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Advancements in Precision Farming: Enhancing Agricultural Sustainability through Technology – A Review

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ABSTRACT

Precision Farming (PF), often referred to as Precision Agriculture (PA) or Site-Specific Land Management (SSLM), is a result of significant knowledge in crop and soil management and advances in agricultural technology. Using a variety of methods, including as GPS, GIS, Remote Sensing, Yield Monitoring, Variable Rate Application, Yield Mapping, and the creation of Site-

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Specific Management Zones (SSMZ), this novel strategy aims to increase soil and crop productivity while reducing effort and expenses. SSMZ is essential for efficient PF because it enhances soil function management by accurately evaluating crop and soil attributes. Beyond conventional techniques, enhanced land management depends on accurate mapping of crop characteristics and soil variability. For effective soil analysis, grid soil sampling which separates fields into square cells is crucial. To save expenses and enhance management zone demarcation, recent research has also used sensors to assess soil characteristics. SSMZ maps, which give farmers important information for improving their operations, can be produced from a variety of sources, including topographic, yield, soil, and nutrient maps, or from specific data layers. minimising expenses, raising farm profitability, and minimising environmental hazards like desertification all depend on improving soil and agricultural productivity. More sustainable agriculture results from precision farming, which increases agricultural yields while using less resources. By supplying reasonably priced, superior produce, it benefits society by lowering environmental impact, lowering farmer expenses, and ensuring food security. The long-term viability of farming systems is supported by increased yields and reduced ecological impacts brought about by sustainable agriculture methods and better soil health.

Keywords: Precision; site-specific; GPS; variable rates; yield mapping; grid.

1. INTRODUCTION

Since the beginning of human civilisation, crop cultivation has been a vital component, developing in parallel with improvements in soil and crop management practices. Early agricultural methods, such as crop rotation, irrigation, shifting cultivation, and manure application, were initially centred on food collecting (Haug, 2000). As knowledge of efficient crop and soil management techniques increased over time, site-specific strategies that consider climate, soil conditions, fertilisation, and pest control were developed, ultimately allowing farmers to improve their operations and boost revenue (Lal, 2009).

However, traditional farming frequently ignores the variation in soil characteristics and environmental conditions, treating fields as homogeneous zones. On the other hand, fields are divided into management zones by Precision Farming (PF), often referred to as Site-Specific Land Management (SSLM), according to factors including soil pH, nutrient content, and yield rates (Mulla, 2013). This approach enables focused management choices and incorporates cutting-edge technologies like remote sensing, GPS, and GIS to apply variable input rates that are customised to meet the unique requirements of each zone (Zhang & Wang, 2018).

In order to meet the food needs of the world's expanding population, new agricultural technology must be used, particularly when urbanisation and the loss of arable land present more difficulties (FAO, 2017). With the use of technologies like wireless sensors, farm management software, and data analytics, precision farming has the potential to boost agricultural productivity by 70% (Jarvis et al., 2010). Precision farming is essential to the agricultural industry because it minimises waste and its negative effects on the environment by optimising the use of resources like water, fertiliser, and pesticides. Farmers may monitor and manage their fields more precisely by utilising technologies like GPS, sensors, and data analytics, which will enhance agricultural yields and save money. This strategy minimises ecological harm and encourages resource efficiency, which further supports sustainable activities. In the end, precision farming contributes to environmental health and food security.

Geostatistics to examine spatial variability across fields and remote sensing technologies like satellites and unmanned aerial vehicles (UAVs) are two essential elements of precision farming (Zhao et al., 2021). By supplying fertilisers like nitrogen, phosphorous, and potassium based on site-specific requirements rather than consistently throughout fields, these technologies increase fertilizer efficiency, improving yields and lessening their negative effects on the environment (Schroeder et al., 2015). Furthermore, by doing Site-Specific Land Management (SSLM) optimizes farming operations by customizing interventions to the distinct features of various locations within a field using cutting-edge technology like GPS, GIS, and remote sensing. Farmers may improve sustainability and productivity by making well-informed decisions based on ongoing field and soil health monitoring. To precisely manage resources and minimize waste, tools such as soil sensors are essential for delivering real-time data on moisture levels, nutrient content, and other important parameters. This focused strategy guarantees that every farm area gets the proper attention for optimal productivity and yield. Variable Rate Application (VRA), which enables the precise management of inputs based on real-time sensor data, precision farming practices lower the environmental concerns related to fertiliser runoff (Rohit et al*.,* 2019). Farmers can optimise agricultural techniques for increased yields and sustainability by integrating technologies like Differential Global Positioning Systems (DGPS) (Bongiovanni & Lowenberg-Deboer, 2004).

There has been a paradigm shift due to recent developments in remote sensing technologies, which offer high-resolution imagery and real-time information. These tools provide unmatched crop health insights, enabling prompt and accurate actions. Farmers may now allocate resources more intelligently because to the development of proximal soil sensing systems, which offer detailed information on soil characteristics. The sophistication of global navigation satellite systems (GNSS) has improved the precision of location-based data that is essential for precision farming operations.

2. PRECISSION FARMING

Precision farming, also known as precision agriculture, is a contemporary management system that uses data and cutting-edge technologies to apply site-specific tactics that enhance sustainability, environmental protection, and economic efficiency (Mulla, 2013; Zhang et al., 2018). To create customised management strategies that maximise yields while preserving resources, this method evaluates soil and crop variability across fields (Bongiovanni & Lowenberg-Deboer, 2004; Zhao et al., 2021). To minimise waste and boost profits, the fundamental ideas of Site-Specific Crop Management (SSCM) and Site-Specific Land Management (SSLM) centre on maximising local environmental conditions and resource utilisation, including water, fertilisers, and pest management (Lal, 2009; Whelan et al., 2016). Using cutting-edge instruments and data-driven choices to improve sustainability, SSLM is a major breakthrough in contemporary soil and crop management practices (Schroeder et al., 2015).

3. BENEFITS OF PRECISION FARMING TECHNOLOGY

Numerous advantages of precision farming include increased agricultural productivity, lower operating costs, and reduced environmental concerns. Among these advantages are:

1. Plant and Soil Monitoring: Detailed monitoring of soil and plant data is made possible by precision farming technology including UAVs (unmanned aerial vehicles), remote sensing, and soil sensors. These instruments track crop health and growth and evaluate soil properties such as nutrient content, pH, and moisture levels (Zhao et al*.,* 2021; Zhang et al., 2018). With this knowledge, growers can more accurately apply inputs, guaranteeing that crops get the nutrition and attention they need to flourish to their full potential.

2. Real-Time Data Access: Farmers may make quick, data-driven decisions by using remote sensing equipment and real-time data collecting to get ongoing updates on field conditions. This reduces resource use, boosts yields, and enhances farm management effectiveness (Jarvis et al., 2010; Mulla, 2013). When problems like pest infestations or water stress are identified, real-time monitoring also enables prompt response (Rohit et al*.,* 2019).

3. Time and Cost Efficiency: Precision farming eliminates the need for extra water, fertiliser, and pesticides. Operational expenses are greatly decreased and the environmental impact is minimised by applying inputs just where and when they are required (Schroeder et al., 2015; Lowenberg-Deboer & Swinton, 2014). Variable Rate Technology (VRT) ensures optimal application by further improving input efficiency.

4. Improved Information Access: Farmers can make informed decisions thanks to the comprehensive insights that precision farming offers. To improve crop performance, pest control, and fertiliser management, tools such as Agrivi and Trimble Ag Software combine sensor data, satellite imaging, and weather forecasts to produce actionable information (Bongiovanni & Lowenberg-Deboer, 2004; Zhao et al., 2021). Farmers are able to make fast, data-driven decisions that optimise productivity through the integration of these instruments.

5. Integrated Management Software: From crop planning and soil analysis to input management and yield evaluation, integrated farm management platforms such as Agrivi and Ag Leader facilitate the smooth tracking and administration of farm operations. By centralising farm data, offering real-time insights, lowering the possibility of human mistake, and improving operational efficiency, these platforms increase production and efficiency (Zhang et al*.,* 2018; Whelan et al., 2016).

4. TECHNIQUES OF PRECISION FARMING EMPLOYED IN VARIOUS GEOGRAPHIC AREAS

Crop types, climate, and geographic location all influence precision farming methods. Here are few instances:

North America (USA, Canada): To keep an eye on agricultural growth, water use, and soil health, these areas frequently employ cutting-edge technologies like GPS, drones, and sensors. In irrigation and fertilisation systems, variable rate technology (VRT) is frequently used to make adjustments based on real-time data.

Europe (France, Germany, Netherlands): Precision farming concentrates on managing soil health, pests, and nutrients in nations that practise intensive crop cultivation. Drone technologies and satellite photography are frequently utilised to track crop health and implement focused interventions.

Asia (China, India): The use of precision farming in the production of wheat and rice is growing. Systems that assist farmers apply water and fertiliser more effectively, such as mobile apps and soil moisture sensors, are growing in popularity in India. China uses satellite technology and sophisticated mechanisation to manage pests and anticipate crop yields.

Africa (South Africa, Kenya): Precision farming is primarily about using weather-based apps and increasing irrigation efficiency in areas with limited access to technology. Smallholder farmers in Kenya employ GPS technology and smartphone applications to access real-time weather and soil data.

Australia: Because of its unpredictable environment, Australia makes substantial use of precision farming methods to manage water resources, especially in arid regions. Satellite-based technologies and variable rate irrigation are frequently utilised to maximize crop yield.

5. PRECISION FARMING'S ECONOMIC VIABILITY

Although precision farming technology can have a high initial cost, their cost-effectiveness varies depending on a number of factors:

1. Return on Investment (ROI): Precision farming lowers operating costs by reducing inputs including labour, water, fertiliser, and pesticides. The return on investment can be substantial over time, particularly for large-scale farms.

2. Scalability: As more technology is implemented, the cost per acre tends to go down for larger farms. Although smaller-scale farmers may have to pay more per acre up front, they may still reap long-term rewards from using less water, fertiliser, and other resources.

3. Labour Efficiency: By eliminating the need for physical labour, automation technologies such as drone-assisted crop monitoring and robotic harvesters further lower operating expenses.

4. Environmental Sustainability: Precision farming is economical both monetarily and environmentally due to the effectiveness of inputs like fertiliser and water. Farmers can also avoid penalties for excessive resource use or expenses associated with environmental harm by reducing waste and runoff.

Agricultural Sensor Efficiency: They provide real-time data to enhance decision-making, sensors are essential to precision farming. The kind, use, and location of sensors all affect their efficiency:

1. Soil Sensors: By measuring the moisture and nutrient content of the soil, soil sensors enable farmers to make informed decisions regarding fertilisation and irrigation. Soil moisture sensors have been shown to maximise water use by permitting watering only when required, enhancing crop output and water conservation (Nouri et al., 2020).

2. Crop Health Sensors: Multispectral and hyperspectral sensors are examples of crop health sensors that track the health of plants by identifying early indicators of pest infestations, illnesses, and nutritional deficits (Zhang & Kovacs, 2012). Farmers may pinpoint problem areas in their fields and apply treatments more precisely by using drones fitted with these sensors, which lowers the need for fertiliser and pesticides (Bausch & Neale, 2015).

3. Weather Sensors: Weather sensors offer local weather information, which is crucial for scheduling plantings and irrigations. For example, farmers can modify their farming methods in response to climate change by combining weather stations with remote sensing technologies (Banerjee et al., 2020).

4. Efficiency of Sensors: The precision of the data gathered and the way it is incorporated into decision-making processes determine how effective agricultural sensors are. According to a study by McBratney et al. (2014), field-level decision-making is greatly enhanced when sensor data is integrated with GPS and satellite information. However, environmental factors, maintenance requirements, and calibration problems can all have an impact on sensor performance (Hunt et al., 2019).

6. THE CYCLICAL PROCESS OF PRECISION FARMING

Precision farming is an adaptive and cyclical process that begins with site-specific management and data collecting, then moves on to analysis and the implementation of customised solutions. Decisions on variable rate fertiliser, water, and pest management treatments are guided by soil analysis conducted at the start of the season (Schroeder et al., 2015; Whelan et al., 2016). Following that, yield monitoring systems give input on crop performance, which helps guide management choices and modifications over the growing season. In order to maximise resource utilisation and boost crop yields, precision farming technologies and real-time data make sure that inputs are administered effectively throughout the cycle (Jarvis et al., 2010; Lowenberg-Deboer & Swinton, 2014).

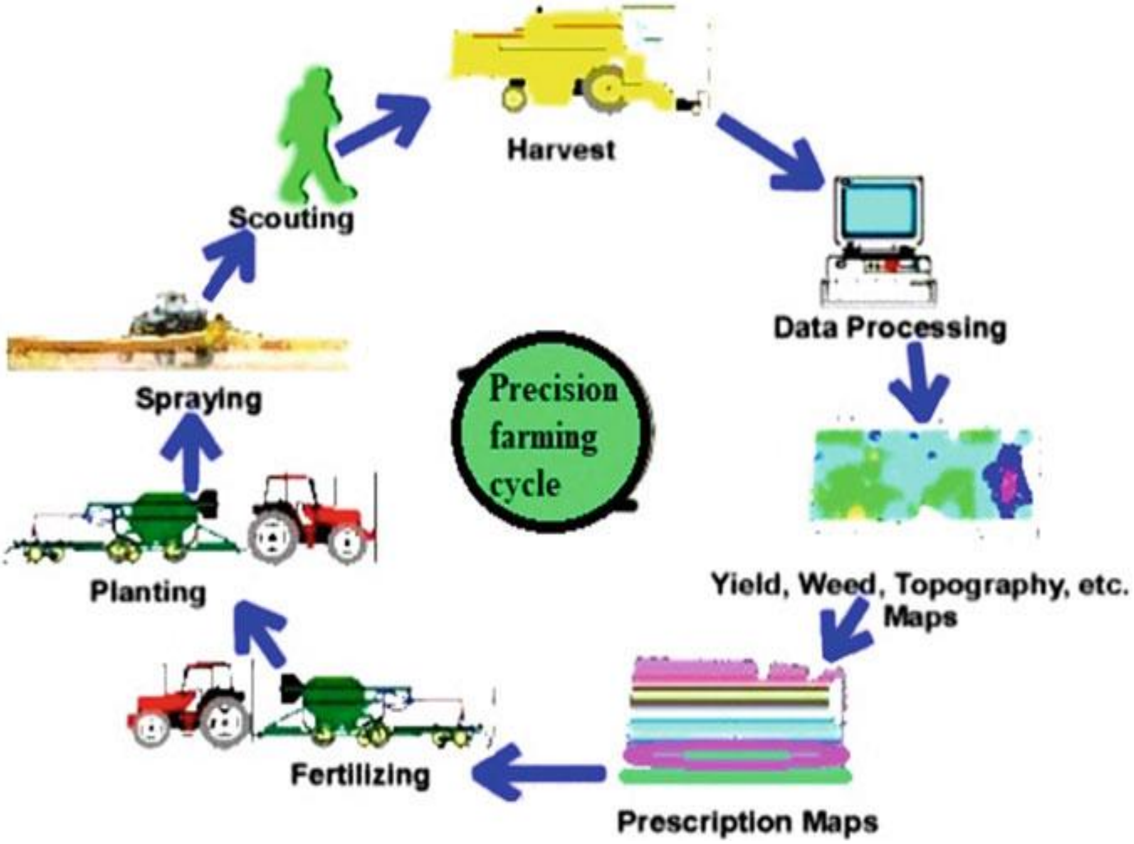


Fig. 1. Precision farming cycle (Goswami et al. 2012)

7. GLOBAL POSITIONING SYSTEMS (GPS) IN PRECISION AGRICULTURE

Precision agriculture relies heavily on Global Positioning Systems (GPS), which provide precise location information to improve a range of farming techniques. With the use of GPS technology, farmers can increase productivity, optimise resources, and make well-informed decisions. The following are some important uses of GPS in precision farming:

1. Mapping Soil and Crop Variability: In their fields, farmers can use GPS to make precise maps that show geographic differences in crop health, nutrient levels, and soil quality (Mulla, 2013). By optimising input utilisation and increasing yield potential, these maps allow for precision management strategies catered to various soil and crop conditions (Bongiovanni & Lowenberg-Deboer, 2004).

2. Farm Management Planning: Farmers can make strategic choices about crop rotation, resource allocation, and operational efficiency by integrating GPS data into farm management systems (Jarvis et al*.,* 2010). According to Schroeder et al. (2015), precise field mapping facilitates the effective use of resources and aids in the development of long-term management plans based on current data.

3. Soil Sampling Design: By giving farmers exact position information, GPS improves soil sampling by enabling them to collect targeted soil samples that increase the precision of nutrient requirements and soil health evaluations (Zhang & Wang, 2018). This minimises waste and the impact on the environment by guaranteeing that fertilisers and amendments are only applied where necessary (Rohit et al., 2019).

4. Machinery Navigation: GPS systems provide highly accurate guidance for farm equipment, guaranteeing the best possible field operations for tasks like planting, fertilising, and harvesting. This improves operational efficiency, minimises overlap, and uses less gasoline (Bongiovanni & Lowenberg-Deboer, 2004). Precision planting and application are becoming more and more common with GPS-driven automated steering systems (Whelan et al., 2016).

5. Crop Monitoring: Farmers can use GPS to locate places that need attention, such weeds, disease outbreaks, or soggy spots. By enhancing crop monitoring and intervention, this focused strategy lessens the need for broad-spectrum therapies while enhancing crop health (Schroeder et al., 2015).

6. Variable Rate Technology (VRT): This technology, which is made possible by GPS, permits the delivery of insecticides, fertilisers, and other inputs at different rates throughout a field. Farmers can optimise input utilisation, lower input costs, and improve crop performance by applying inputs based on real-time field data (Mulla, 2013; Zhao et al., 2021).

7. Application and Yield Mapping: GPS makes it easier to create accurate maps for tracking crop yields and applying inputs. This enables farmers to monitor success in various fields' zones and modify future methods in light of past data (Zhao et al*.,* 2021). Farmers can identify high- and low-yielding areas and make more informed decisions for upcoming cropping cycles with the aid of yield mapping in particular (Rohit et al., 2019).

8. ADVANTAGES OF GPS IN VARIOUS CONDITIONS

The capacity of GPS technology to work well in a variety of weather conditions, including rain, fog, dust, and darkness, is one of its main benefits. For large-scale farming operations that must remain efficient all year round, this guarantees constant productivity regardless of the time of day or weather conditions (Whelan et al., 2016).

Development of GPS Tools:

In order to assist farmers and agribusinesses in becoming more productive and efficient, manufacturers are constantly creating GPS-based equipment. A variety of applications are supported by these tools, such as:

1. Field Boundary Mapping: By precisely defining field boundaries using GPS, better resource management and the implementation of farm-specific techniques like crop rotation and irrigation are made possible (Schroeder et al*.,* 2015).

2. Irrigation and Drainage Management: Farmers can guarantee that water is used effectively, minimising water waste and increasing crop yields, by optimising irrigation and drainage systems with the help of GPS data (Zhang & Wang, 2018).

3. Crop Surveillance: By identifying regions that need attention, such as those impacted by pests or nutrient shortages, GPS-based systems assist farmers in keeping an eye on the health of their crops. This method saves time and money by reducing the requirement for blanket treatments (Zhao et al., 2021).

Improved Accuracy with DGPS:

Differential Global Positioning Systems (DGPS) are used to further improve GPS accuracy. By instantly fixing GPS faults, DGPS offers extremely accurate location data, which makes it more appropriate for use in agricultural applications. DGPS operates using a two-component system:

1. Fixed Reference Points: According to Bongiovanni and Lowenberg-Deboer (2004), a stationary reference receiver at a known location determines the difference between its real position and the position calculated by GPS. Mobile receivers around the field receive the error adjustments from this reference receiver.
2. Error Correction: Accurate position adjustments are made possible by the real-time corrections sent to the mobile receivers. This greatly increases GPS systems' positioning precision, allowing for more accurate operations for tasks like fertilising, spraying, and planting (Rohit et al., 2019).

For agricultural applications, DGPS corrections provide increased precision and dependability and can be provided using satellite-based or tower-based systems (Mulla, 2013). This improved precision is essential for making sure that equipment and inputs are used appropriately, which lowers waste and its negative effects on the environment.

9. REMOTE SENSING IN PRECISION AGRICULTURE

The process of gathering data remotely, without making direct physical contact, then analysing and interpreting that data is known as remote sensing (RS). In order to collect data essential for managing crops and soil, remote sensing in precision agriculture measures electromagnetic energy at different wavelengths, such as visible light and other satellite signals. In agricultural decision-making, remote sensing technologies are essential because they enable farmers to evaluate soil conditions, track crop health, and maximise resource utilisation. Colour and colour infrared aerial photography, videography, and satellite-based sensors are important instruments in remote sensing that assist farmers in gathering vital information on crop and field conditions. All things considered, remote sensing technologies offer insightful information that improves and informs agricultural management techniques.

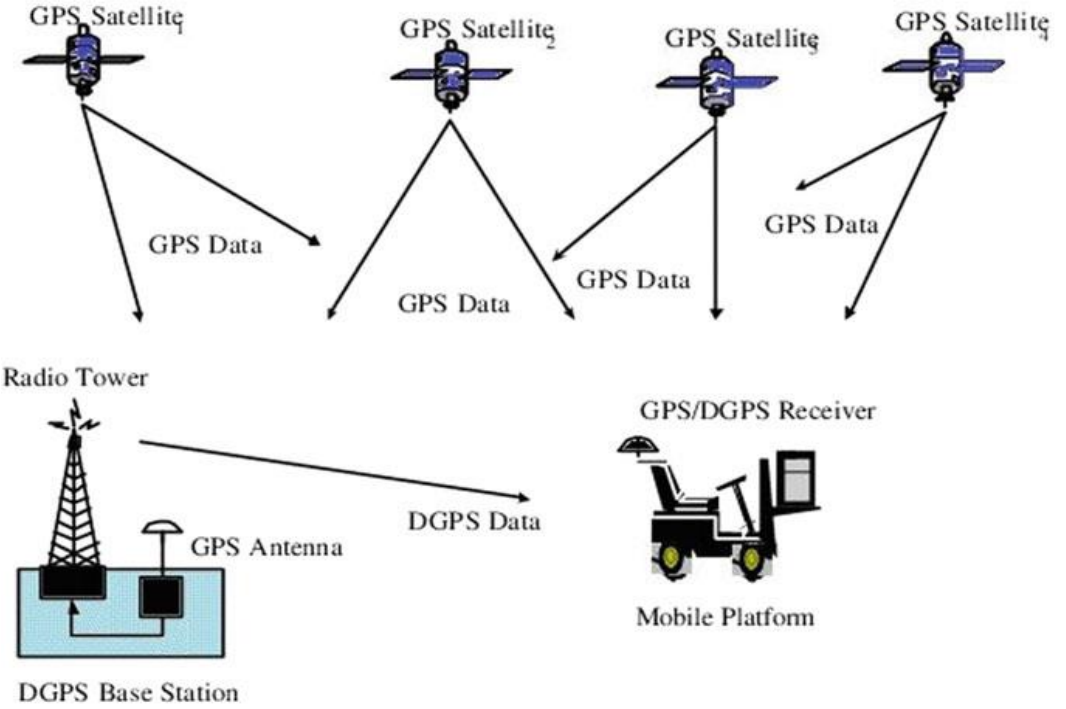


Fig. 2. DGPS tower-based and satellite-based systems (modified after Soares et al. 2004)

Satellite and Aerial Photography Remote Sensing in Precision Farming: Even in the absence of yield monitoring technologies, remote sensing photos taken during the growing season are essential for evaluating crop health (Mulla, 2013). Farmers can monitor changes in crop health, soil moisture, and pest infestations thanks to these photos, which offer a detailed view of field conditions. Crop yield and the normalised difference vegetation index (NDVI) have a significant 95% connection, which makes it possible to predict yield using NDVI measurements (Zhang et al., 2018).

Hyperspectral remote sensing gathers data across a wide spectral range (about 10 nm), it is very useful in agriculture. Conventional visible light photography is unable to identify the detailed information that hyperspectral sensors record about crop and soil properties. Hyperspectral remote sensing has the following uses:

1.Mapping Bare Soil for Management Zones: Farmers can establish management zones based on crop and soil health by using hyperspectral data to pinpoint areas of bare soil or failing crops (Bongiovanni & Lowenberg-Deboer, 2004).
2. Weed Distribution Detection: Farmers may map and track weed populations in the field using remote sensing technologies, which makes weed eradication more effective and focused (Mulla, 2013).
3. Monitoring Nitrogen Stress: By examining the amount of chlorophyll in plants, hyperspectral sensors may identify nitrogen deficits. Applying accurate nitrogen fertilisers is crucial for increasing crop output and growth (Bongiovanni & Lowenberg-Deboer, 2004).
4. Monitoring Plant Diseases and Pests: Early disease and pest infestation detection relies heavily on remote sensing. Farmers can detect stressed areas before they are apparent to the human eye by examining the spectral signatures of crops, which allows for early intervention (Zhao et al., 2021).
5. Creating production Maps: To monitor changes in crop production across the field, remote sensing is utilised. Farmers can produce comprehensive yield maps that guide future crop management choices by fusing satellite imagery with historical yield data (Rohit et al., 2019).

During the growth season, hyperspectral imaging is crucial for creating management strategies, especially for maximising the use of nitrogen fertiliser. Farmers may apply the right quantity of nitrogen based on real-time crop health data by monitoring geographical fluctuations in chlorophyll content. This reduces waste and maximises crop yields (Rohit et al*.,* 2019).

Unmanned Aerial Vehicles (UAVs) in Precision Farming: Unmanned Aerial Vehicles (UAVs), commonly referred to as Unmanned Aircraft Systems (UAS), have overcome some of the drawbacks of more conventional remote sensing techniques like satellites and aerial photography to become an essential tool in precision agriculture. A more adaptable and high-resolution option is provided by UAVs, as satellites may have trouble with timely picture acquisition, spatial resolution, and update frequency. Farmers may obtain more accurate and timely data thanks to UAVs' ability to capture comprehensive, real-time imagery for a variety of agricultural applications.

These systems are especially helpful for many agricultural chores, such as:

1. Mapping Weeds and Plant illnesses: UAVs with high-resolution multispectral and hyperspectral cameras are able to identify plant illnesses, stress, and weed infestation early on, allowing for targeted treatments and prompt intervention (Zhang et al., 2019).
2. Determining Fertilisation Problems: By identifying changes in plant colour and health, UAVs can determine nitrogen levels and other nutrient shortages, allowing for more accurate fertiliser application and increased crop output (Jensen et al., 2017).
3. Evaluating Crop Maturity: Farmers can optimise harvesting schedules and minimise losses by using UAVs to track crop growth stages and estimate harvest time (Torres-Sánchez et al., 2018).
4. Analysing Soil Variability: By producing high-resolution maps, UAVs may examine soil characteristics such as texture, organic matter, and moisture content, allowing for more effective soil management (Li et al., 2020).
5. Disease and Pest Management: By enabling farmers to identify pest outbreaks early, UAVs guarantee the application of tailored pesticides and lessen their negative effects on the environment (Gonzalez et al., 2019).
6. Frost Mitigation: To identify temperature dips that can cause frost damage, UAVs fitted with temperature sensors assist in monitoring field conditions during crucial periods, like at night. Farmers are able to act promptly as a result (Das et al., 2020).

7. Measuring Plant and Fruit Ripeness: UAVs assist in tracking the ripening phase of fruits and other crops using thermal and multispectral sensors, offering useful information for harvest forecasts (Mulla, 2013).

The efficiency of UAVs in agriculture has been greatly increased by technological miniaturisation and the creation of sophisticated sensors. Compact RGB, hyperspectral, LiDAR, and multispectral sensors are all available on modern UAVs, and each has unique benefits for various agricultural uses (Aasen et al., 2015). Additionally, UAVs enable farmers to produce high-frequency, detailed imagery that is both more immediate and has a greater spatial resolution than satellite imaging, which facilitates the monitoring of even the tiniest changes in the field.

Technological Advancements and Cost-Effectiveness: UAVs are becoming a more and more appealing tool for farmers due to their rising affordability, flexibility, and precision, even in spite of regulatory obstacles and their initial cost. Longer flight times, higher image quality, and increased cargo capacities have all been made possible by the development of lighter, smaller UAVs (Zhang et al., 2018). The total effectiveness of UAVs in farming operations is also influenced by developments in autonomous navigation, battery life, and onboard processing systems.

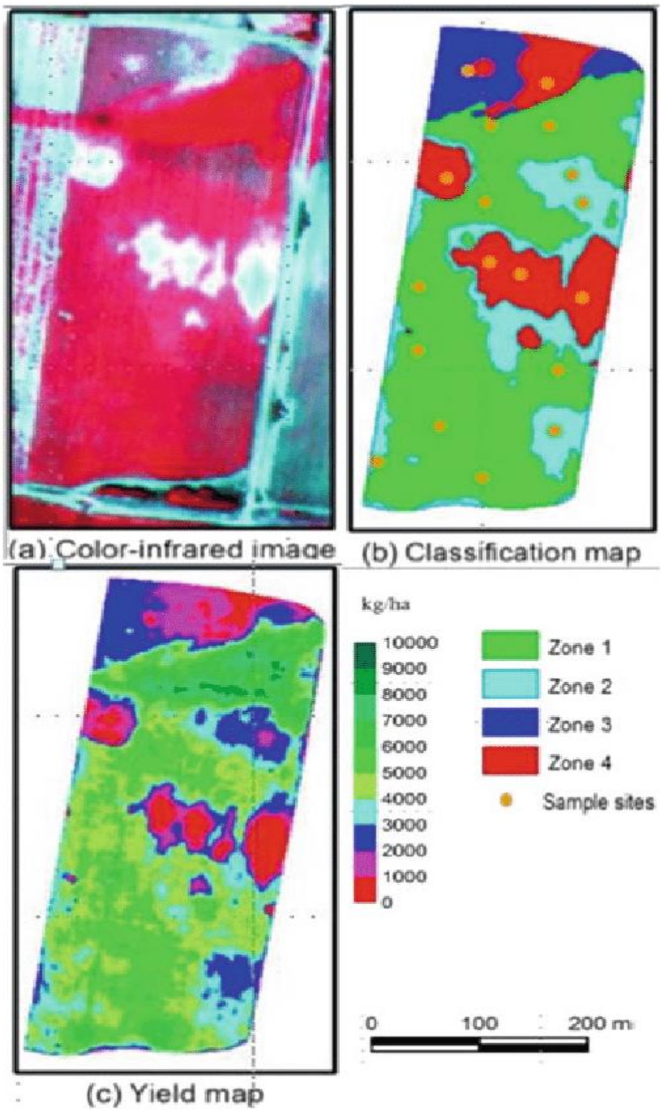


Fig. 3. A colour-infrared digital image, b a four-zone classification map, and c a yield map (modified after Yang et al.)

Fig. 4. Three examples of UAVs: a fixed-wing; b helicopter; c quadrotor (after Valavanis et al. 45)

The following are the primary UAV types utilised in agriculture:

- **Fixed-Wing UAVs:** Due to their extended flight durations and ability to effectively cover wide regions, these are most appropriate for larger fields (Wang et al., 2020). Usually, they are employed for tasks like crop scouting and soil variability monitoring.
- **Helicopter UAVs:** Due to their adaptability and ability to perform vertical take-off and landing (VTOL), these UAVs are appropriate for locations with more complicated topography or small, constrained places (Rango & Lal, 2015).
- **Multi-Copter UAVs:** According to Rajak et al. (2020), multi-copters are perfect for precision applications like fertiliser and pesticide spraying as well as close-range crop monitoring because they are lightweight, agile, and simple to use. Usually, these UAVs are used for specialised precision tasks or smaller-scale operations.

A number of parameters, including payload capacity, flight range, flight time, operational expenses, and the ability to integrate data with farm management systems, affect how useful UAVs are in precision farming (Sehgal et al., 2018).

Advantages of UAVs in Precision Agriculture:

- **Real-Time Data Collection:** According to Zhang et al. (2020), UAVs give farmers instantaneous insights into field conditions, enabling them to make decisions that maximise farm management and boost output.
- **Lower Operational Costs:** Compared to conventional techniques, UAVs offer more affordable choices for soil and crop monitoring and eliminate the need for labour-intensive field scouting (Kumar et al., 2017).
- **High-Resolution Imaging:** UAVs provide far more accurate and localised data than satellites since they can take pictures at far higher resolutions, which is essential for precise field analysis and decision-making (Mulla, 2013).

10. PROXIMAL SOIL AND CROP SENSORS FOR PRECISION FARMING

Precision farming relies heavily on proximal soil and crop sensors, which provide real-time data in the field for assessing crop and soil health. Proximal sensors are situated close to the ground, enabling them to assess both surface and subsurface soil parameters at particular places, in contrast to traditional remote sensing, which frequently depends on aerial or satellite-based imaging. This makes it possible to produce high-resolution digital soil maps, which are crucial for deliberating wisely about crop management and resource allocation (Franzen, 2018). These sensors are essential for boosting agricultural efficiency and site-specific management.

Proximal sensors come in two main varieties: those used to measure soil characteristics and those used to track crop health. These sensors can provide continuous data gathering while moving over the field and are frequently mounted on ground vehicles like tractors or all-terrain vehicles (ATVs). Real-time processing of the data they gather yields insightful information that may be used right away to improve farming methods (Cai et al., 2020).

Soil Sensors: Salinity, pH, wetness, texture, and other basic characteristics of soil, as well as more intricate ones like the amount of organic matter and microbial activity, can all be measured by soil sensors. One of the most significant developments in soil sensor technology is the measurement of soil salinity (also known as electrical conductivity, or EC), which is essential for figuring out soil fertility and evaluating whether a piece of land is suitable for a given crop.

- **Contact Sensors:** These sensors detect electrical conductivity by making physical contact with the soil using electrode coulters. In order to provide accurate measurements of soil salinity, they usually comprise pairs of electrodes that send current through the soil and detect the voltage drop (Chien et al*.,* 2017).
- **Non-Contact Sensors:** These assess soil salinity without coming into contact with the soil by using electromagnetic induction (EMI) technology. This technique generates and detects electromagnetic fields that are changed by the soil's salinity using one coil as the transmitter and another as the receiver (Zhao et al*.,* 2019). These sensors are very helpful for high-throughput field monitoring and provide the benefit of quick, non-invasive measurements.

Crop Sensors:

A number of plant traits that are suggestive of crop health and growth status are assessed concurrently by crop sensors. These sensors keep an eye on variables like:

1**. Leaf Area Index (LAI):** LAI is a vital indicator of canopy development and plant growth. The total leaf area, which is correlated with photosynthetic capability, can be estimated from photographs taken by crop sensors mounted on vehicles or UAVs (Petersen et al., 2020).
2. **Plant Height and Biomass:** As indirect measures of crop vigour and productivity, plant height and biomass are being measured by crop sensors more often (Li et al., 2020).
3. Water Stress: Crop water stress sensors can be used to pinpoint regions that require watering or where crop productivity is starting to be impacted by drought stress. Sensors can give a clear image of water availability by measuring the reflectance of particular wavelengths linked to water content (Yin et al., 2021).
4. Nitrogen Levels and Chlorophyll Content: For effective nutrient management, it is essential to track the amounts of nitrogen and chlorophyll in crops. Changes in chlorophyll content, which is directly related to nitrogen levels and general plant health, can be detected by sensors (Schmidt et al., 2020). By using this information, farmers may maximise crop output and reduce nutrient runoff by using fertiliser more efficiently.

These crop sensors, which frequently function in the visible, near-infrared (VNIR), and shortwave infrared (SWIR) spectral ranges, offer information about the health of the plants and allow for more focused treatments to increase sustainability and yield (Hu et al., 2021).

Integration with Variable-Rate Technology (VRT): VRT uses real-time data from crop and proximal soil sensors to modify irrigation, fertiliser, and pesticide application rates according to the unique requirements of various fields' zones. For example, these sensors can accurately map regions with different soil or crop conditions using data from the Global Navigation Satellite System (GNSS), enabling focused interventions that optimise input efficiency and reduce waste (Harrison et al., 2019). This method is essential to sustainable farming since it lessens the excessive use of pesticides and water, which lowers operating costs and the impact on the environment.

Sensor Fusion Approach: The sensor fusion approach is a cutting-edge development in proximal soil and crop sensing that improves the precision and thoroughness of soil and crop assessments by combining data from several sensor types. For instance, a more comprehensive assessment of the physical and biological characteristics of soil can be achieved by combining VNIR spectroscopy, penetration resistance (cone index) measurements, and apparent electrical conductivity (ECa) data (Sudduth et al., 2018). Since several critical soil characteristics, such soil compaction or organic matter content, do not show substantial reflectance in the VNIR band, this data fusion is particularly crucial. Farmers may make better decisions and optimise farming methods by employing this multi-sensor data technique, which provides a more comprehensive picture of crop conditions and soil health. The creation of a soil health index, which integrates physical, chemical, and biological markers of soil quality, also depends on these integrated systems. According to Tao et al. (2020), these indicators can help with initiatives aimed at improving soil sustainability, boosting profitability, and reducing environmental degradation.

Advantages and Effect on Precision Farming: Nearby soil and crop sensors provide a number of significant advantages for precision farming, such as:

1. High-Resolution Data: According to Mulla (2013), these sensors offer precise, field-specific data that can be utilised to improve farming methods and raise potential production.

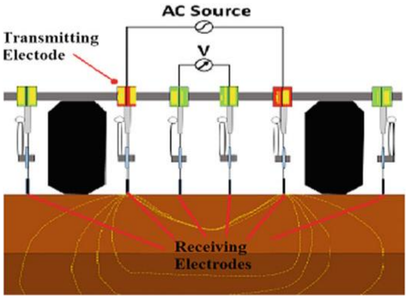


Fig. 5. Contact type EC sensor (modified after Grisso et al.2009)

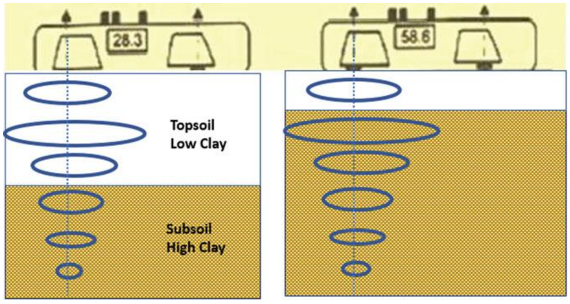


Fig. 6. Non-contact type EC sensor (modified after Grisso et al. 2009)

2. Real-Time Insights: According to Zhang et al. (2020), proximal sensors allow for real-time monitoring of crop and soil health, which speeds up decision-making and improves management.
3. Cost-Effectiveness: These instruments are now more accessible to a larger spectrum of farmers, including those running smaller-scale enterprises, thanks to developments in sensor technology (Kumar et al., 2017).
4. Sustainability: By enhancing input utilisation efficiency, proximal sensors support sustainable agricultural methods by lowering waste, lowering chemical runoff, and maintaining soil health (Merrill et al., 2020).

GIS and Precision farming: Precision agriculture relies heavily on Geographic Information Systems (GIS), which make it easier to gather, analyse, store, and manage spatial and temporal data for better farm management. By addressing field variability, GIS aids in precision farming decision-making and promotes the use of optimal techniques for sowing, irrigation, nutrient management, and pest control. GIS is a crucial tool for contemporary agricultural practices because it visualises geographic data and offers in-depth insights into spatial patterns that impact farming decisions (Zhang et al., 2020).

For farmers to better understand field conditions and adjust their inputs to meet local needs, GIS is essential for data creation, analysis, and interpretation. Spatial variability in crop health, environmental circumstances, and soil characteristics can be managed with the aid of GIS tools. For instance, GIS may combine data from yield maps, soil sensors, and remote sensing imagery to assist farmers in deciding where to apply resources, such as pesticides, fertiliser, or irrigation (Whelan et al., 2018). GIS also contributes to the mapping of crop health, soil health, and yield potential—all of which are essential for developing effective management plans that are site-specific (Lamb et al., 2019).

Field-level Geographic Information Systems (FIS), a raster-based GIS technique, are intended to analyse and display agricultural data that farmers have gathered for precision agriculture. Farmers can use FIS systems, like the ones created by Zhang and Taylor (2019), to process large amounts of data and extract useful insights. Maps of several field variables, including as soil nutrient levels, pH, and moisture content, are produced by these systems and can be used to inform precision farming techniques.

With the help of GIS technology, precision farming makes it possible to combine data from multiple sources—including GPS, remote sensing, and field-mounted sensors—into a single, cohesive platform. These connections guarantee the efficient analysis and visualisation of the raw data gathered, including crop and soil properties. By taking farm heterogeneity into account, GIS improves field management techniques by laying the groundwork for data-driven decision-making. This results in improved environmental sustainability, lower input costs, and better resource allocation (Cook & Donnelly, 2007; Cabrera et al*.*, 2017).

In nutrient management, GIS is also essential since it helps identify fluctuating nutrient rates throughout a field and guarantees that fertilisers are delivered as effectively and efficiently as feasible. This technique, called variable-rate application (VRA), uses GIS mapping tools in conjunction with soil nutrient data to make sure nutrients are given only where necessary, increasing crop yields and reducing environmental impact (Khosla et al., 2002). Another area where GIS is essential is proper soil sampling, which enables precise evaluation of soil fertility and nutrient levels. This is essential

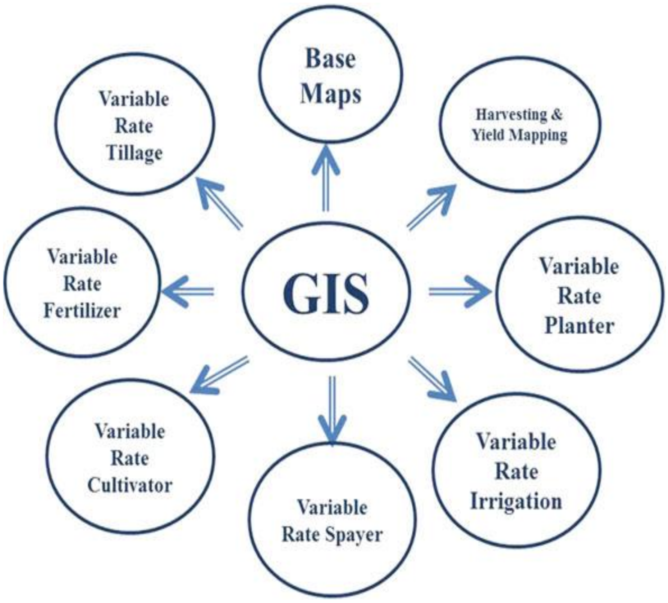


Fig. 7. Some of the components related to GIS in precision farming (modified after Zhang and Taylor)

for efficient nutrient management and increasing crop output (Zhang et al., 2020).

Soil Sampling Techniques for Precision Farming:

In order to make well-informed decisions regarding crop management, irrigation, and fertiliser application, soil sampling is a crucial part of precision farming. Farmers can more effectively utilise resources and maximise crop yields by identifying geographical variability in soil parameters through the data obtained from soil sampling. Grid soil sampling, which separates fields into square cells and takes soil samples from each cell, is one of the main techniques used in precision farming. According to Khosla et al. (2002), this method makes it possible to produce intricate soil maps that depict field variability.

Precision farming uses a variety of grid soil sampling techniques, each with unique benefits based on the objectives of the agricultural operation:

1**. Regular Systematic Sampling:** This technique uses systematic sites inside the grid or set intervals for sampling. In order to provide an organised representation of soil characteristics throughout the field, the samples are often taken from the centre of designated cells (Schroeder et al., 2018).

2**. Staggered Starting Points:** To lessen the possibility of systematic bias, this variation on systematic sampling offsets the beginning point in each row. It is especially helpful for big fields and can result in improved coverage of field variability (Kitchen et al., 2005).
3. **Systematic Unaligned Sampling:** This technique offers a randomised yet structured sampling method that reduces sampling bias by using sampling sites that are routinely dispersed but not aligned with field boundaries (Khosla et al., 2002).
4. **Random Composite Sampling:** Using this technique, samples are drawn randomly from different grid locations. This method may require access to several places across the grid and might be time-consuming, particularly for bigger fields, even if it guarantees good randomisation (Gbehor et al*.,* 2016).

With the help of GIS software tools like "Feature to Point" and "Create Random Points," each of these grid sampling strategies can be further refined to produce more accurate sampling sites for data collecting (Zhang et al., 2019).

Management zone sampling is another crucial precision farming method. Management zone sampling concentrates on regions of the field that show notable variations in soil properties or yield patterns, as opposed to grid sampling, which entails taking many samples from homogeneous grid cells. With this approach, fewer samples are required while still taking into consideration variations in soil fertility, moisture content, and other important variables (Bajwa et al., 2017). Based on variables like agricultural production variation, soil properties, and land management techniques, management zones are established (Fitzgerald et al., 2021). For instance, the sampling effort is focused on places where consistent soil characteristics, including nitrogen levels, have a significant impact on crop productivity (Frye et al., 2020).

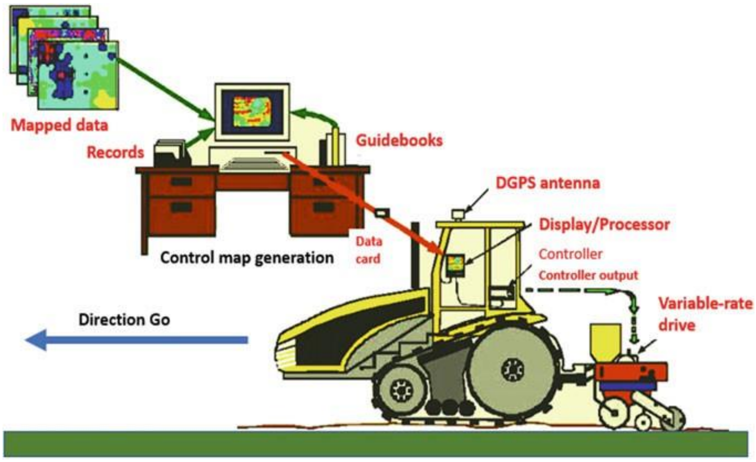
Farmers can avoid oversampling while still obtaining sufficient information to make well-informed decisions about irrigation, fertiliser application, and other agricultural inputs by concentrating on management zones. Particularly in vast fields, the objective is to strike a compromise between the practical considerations of cutting labour costs and sample expenses and the requirement for adequate data. All things considered, both grid sampling and management zone sampling provide insightful information about soil variability, assisting farmers in better field management, crop performance enhancement, and input cost reduction.

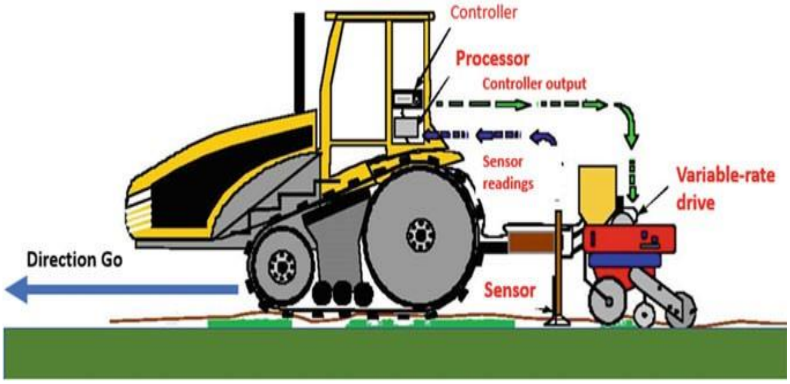
Variable Rates Tecgnology (VRT): A game-changer in contemporary agriculture, variable rate technology (VRT) enables the administration of inputs, including water, fertiliser, and pesticides, at different rates throughout a field according to temporal and spatial variability. VRT helps farmers maximise resource utilisation, lessen their impact on the environment, and boost crop yields by customising input application to the unique requirements of various field zones. Data from multiple sources, such as GPS, remote sensing, and soil sensors, power VRT systems. They are essential for raising farm profitability, promoting sustainability, and increasing agricultural efficiency.

Two main categories of variable rate technology exist:

1. Map-Based VRT: This system generates maps that direct input applications based on historical data, including soil properties and past crop yields. These maps, which were created with the aid of Geographic Information Systems (GIS) and other mapping tools, assist farmers in determining whether parts of their fields need a certain input more or less. Farmers can prevent overuse in high-fertility areas and remedy shortages in low-fertility areas by applying inputs at different rates throughout the field (Schröder et al., 2013). In fertiliser application, when soil nutrient content is mapped and inputs are applied based on the spatial variability of these nutrients, map-based VRT is most frequently utilised.

2. Sensor-Based VRT: This type of VRT uses on-the-ground sensors to measure particular soil and crop conditions in real-time, as opposed to map-based VRT, which depends on historical data. By measuring variables like soil moisture, chlorophyll content, and crop health, these sensors modify the way inputs (such water, phosphorus, or nitrogen) are applied. By modifying rates to guarantee the crop receives precisely the proper quantity of nitrogen fertiliser for optimal growth, sensors that assess chlorophyll levels, for example, can assist optimise nitrogen fertiliser application (Mulla, 2013). Sensor-based VRT is particularly helpful for tasks like fertiliser management and irrigation since it is very responsive to changing field conditions.





Figs. 8 and 9. The map-based and sensor system for variable application rates (Ess et al. 2001)

Variable rate technology has the following advantages:

- Increased Resource Efficiency: VRT lowers input costs and waste by applying inputs only where and when they are required. It guarantees the efficient use of water, herbicides, and fertilisers, maximising their efficacy while lowering the total amount applied (Bajwa et al., 2017). Improved Crop Health: VRT makes it possible to manage nutrients more precisely, which improves crop health and yields. Nitrogen sensors, for instance, might assist in avoiding overfertilization, which may result in environmental contamination or nutritional imbalances (Pereira et al., 2017).
- Environmental Sustainability: VRT lowers the environmental impact of farming operations and minimises the danger of nutrient runoff into waterways by minimising the overapplication of chemicals and fertilisers (Schröder et al., 2013).
- Increased Productivity: Accurate input application based on real-time data guarantees that crops get the nutrients they require at the appropriate moment, increasing productivity. VRT makes it possible to pinpoint portions of a field that aren't doing well and implement focused treatments to increase yield (Mulla, 2013).

Variable Rate Technology with Optical Sensors (VRT): In precision agriculture, optical sensors are essential for measuring light reflectance and assessing crop and soil properties. By identifying visible, near-infrared (NIR), and mid-infrared (MIR) light spectra, these sensors mimic the human eye and enable the identification of many soil and crop characteristics, including moisture content, nitrogen levels, and organic matter (Dandois et al., 2017). To evaluate the health and nutritional content of plants and soil, the sensors use spectroscopy techniques to quantify light reflection and absorption (Jia et al*.,* 2021). To enable accurate measurements in the field, these optical sensors can be installed on a range of platforms, such as tractors, UAVs, and even handheld devices.

Variable Rate Technology (VRT) is a precision farming technique that uses optical sensors to control the real-time, variable application of inputs including water, fertiliser, herbicides, and even tillage activities. By modifying application rates in response to spatial variability, VRT systems enable customised treatments for various field regions. In order to optimise the application process and guarantee effective and efficient input management, these systems are integrated with GPS, GIS, and real-time sensor data (Mulla, 2013).

Based on the type of input or fertiliser being applied, VRT systems can be divided into three categories: gaseous, liquid, and granular. For instance, liquid systems handle fertilisers in liquid form for crops that need more frequent applications, whereas granular VRT systems apply solid fertilisers at variable rates according to the soil's nutrient requirements (Fleming et al., 2018). According to Sudduth et al. (2010), gaseous VRT systems are mostly utilised for the application of goods such as anhydrous ammonia, which can be delivered in different ways based on the nitrogen requirements of the soil.

Several elements cooperate in a typical VRT setup to maximise the input application process:

- **GPS Antenna:** Assures accurate input placement by giving the system real-time geospatial location data.

- **Computer and Controller:** The central component of the system that handles data processing and regulates input application rate.
- **GIS Database:** Offers comprehensive field maps, information on crops, soil properties, and past input records to help in decision-making.
- **Flow Rate System:** The system can automatically adapt to field variations since precomputed flow rates are based on input requirements (Robinson et al., 2009).

The GIS system modifies the application rates in accordance with the GPS receiver's constant location updates as the equipment travels through the field. In order to optimise agricultural practices, these devices can document the actual application rates at each site and save the data for further research.

Advantages of VRT and optical sensors:

- **Increased Precision:** Accurate variable-rate applications are ensured by optical sensors' high spatial resolution for evaluating crop and soil conditions.
- **Increased Efficiency:** Farmers can prevent misuse and lower expenses related to excessive fertiliser or water application by applying inputs based on real-time data.
- **Sustainability:** VRT systems help reduce environmental effect, such as greenhouse gas emissions and fertiliser runoff, by lowering the overall consumption of agricultural inputs (Schröder et al., 2013).

Yield Monitoring Systems and Mapping: The ability to comprehend and control the variation in soil properties, crop output, and growing conditions across various areas of a field is essential to precision farming. Throughout the growing season, farmers can collect comprehensive data on crop performance using mapping technology and yield monitoring systems (YMS). With the help of these technologies, farmers can make well-informed decisions on how to best optimise productivity and sustainability by modifying techniques like planting populations, fertiliser application rates, and other inputs. Farmers can pinpoint underperforming areas in their fields and implement remedial actions by combining yield data analysis with other environmental and soil data (Fountas et al., 2006).

Yield maps that show variations within fields can now be created because to the development of yield monitoring technology, which has made information more accurate and useful. By displaying the regional distribution of agricultural yields, these maps assist farmers in determining which regions are productive and which require further treatment. Understanding regions with higher production, for example, may lead the farmer to choose particular crop varieties that are more appropriate for these zones or modify fertiliser application. Furthermore, yield mapping helps with long-term planning, including enhancing crop rotations in the future and evaluating the success of previous input management techniques (Sudduth et al., 2005).

Components of Yield Monitoring Systems: Generally, yield monitoring systems are made up of three major parts:

1. **User interface:** It provides real-time data on crop yield, moisture content, and other factors, consists of the keypad and display that the operator uses to communicate with the system.
2. **Console:** The console, which is housed inside the combine's cab, interprets the information gathered by the system and shows it to the operator. If there are anomalies in the data or if calibration is required, it frequently contains alerts or notifications.
3. **Data Storage Device:** This device, which is typically a cloud-based platform or an external memory card, saves the yield data that has been gathered for further analysis.

The system has other sensors that track important factors in addition to these main parts:

- **Grain Flow Sensor:** This device gauges the grain flow from the harvest system of the combine.
- **Moisture Sensor:** Determines the grain's moisture content, which is crucial for maintaining grain quality and modifying harvest timing.
- **Speed Sensors:** These sensors track the speed of the ground and the combine's header, allowing yield calculations to be modified according on the combine's speed and field position.
- **Header height sensors:** These are crucial for making sure the crop is being harvested efficiently and at the proper height. They measure the height of the combine's header (Davis et al., 2011).

Factors Influencing Accuracy and Calibration: Sensor calibration is one of the key elements influencing yield monitoring systems' accuracy. Accurate and representative data of the yield is guaranteed by proper calibration. For instance, the moisture sensor needs to be adjusted to take into consideration the fact that different areas of the field have variable moisture contents. To precisely reflect the weight or volume of the crop, the grain flow sensor must also be calibrated (Johnson et al., 2003).

According to Gaumitz (2008), the accuracy of yield monitoring systems can also be impacted by the harvester's size. Compared to conventional, larger harvesters, smaller research combines can provide more precise yield statistics and typically cover less ground.

Creating Yield Maps: After being gathered, the data is analysed and displayed as yield maps, which show how yields are distributed geographically over the field. The yield data from thousands of data points gathered by the system is recorded to create yield maps. Field size, combination model, and GPS precision are some of the variables that affect the quantity of data points (Fountas et al., 2006). These maps offer useful information that may be utilised to make zone-based decisions about planting plans, irrigation techniques, and nutrient management that are more precise.

Farmers can forecast soil nutrient depletion and modify fertiliser application rates by using historical yield maps. For example, if some fields continuously produce less than others, it can mean that those areas require more fertiliser input (Mulla, 2013). According to Sudduth et al. (2005), yield mapping also makes it easier to identify field zones that can benefit from variable rate seeding, which can maximise planting density depending on regional soil and environmental conditions.

Advantages and Uses:

There are many advantages to mapping and yield monitoring systems:

- **Better Resource Management:** Farmers may more accurately apply fertilisers, insecticides, and other inputs by identifying high and low production areas. This reduces waste and increases overall resource efficiency (Mulla, 2013).
- **Economic Optimisation:** Farmers can improve their operations by using yield maps to allocate resources where they will have the biggest impact, which boosts profitability (Fountas et al., 2006).
- **Long-Term Sustainability:** Enhancing soil health, optimising crop rotations, and promoting sustainable farming methods are all made possible by an understanding of field variability and modifying methods in light of past yield data (Sudduth et al., 2005).
- **Data-Driven Decisions:** According to Davis et al. (2011), yield maps are effective instruments for making data-driven decisions about input management, field management techniques, and general farm management methods.

11. CONCLUSION

A revolutionary approach to contemporary agriculture, precision farming allows farmers to increase yield, cut expenses, and advance sustainability. By combining cutting-edge technology like GPS, GIS, remote sensing, and real-time data collection, precision farming makes it possible to apply inputs precisely according to site-specific needs. As a result, resources like water, fertiliser, and pesticides are used more effectively, which eventually boosts agricultural yields and lessens their impact on the environment. At the heart of this strategy is the idea of Site-Specific Land Management (SSLM), which enables farmers to make data-driven, well-informed decisions that take soil and crop conditions into consideration. Variable rate application (VRA), integrated management software, and soil sensors are some of the instruments that farmers can use to streamline their processes, cut waste, and enhance ecological and financial results. Precision farming is a vital tactic for satisfying the rising demands of global food production since its long-term advantages go beyond increased productivity and include improved soil health, reduced environmental risks, and increased sustainability. Precision farming is a crucial solution that has the potential to transform food production and ensure that agriculture continues to be both environmentally conscious and productive for future generations as the agricultural industry grapples with the problems of urbanisation and climate change.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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