maps of fields. It integrates various data layers such as soil types, topography, yield history, and crop health. GIS technology enables farmers to visualize and analyse spatial patterns, make informed decisions about resource allocation, and implement site-specific management practices.
 - **Sensors and IOT Devices:** Various sensors, such as soil moisture sensors, **weather** stations, and nutrient sensors, collect real-time data on crop health, soil conditions, and environmental factors. Internet of Things (IoT) devices facilitate connectivity and data transmission.
 - **Drones and Remote-Controlled Vehicles:** Unmanned aerial vehicles (UAVs) or drones are equipped with cameras, sensors, and remote sensing technologies. Drones capture high-resolution aerial imagery of fields, providing detailed and up-to-date information on crop health, growth stages, and variability. They enable rapid data acquisition over large areas, enhancing field scouting, crop monitoring, and identification of specific areas that require attention.

- **Robotics:** Robotics technology is increasingly being integrated into precision agriculture. Robotic systems automate tasks such as seeding, planting, spraying, and harvesting. They can operate with high precision, reducing human error and enabling accurate application of inputs. Robotic devices equipped with cameras and sensors can also collect data on crop conditions and field parameters.
- **Data Analytics:** The vast amount of data collected from sensors, imagery, and other sources requires sophisticated analytics to extract meaningful insights. Data analytics techniques applied in precision agriculture include:
 - **Machine Learning:** Machine learning algorithms analyse large datasets to identify patterns, correlations, and anomalies. They can predict crop yields, detect diseases, and recommend optimal management practices based on historical and real-time data.
 - **Predictive Modelling:** Predictive models use historical data and statistical techniques to forecast future outcomes. These models help farmers make informed decisions regarding planting, irrigation, fertilization, and pest management.
 - **Big Data Analytics:** Precision agriculture generates enormous amounts of data. Big data analytics enables efficient storage, processing, and analysis of this data, facilitating data-driven decision-making on a large scale.
- **Remote Sensing:** Remote sensing involves capturing data about crops and fields from a distance, using technologies such as satellite imagery, aerial photography, and drones. Remote sensing offers valuable insights into crop health, growth stages, variability, and other site-specific characteristics. Some remote sensing applications in precision agriculture include:
 - **Normalized Difference Vegetation Index (NDVI):** NDVI calculates the vegetation health and vigor based on the reflectance of near-infrared and red light. It helps identify areas of stress, nutrient deficiency, or pest infestation.
 - **Thermal Imagery:** Thermal cameras capture temperature variations, enabling the detection of irrigation issues, water stress, and disease patterns.
 - **Hyperspectral Imaging:** Hyperspectral sensors capture data across a broad spectrum, allowing for detailed analysis of crop composition, disease detection, and nutrient deficiencies.
 - **LIDAR (Light Detection and Ranging):** LIDAR uses laser beams to measure distances and create 3D models of fields, assisting in terrain mapping, crop height estimation, and drainage analysis.

How These Technologies Enable Data Collection, Analysis, and Decision-Making in Crop Management:

- **Data Collection:** GPS technology, combined with sensors and drones, enables precise and georeferenced data collection. GPS provides accurate field coordinates, allowing farmers to record and map spatial information. Sensors collect real-time data on soil moisture, temperature, nutrient levels, and crop health. Drones capture aerial imagery, providing detailed visuals of fields. These technologies facilitate efficient and systematic data collection, creating a foundation for informed decision-making.
- **Data Analysis:** Advanced data analytics techniques are applied to the collected data. Machine learning algorithms, statistical models, and predictive analytics extract meaningful insights from the data sets. Data analysis helps identify patterns, correlations, and anomalies. It allows farmers to detect early signs of crop stress, disease outbreaks, or nutrient deficiencies. By analysing historical data, farmers can also develop predictive models for yield forecasting and optimal management practices.
- **Decision-Making:** The integration of advanced technologies and data analytics supports decision-making in precision agriculture. Decision support systems (DSS) use the collected and analysed data to provide recommendations and actionable insights to farmers. DSS tools consider factors such as weather conditions, soil conditions, and crop growth stages. They assist in determining the appropriate timing and rates for inputs like irrigation, fertilizers, and pesticides. DSS helps farmers make informed decisions, optimize resource utilization, mitigate risks, and maximize crop productivity.

Advanced technologies such as GPS, GIS, sensors, drones, and robotics are instrumental in precision agriculture. They enable precise data collection, facilitate data analysis for insights, and provide valuable information for decision-making in crop management. The integration of technology, data analytics, and remote sensing in precision agriculture empowers farmers with accurate, real-time information for effective decision-making. By precisely managing inputs such as fertilizers, water, and pesticides according to the specific needs of different areas within a field, farmers can optimize resource utilization, reduce costs, minimize environmental impacts, and maximize crop yields. This holistic approach to farming enhances sustainability, resilience, and productivity, paving the way for a more efficient and sustainable agriculture sector.

III. SECTION 2: DATA COLLECTION AND ANALYSIS IN PRECISION AGRICULTURE

1. **Remote Sensing and Imaging Techniques:** Remote sensing plays a crucial role in identifying crop stress, variability, and other site-specific characteristics in precision agriculture (Schepers & Francis, 1998). It offers numerous benefits that aid in efficient crop management and decision-making. Remote sensing brings significant benefits to

precision agriculture by facilitating the identification of crop stress, variability, and other site-specific characteristics. Its large-scale coverage, timely data acquisition, high spatial resolution, multispectral/hyperspectral capabilities, quantitative analysis, and integration with GIS and DSS contribute to informed decision-making, efficient resource allocation, and effective management strategies in modern agriculture.

Let's explore the advantages of remote sensing in this context:

- **Large-Scale Coverage:** Remote sensing allows for the monitoring of crops and fields over large geographic areas. Satellite imagery, aerial photography, and drones capture data that cover extensive regions, enabling farmers to assess crop conditions on a regional or even global scale (**Raj *et al.*, 2020**). This wide coverage helps identify spatial patterns, trends, and variations across fields.
- **Timely and Regular Data Acquisition:** Remote sensing technologies provide the ability to collect data in a timely and regular manner. Satellite imagery is regularly updated, and drones can be deployed as frequently as needed. This enables farmers to monitor crops at different growth stages, detect changes, and take prompt action when required. Timely data acquisition is essential for detecting early signs of crop stress, disease outbreaks, nutrient deficiencies, or pest infestations.
- **High Spatial Resolution:** Remote sensing techniques offer high spatial resolution, allowing for the identification of fine-scale (**Fraser & Congalton, 2021**) details within crops and fields. This capability helps in differentiating between healthy and stressed areas, detecting variability, and assessing the health and vigor of individual plants. High-resolution imagery aids in identifying specific site-specific characteristics such as topographic variations, soil types, or microclimatic conditions.
- **Multispectral and Hyperspectral Capabilities:** Remote sensing provides access to multispectral and hyperspectral data. Multispectral sensors capture data across multiple bands of the electromagnetic spectrum, including visible and near-infrared regions. Hyperspectral sensors capture data in many narrow and contiguous bands across the electromagnetic spectrum. These capabilities enable the extraction of valuable information about vegetation health, biomass, water stress, nutrient content, and other crop-related parameters (**Moreira *et al.*, 2015**). The spectral signatures obtained from remote sensing data help in identifying stressors, distinguishing between healthy and unhealthy vegetation, and quantifying the severity of stress.
- **Quantitative and Objective Analysis:** Remote sensing data can be processed and analyzed using advanced techniques, including machine learning algorithms and data analytics. These methods provide quantitative and objective analysis, allowing for accurate assessment and characterization of crop stress, variability, and other site-specific characteristics. By quantifying stress levels, farmers can prioritize management interventions, allocate resources efficiently, and implement precise interventions (**Kumar *et al.*, 2022**).

- **Integration with GIS and Decision Support Systems:** Remote sensing data can be integrated with Geographic Information Systems (GIS) and Decision Support Systems (DSS). GIS combines remote sensing data with other spatial layers such as soil maps (AbdelRahman *et al.*, 2016), topographic data, and weather information. This integration helps in spatial analysis, mapping of variability, and generating actionable insights. DSS tools utilize remote sensing data along with historical data, weather forecasts, and agronomic models to provide recommendations and decision support for optimized crop management.

The use of satellite imagery, aerial photography, and drones has revolutionized the acquisition of high-resolution data about crops and fields in precision agriculture (Tsouros *et al.*, 2019). These technologies provide detailed visuals and valuable information that enable farmers to monitor crop health, detect variability, and make informed management decisions. Let's explore each of these technologies and their applications:

- **Satellite Imagery:** Satellite imagery involves capturing images of the Earth's surface using satellites orbiting the planet. This technology provides a broad and comprehensive view of large areas, allowing for the monitoring of crop conditions on a regional or even global scale. Key features of satellite imagery include:
 - **Coverage and Frequency:** Satellites can capture images regularly and consistently over wide geographic areas, providing a historical record of crop growth and changes over time.
 - **Multispectral and Hyperspectral Data:** Satellites can capture data across multiple wavelengths, including visible, near-infrared, and thermal bands. This enables the extraction of valuable information about vegetation health, biomass, water stress, and other crop-related parameters.
 - **Large-Scale Monitoring:** Satellite imagery enables the assessment of crop performance, land use changes, and the identification of areas with specific characteristics or issues such as pest outbreaks or nutrient deficiencies.

Applications of satellite imagery in precision agriculture include:

- **Crop Health Monitoring:** By analysing satellite imagery, farmers can identify areas of stress, nutrient deficiencies, or disease outbreaks across large fields. This information helps in implementing targeted interventions and management strategies.
- **Yield Estimation:** Satellite imagery combined with data analytics allows for the estimation of crop yields on a regional or field-specific level. This information helps with planning harvest operations, storage, and marketing.

- **Land and Crop Mapping:** Satellite imagery aids in mapping fields, identifying crop types, monitoring land use changes, and detecting encroachment or unauthorized activities.
 - **Aerial Photography:** Aerial photography involves capturing images of the Earth's surface using manned aircraft or helicopters equipped with high-resolution cameras. It provides detailed visuals and allows for close-range observations of crops and fields. Key features of aerial photography include:
 - **High Spatial Resolution:** Aerial photographs can capture fine details of crops, such as individual plants or specific areas within a field.
 - **Flexibility and Customizability:** Aerial photography can be conducted at specific times or in response to specific needs, allowing farmers to target areas of interest or concern.

Applications of aerial photography in precision agriculture include:

- **Crop Scouting and Monitoring:** Aerial photographs provide detailed visual information that helps identify crop health issues, pests, diseases, and other localized problems.
- **Field Variability Analysis:** Aerial photographs allow for the identification and analysis of variability within a field, helping farmers to implement site-specific management practices.
- **Precision Irrigation and Fertilization:** Aerial imagery helps in determining the water and nutrient needs of crops, enabling precise application to specific areas within a field.
- **Drones:** Drones, also known as unmanned aerial vehicles (UAVs), have gained significant popularity in precision agriculture due to their versatility, affordability, and accessibility. Drones are equipped with high-resolution cameras, sensors, and sometimes even hyperspectral or thermal imaging capabilities. Key features of drones include:
 - **Flexibility and Mobility:** Drones can be deployed quickly and easily, allowing for rapid data collection and real-time monitoring.
 - **High-Resolution Imagery:** Drones capture images at a very high spatial resolution, enabling detailed analysis of crop health, growth stages, and variability.

Applications of drones in precision agriculture include:

- **Crop Health Assessment:** Drones provide real-time monitoring of crops, allowing

2. Sensor-Based Technologies: Various sensors play a crucial role in real-time data collection for monitoring crop health, soil conditions (Yin *et al.*, 2021), and environmental factors in precision agriculture. These sensors provide valuable insights into the dynamic conditions of crops and their surrounding environment, enabling farmers to make informed decisions and implement site-specific management practices. Let's explore the application of different sensors and their role in data collection:

- **Soil Moisture Sensors:** Soil moisture sensors measure the water content in the soil, allowing farmers to monitor soil moisture levels in real time. These sensors can be installed at different depths within the soil profile. By continuously monitoring soil moisture, farmers can determine the optimal timing and amount of irrigation required. This information helps prevent under or overwatering, ensuring efficient water usage, preventing water stress, and optimizing crop growth.
- **Weather Stations:** Weather stations are equipped with multiple sensors that measure various environmental parameters such as temperature, humidity, wind speed, solar radiation, and rainfall. These sensors provide real-time weather data at the farm level. Weather station data helps farmers monitor weather conditions and make decisions related to irrigation, pest management, and disease control. For example, if the weather station indicates high wind speeds or low humidity, farmers can adjust irrigation schedules or take measures to protect crops from moisture loss.
- **Nutrient Sensors:** Nutrient sensors measure the concentration of essential elements in the soil, such as nitrogen, phosphorus, and potassium. They help assess nutrient levels and ensure that crops receive adequate nutrition. Nutrient sensors can be used to determine nutrient deficiencies or excesses in real time. This information guides farmers in implementing precise fertilizer applications, reducing nutrient runoff, and optimizing nutrient management.
- **Crop Health Sensors:** Crop health sensors, such as chlorophyll meters or spectral sensors, measure various indicators of plant health. These sensors capture reflectance or fluorescence data from the plants, which can be used to estimate chlorophyll content, vegetation indices (e.g., NDVI), or stress-related parameters. Crop health sensors provide insights into the overall vigor and health of plants, helping farmers detect stress conditions (Mahlein *et al.*, 2012), nutrient deficiencies, or disease outbreaks at an early stage. This information guides timely interventions and supports efficient crop management.
- **Environmental Sensors:** Environmental sensors monitor specific environmental conditions that can affect crop growth, such as air temperature, relative humidity, and CO₂ levels. These sensors help farmers understand the microclimate within the crop canopy and make adjustments accordingly. For example, if high temperatures are recorded, farmers may consider implementing shading or cooling techniques to mitigate heat stress. Environmental sensors enable farmers to optimize growing conditions, enhance crop performance, and minimize stress-related issues.

The role of sensor data in monitoring crop health, soil conditions, and environmental factors is multifaceted:

- **Early Detection of Stress:** Sensor data provides real-time information on factors that can stress crops, such as water stress, nutrient deficiencies, or disease infestations. By detecting stress conditions early, farmers can take prompt action to mitigate the impact on crop health and productivity.
 - **Precise Resource Management:** Sensor data enables precise resource management. For instance, soil moisture sensors help optimize irrigation schedules, avoiding both waterlogging and drought conditions. Nutrient sensors guide the application of fertilizers at the right time and in the right quantities, minimizing nutrient wastage and maximizing nutrient uptake by crops.
 - **Decision Support:** Sensor data serves as a valuable input for decision support systems (DSS). DSS tools analyse sensor data along with other relevant data sources (e.g., weather forecasts, crop models) to provide farmers with actionable recommendations for optimized crop management. Sensor data enhances the accuracy and reliability of DSS outputs.
 - **Site-Specific Management:** Sensor data supports site-specific management practices in precision agriculture. By capturing data at specific locations within a field, sensors help identify spatial variability in soil conditions, moisture levels, or nutrient distribution.
3. **Data Management and Analytics:** Data management systems play a crucial role in precision agriculture by enabling the organization, storage, and processing of large volumes of data generated from various sources, such as sensors, satellites, drones, and weather stations. These systems ensure data integrity, accessibility, and reliability, allowing farmers to effectively utilize the vast amount of information for making informed decisions. Let's explore the importance of data management systems and the role of data analytics techniques in deriving insights and making informed decisions:
- **Data Organization and Storage:** In precision agriculture, data management systems provide a structured framework for organizing and storing diverse datasets. They help categorize and store data according to their types, sources, and timestamps. By maintaining data integrity and ensuring consistency, data management systems facilitate efficient data retrieval and analysis. These systems also support data backup and security measures to protect against data loss and unauthorized access.
 - **Data Integration and Interoperability:** Precision agriculture involves the integration of data from multiple sources, such as weather data, soil data, crop data, and management practices. Data management systems enable the integration and interoperability of these diverse datasets, allowing farmers to combine and analyse data from different sources. Integrated data provides a comprehensive view of crop performance, environmental conditions, and management practices, facilitating better decision-making.

- **Data Processing and Analysis:** Data management systems provide the infrastructure and tools for processing and analysing large volumes of data. Data analytics techniques, such as machine learning, predictive modeling, and statistical analysis, are applied to extract meaningful insights and patterns from the data. These techniques enable the identification of relationships between variables, prediction of crop performance, detection of anomalies, and optimization of management practices.
- **Decision Support and Actionable Insights:** Data analytics techniques applied within data management systems generate actionable insights that support decision-making in precision agriculture. Machine learning algorithms, for example, can analyse historical data to predict crop yields, assess disease risks, or optimize fertilizer application rates. These insights enable farmers to make informed decisions regarding irrigation scheduling, pest management, nutrient application, and other critical aspects of crop production.
- **Real-Time Monitoring and Alert Systems:** Data management systems, in combination with data analytics techniques, enable real-time monitoring and alert systems. By continuously analysing incoming data, these systems can detect anomalies, deviations from desired conditions, or critical events. For instance, if a sensor detects abnormal soil moisture levels, an alert can be generated to notify the farmer of potential water stress. Real-time monitoring and alert systems facilitate timely interventions, reducing crop losses and optimizing resource utilization.
- **Continuous Improvement and Learning:** Data management systems support continuous improvement and learning in precision agriculture. By capturing and analysing data over multiple seasons or years, farmers can identify long-term trends, assess the effectiveness of management practices, and refine their strategies. Data analytics techniques can help identify areas for improvement, optimize resource allocation, and guide future decision-making based on historical data.

Data management systems are essential in precision agriculture for organizing, storing, and processing large volumes of data. They enable data integration, interoperability, and analysis, facilitating the application of data analytics techniques to derive insights and make informed decisions (Ouafig *et al.*, 2022). By harnessing the power of data analytics, farmers can optimize crop management practices, enhance resource efficiency, mitigate risks, and ultimately improve productivity and sustainability in modern agriculture.

IV. SECTION 3: APPLICATIONS OF PRECISION AGRICULTURE

1. **Variable Rate Technology (VRT):** Variable rate technology (VRT) is a powerful tool in precision agriculture that allows for the precise application of inputs, such as fertilizers, pesticides, and water, based on the spatial variability of crop needs within a field. VRT utilizes data from various sources, such as soil maps, remote sensing, and yield data, to

create prescription maps that guide the application of inputs at different rates in specific areas of the field.

- Variable Rate Seeding:** Using a precise agricultural technique called variable rate seeding (VRS), the seeding rate can be precisely adjusted to consider changes in terrain, weather, and other variables. VRS can boost crop yields by lowering seed consumption in addition to offering improved options for utilising the changing soil nutrient and water storage capacity characteristics (Munnaf *et al.* 2020). In order to increase agricultural yields and production profitability, VRS links seed quantities to a specific location. This is because seed germination, crop growth, and yield potential may differ in different parts of a field. By adjusting the sowing rate in accordance with the crop's growth environment, variable-rate seeding (VRS) technology can increase agricultural production and resource efficiency. The sensor-based VRS's information gathering is done concurrently with the seeding process, which increases operation effectiveness and lowers operating costs. The secret to sensor-based VRS is adjusting the seeding rate in accordance with the signs that define soil fertility (Du *et al.* 2022). Farmers can manage farm risk more effectively and concentrate their investments in regions with higher return potential by putting VRS practises into practise. In fields with wildly divergent soil organic matter levels or water retention capacities, seeding and planting at a variable rate is especially helpful. A precision farming system is used to measure the characteristics of the soil, the health of the plants, and the yield. The data obtained is used to change the drill's technological parameters, optimise the amount of seeds to be implanted, raise the yield potential, and enhance plant quality (Šarauskis *et al.* 2022). VRS is probably going to be effective in modifying crop nutrition and crop protection techniques.

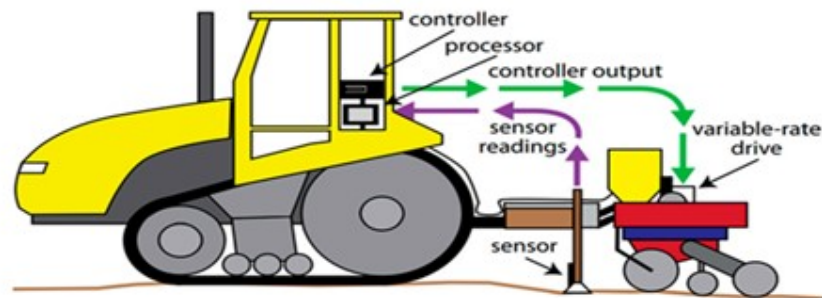


Figure 1: Variable Rate Seeding for Seed Rate Adjustment (Šarauskis *et al.* 2022)

- Variable Rate Irrigation:** Since 2004, commercially available mechanical move irrigation systems (centre pivot or lateral move) with variable rate irrigation (VRI) sprinklers have been available. Although fewer VRI, zone or individual sprinkler systems have been implemented than anticipated, there is still interest in using this technology, particularly given how climate variability, nutrient management regulations, water conservation policies, and a decline in agricultural water supplies make it more difficult to produce irrigated crops (Barke *et al.* 2018; O'Shaughnessy *et al.* 2019). VRI technology have varied degrees of positive and negative effects

depending on the field because each one has a distinct type and level of variability depending on a number of variables, such as the type of crop, the equipment's usable life, the price of water, and the cost to pump the water (Marek *et al.*, 2001; Almas *et al.*, 2003; Pokhrel *et al.* 2018).

Advantages	Disadvantages
Economics	High upfront cost for VRI zone control
Reduce water wastage	Increase payback period
Reduce pumping costs	Inability to finance improvement
Improve water conservation	Benefits are difficult to quantify in financial terms
Environmental	Additive factors increase cost
Gain of land use for dairy or cattle waste disposal	Variable frequency drives must be considered
Reduce leaching below the root zone	ECA field or topography mapping
Reduce runoff and nonpoint source pollution	Within-field or on-sprinkler sensor for precision irrigation, data acquisition from aerial imagery
Agonomic	Additional hardware
Reduce inputs of water, fertilizer, chemicals	Increase labour for troubleshooting and repair
Improve whole-field crop water productivity	Limited alarm system to alert malfunctions
Provide a means to implement precision irrigation	Increase time invested in maintenance
Risk management	Complexity
Address variable or limited water supplies	Step initial learning curve and increase in time investment to implement
Sustain irrigated agriculture	Matching watering rates to variable spatiotemporal crop water needs
	Risk of reducing in yield or crop quality

- Variable Rate Fertilization:** Variable rate fertilisation (VRF) is a precision agriculture technique made possible by high-speed embedded computers, precise Global Positioning System (GPS) receivers, Geographic Information Systems (GIS), remote sensing, yield or soil maps, actuators, and electronic sensors that can measure and even forecast crop properties in real time (Schumann *et al.* 2010). The variable rate management of fertilizers is directly influenced by the variability of the soil and crop. Real-time automatic control equipment is available to adjust the pace at which liquids or solids are applied, allowing for the management of application quality. Such a system is capable of real-time operation with the help of a geo-referenced application map and GPS. The segmentation of a field into management zones (MZ), or areas of uniform conditions within a field, has been the starting point for specific site nutrient management (SSNM), but there are various levels of implementation (Reyes *et al.* 2015).

- **Variable Rate Spray:** Variable rate spray is one of the important ways for precision applying pesticide. In the past decade, great progress has been made in the technology and applications of variable spray (**Baijing *et al.* 2015**). The typical components of a variable-rate spray system are a detecting unit, a data processing algorithm, and a variable control unit. To be more precise, the detecting unit makes use of cutting-edge sensors to identify target parameters, the severity of plant diseases and insect pests, as well as the weather in the target growing region. The data processing algorithm, which is stored in the computer, first translates the detection data from the detection unit into an anticipated flow rate or other operating parameters of the sprayer, and then it transforms the intended flow rate or air volume into the control signal of the appropriate actuator. Based on the control signal, the variable control unit executes the variable-flow-rate spray output, the variable concentration, the variable air supply, and the variable nozzle position and type (**Wei *et al.* 2022**).

Let's explore how VRT enables precise input application and the benefits it offers in optimizing resource utilization, reducing input costs, and minimizing environmental impact:

- **Precise Input Application:** VRT considers the spatial variability of crop needs within a field. By utilizing detailed data about soil properties, nutrient levels, moisture content, and crop health, VRT generates prescription maps that specify the optimal input rates for different areas. These prescription maps can be used to control machinery, such as variable rate spreaders or sprayers, which adjust the application rates in real time as the equipment moves across the field. This precision ensures that inputs are applied precisely where they are needed, matching the requirements of specific areas and maximizing their effectiveness.
- **Optimized Resource Utilization:** One of the key benefits of VRT is the optimization of resource utilization. By applying inputs at variable rates according to crop needs, farmers can ensure that resources are allocated efficiently. Instead of uniformly applying inputs across the entire field, VRT allows for targeted application, supplying nutrients, water, or pesticides where they are most needed. This targeted approach minimizes waste, reduces the risk of over-application or under-application, and maximizes the utilization of available resources.
- **Reduced Input Costs:** VRT offers significant cost-saving advantages by enabling farmers to apply inputs in a more targeted and efficient manner. With VRT, farmers can avoid unnecessary applications in areas that do not require inputs, thereby reducing input costs. By matching input rates to specific crop needs, farmers can optimize the use of expensive inputs, such as fertilizers or pesticides, resulting in cost savings over time. VRT also helps prevent over-application, which not only saves costs but also mitigates the risk of environmental contamination.
- **Minimized Environmental Impact:** VRT plays a crucial role in minimizing the environmental impact of agricultural practices. By applying inputs at variable rates based on crop needs, VRT helps reduce the risk of nutrient runoff and

leaching, as well as the potential for groundwater contamination. By targeting inputs to specific areas, farmers can avoid applying excessive amounts of fertilizers or pesticides, reducing their environmental footprint. VRT also contributes to the overall sustainability of farming practices by minimizing the use of inputs and promoting precision in resource management.

- **Improved Crop Performance and Yield:** By precisely matching input application to crop needs, VRT helps optimize crop performance and yield. The spatial variability within a field can significantly impact crop growth and productivity. VRT allows for site-specific management, ensuring that each area receives the appropriate amount of nutrients, water, or pest control measures. This tailored approach supports optimal crop growth, minimizes stress conditions, and maximizes yield potential.

2. Site-Specific Crop Management: Site-specific crop management is a key component of precision agriculture that involves tailoring management practices to specific areas within a field based on their unique characteristics and needs (**Kitchen et al. 2002**). Precision agriculture technologies, such as GPS, GIS, remote sensing, and data analytics, enable farmers to gather and analyse data at a fine-scale resolution, allowing for customised strategies and targeted interventions (**Tantalaki et al. 2019**). Let's explore the concept of site-specific management and examples of site-specific practices:

- **Customized Strategies:** Site-specific management recognizes that different spots within a field which having different soil properties, nutrient levels, moisture content, and pest pressures. Precision agriculture tools enable farmers to identify and map these variations, creating prescription maps that guide management practices in a customized manner (**Carrascosa et al. 2015**) Rather than employing a uniform approach across the entire field, customized strategies can be implemented to optimize crop performance and resource utilization for each specific area.
- **Variable Planting Density:** Site-specific management allows farmers to adjust planting density based on soil conditions, topography, and historical performance. By using GPS and GIS technologies, farmers can generate planting maps that recommend varying seed populations for different areas within a field (**Lee et al., 2010**). For instance, areas with higher soil fertility or more favourable moisture retention may warrant higher planting densities, while areas with poorer soil quality or drainage issues may require lower planting densities. Variable planting density optimizes crop establishment, promotes uniform growth, and maximizes yield potential across the field.
- **Irrigation Scheduling:** Precision agriculture techniques enable site-specific irrigation scheduling, ensuring that water is applied efficiently based on the specific moisture needs of different areas within a field (**Mc Cready et al., 2009**). Soil moisture sensors, weather data, and evapotranspiration models are used to monitor soil moisture levels and calculate crop water requirements. By integrating this information with spatial data, farmers can create irrigation prescription maps that guide the timing and amount of water application (**Jimenez et al., 2021**). This approach minimizes

water wastage, reduces the risk of over-irrigation or under-irrigation, and maintains optimal soil moisture levels for crop growth.

- **Targeted Pest Control:** Site-specific management allows for targeted pest control measures based on pest pressure and crop vulnerability in specific areas of a field (**Mogili and Deepak, 2018**). By using remote sensing technologies, such as satellite imagery or drone imagery, farmers can detect and monitor areas with higher pest activity or disease prevalence. This information, combined with historical data and pest scouting reports, enables farmers to implement targeted interventions (**Wohleb et al., 2021**), such as localized pesticide application or specific pest monitoring in high-risk areas. Targeted pest control reduces pesticide usage, minimizes environmental impact, and ensures effective pest management while minimizing costs.
- **Fertilizer Application (Cahn et al., 1994; Khosla et al., 2002):** Precision agriculture facilitates site-specific fertilizer application, optimizing nutrient inputs based on soil fertility variations within a field. Soil sampling and analysis, coupled with remote sensing data or crop sensors, help farmers identify areas with varying nutrient levels. Prescription maps are then created, indicating the appropriate rates and locations for fertilizer application. By precisely targeting fertilizer inputs, farmers can avoid over-application in areas with sufficient nutrients and provide adequate supplementation in areas with nutrient deficiencies. This approach improves nutrient use efficiency, reduces environmental impact, and promotes balanced crop nutrition.

Site-specific crop management, enabled by precision agriculture, offers numerous benefits, including optimized resource utilization, improved crop performance, reduced input costs, and enhanced sustainability. By tailoring management practices to specific areas within a field, farmers can maximize the productivity and profitability of their operations while minimizing environmental impact. Site-specific practices, such as variable planting density, customized irrigation scheduling, targeted pest control, and precise fertilizer application, exemplify the implementation of site-specific management in precision agriculture.

3. **Decision Support Systems (DSS):** Decision support systems (DSS) play a crucial role in precision agriculture by providing real-time recommendations and decision support to farmers based on data inputs and algorithms. DSS leverage various data sources, including field data, weather data, sensor data, and historical information, to generate actionable insights and support informed decision-making (**Christie et al., 2020**).
 - **Components of DSS:** Every DSS is a combination of two or more designs and does not cleanly fall into any one category. The Database Management Subsystem, Knowledge-based Management Subsystem, User Interface Subsystem, and the User are the four subsystems that make up the most general architecture of DSS.

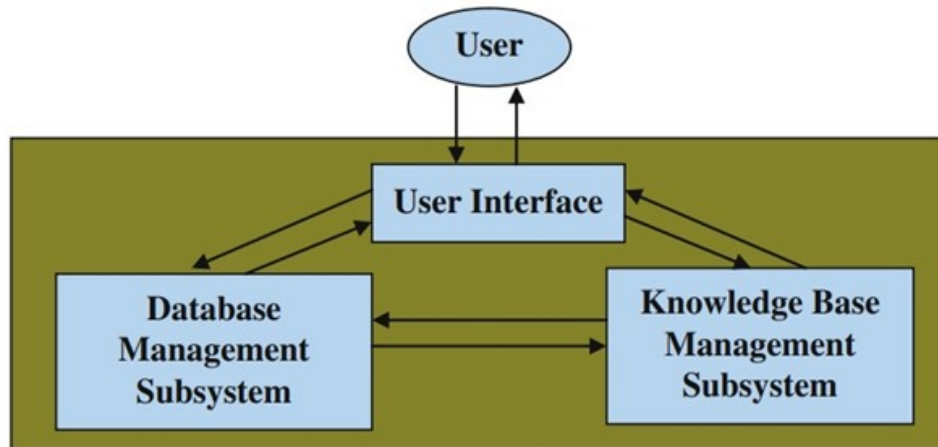


Figure 2 : Components of decision support system (Mir and Quadri, 2009)

Let's discuss the role of DSS in optimizing crop management, mitigating risks, and maximizing yields:

- **Real-Time Recommendations:** DSS analyze real-time data inputs to provide farmers with timely recommendations and actionable insights. By integrating data from various sources, such as weather forecasts, soil moisture sensors, and crop models, DSS can provide recommendations for irrigation scheduling, fertilizer application, pest management, and disease control (Kukar *et al.*, 2019). These recommendations take into account current field conditions and help farmers make informed decisions in response to dynamic changes in the environment.
- **Optimal Resource Allocation:** DSS help optimize resource allocation in crop management. By analyzing data on soil conditions, crop growth stage, and nutrient requirements, DSS can generate prescriptions for variable rate application of inputs, such as fertilizers or water (Mc Cown *et al.*, 2001). This ensures that resources are allocated efficiently, matching the specific needs of different areas within a field. By optimizing resource allocation, DSS enable farmers to minimize waste, reduce input costs, and maximize resource utilization, leading to improved efficiency and profitability.
- **Risk Mitigation:** DSS assist in mitigating risks associated with crop production. By considering various risk factors, such as weather conditions, pest and disease outbreaks, and market trends, DSS can provide early warnings and recommend preventive or corrective measures (Yazdani *et al.*, 2017). For example, if a DSS detects high humidity levels and predicts a high risk of fungal disease, it can recommend appropriate fungicide application or changes in irrigation practices to minimize the risk. DSS help farmers anticipate and manage risks proactively, reducing the likelihood of crop losses and improving resilience.

- **Yield Optimization:** DSS contribute to yield optimization by providing insights into crop growth and performance (**Hansen, 2005**). By analyzing data on historical yields, soil characteristics, weather patterns, and management practices, DSS can generate predictive models that estimate future crop yields. Based on these models, DSS can recommend specific management strategies to optimize yields. For instance, if a DSS predicts a yield gap, it can suggest adjustments to irrigation, nutrient application, or planting density to bridge the gap and maximize yields.
- **Data Integration and Visualization:** DSS integrate and visualize data from various **sources**, enabling farmers to gain a holistic view of their farming operations (**Zhai et al., 2020**). By presenting data in a user-friendly format, such as maps, charts, or dashboards, DSS make complex information more accessible and comprehensible (**Oliver et al., 2012**). This empowers farmers to monitor and analyze data effectively, identify patterns or anomalies, and make data-driven decisions. DSS enhance data-driven decision-making by transforming raw data into meaningful insights that farmers can easily interpret and act upon.
- **Continuous Improvement and Learning:** DSS facilitate continuous improvement and learning in precision agriculture. By capturing and analyzing data over multiple seasons or years, DSS help farmers identify trends, evaluate the effectiveness of management practices, and refine their strategies (**Lindblom et al., 2017**). The feedback loop between data collection, analysis, and decision-making enables farmers to continuously learn and adapt their approaches, leading to improved performance and increased sustainability over time.

DSS provide real-time recommendations and decision support to farmers by analysing data inputs and algorithms. They optimize crop management by allocating resources efficiently, mitigating risks, and maximizing yields. DSS empower farmers with timely insights, enhance data-driven decision-making, and foster continuous improvement in precision agriculture.

V. CONCLUSION

Precision agriculture represents a significant advancement in modern farming practices, harnessing advanced technologies, data analytics, and remote sensing to optimize crop management and resource utilization. The integration of these innovative tools and techniques has the potential to revolutionize agriculture, making it more efficient, sustainable, and productive. Precision agriculture enables farmers to make informed decisions based on real-time data and site-specific information, allowing for targeted interventions at the field level. Through the use of sensors, drones, satellite imagery, and GPS technology, farmers can monitor crop health, soil conditions, and water availability with unprecedented accuracy. This data-driven approach facilitates precise application of inputs such as fertilizers, water, and pesticides, optimizing their use and minimizing wastage. The application of data analytics in precision agriculture enables farmers to analyse vast amounts of information and gain valuable insights. Machine learning algorithms can process data on weather patterns, historical crop performance, and pest and disease occurrences to generate predictive models

and recommend optimal management strategies. This empowers farmers to anticipate challenges, mitigate risks, and make proactive decisions, ultimately enhancing productivity and profitability. Remote sensing technologies, including satellite imagery and aerial surveys, provide valuable information on crop health, nutrient deficiencies, and pest infestations over large areas. This enables farmers to identify spatial variations within their fields and implement site-specific management practices. By tailoring interventions to specific crop needs, farmers can optimize resource allocation, minimize environmental impact, and reduce input costs. The adoption of precision agriculture is not without challenges. It requires initial investment in technology, infrastructure, and data management systems. Additionally, the digital divide and limited access to technology in rural areas pose barriers to widespread adoption. However, as technology becomes more affordable and accessible, and as governments and organizations provide support and training, these challenges can be overcome.

In conclusion, precision agriculture has the potential to transform the agricultural landscape, promoting sustainable and efficient farming practices. By harnessing advanced technologies, data analytics, and remote sensing, farmers can achieve site-specific crop management, optimize resource utilization, and enhance productivity. As the world faces increasing food demand and resource constraints, precision agriculture offers a promising solution for meeting these challenges while minimizing environmental impact. It is imperative that farmers, researchers, policymakers, and technology providers continue to collaborate and invest in precision agriculture to unlock its full potential and secure a more sustainable and resilient future for global agriculture.

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