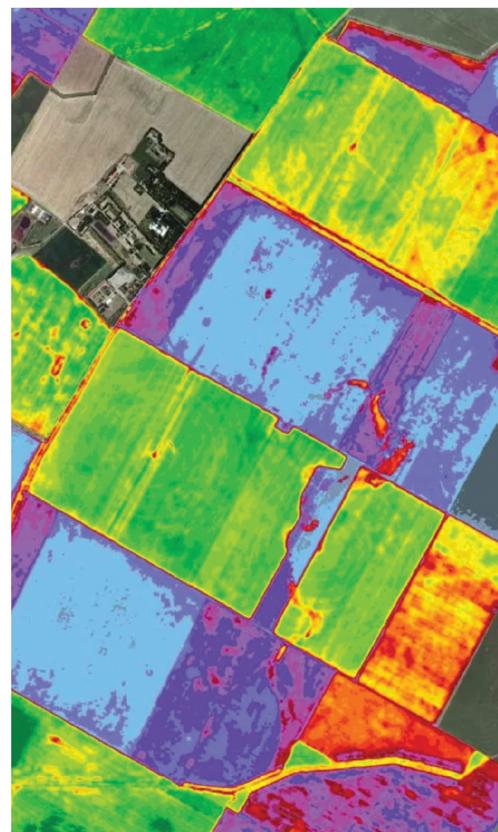
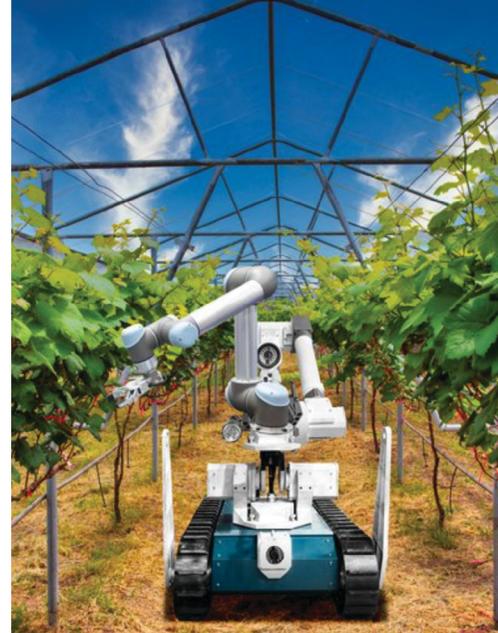


Ted Goldammer

# Precision Agriculture

A Guide to Operations and  
Technologies in Crop Production



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Production



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First Edition

**APEX**  
Publishers

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A Guide to Operations and Technologies in Crop Production

By Ted Goldammer

Apex Publishers  
13004 Hylamore Court  
Haymarket, Virginia 20169  
<http://www.apex-books.com>

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ISBN-979-8-89852-137-0

**Printed in the United States of America**

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# Preface to First Edition

*Precision Agriculture: A Guide to Operations and Technologies in Crop Production* integrates key concepts behind the technologies involved in precision agriculture with practical concerns and real-world applications. Recognizing that many potential readers are nonspecialists, this book is designed to be accessible, pragmatic, and concise. Written in layman's terms, the book systematically starts the reader off by providing an in-depth discussion on all key subjects within precision agriculture, including Internet of Things, artificial intelligence, wireless sensor networks, GPS technology, remote sensing, satellites, unmanned aerial vehicles, ground-based proximal sensing, variable-rate application, digital image processing, and geographical information systems, and so forth. These technologies enable farmers to collect and analyze data to optimize resource use, enhance productivity, and improve crop quality. The information in this book is distilled from a variety of sources, including scientific literature, extension publications, trade publications, reader feedback, and industry experts who have generously shared their years of experience. This book also has the added value of numerous citations to more in-depth discussions on many topics. The book is thoughtfully organized in an easy-to-read format, presenting a seamless flow of topics within chapters. This book has removed some of the intuition and guesswork in understanding the subject of precision agriculture, its operations, and technologies. The result is a more consistent product of higher quality, providing practical "real-world" applications. The primary audience includes growers, technical industry representatives, and undergraduate and graduate students in the technical disciplines.



# 1

## Precision Agriculture in Crop Production

The development of agriculture has experienced a transformation over the years from traditional agriculture to precision agriculture. Conventional agriculture is an age-old practice that relies on manual labor and historical knowledge, while precision agriculture (PA) is a farming management concept that uses technology and data to optimize agricultural practices. It involves observing, measuring, and responding to variations within a field to make more informed decisions about resource application, crop management, and overall farming operations. Precision farming distinguishes itself from traditional agriculture by its level of management. Instead of managing whole fields as a single unit, it attempts to match the kind and amount of inputs with the actual crop needs within a field. Precision agriculture allows farmers to control important processes, saving time, energy, and resources. Precision agriculture will not only improve yield but could also impart predictive forecasting, which leads to appropriate and timely action. Precision agriculture also allows for greater flexibility in adapting the entire harvest to extreme weather events since forecasting and other data-driven environmental factors can be formulated and updated in real time. The technologies used in precision agriculture are constantly evolving. The Internet of Things (IoT), Big Data analysis, artificial intelligence (AI), and global positioning systems (GPS), among other technologies, enhance production and reduce inputs and yield losses. Precision agriculture can be applied to multiple cultural practices, including tillage, precision seeding, variable-rate fertilizer application, precision irrigation, and selective pesticide application, and facilitates other management decisions, such as site-specific deep tillage to remove soil compaction. Precision agriculture has the potential to not only improve the use efficiency of farm inputs but also increase farm profits, reduce adverse environmental impacts, and improve agricultural sustainability.

### 1.1 Advantages and Limitations of Precision Agriculture

#### Advantages of Precision Agriculture

Precision agriculture advocates the need for precise agricultural input management in an environmentally sensible manner, consistent with the long-term sustainability of production agriculture. Precision agriculture takes into account crop protection, growth monitoring, soil mapping, soil type, soil nutrient level, supply of irrigation and water levels, and their cumulative environmental impact. Precision agriculture enables the use of a precise amount of fertilizer at a precise location and at a precise time to derive maximum yield in the context of different soil types and crop requirements. In conventional farming systems, farmers generally uniformly apply inputs such as fertilizer and pesticides to the whole field. They rarely consider spatial variations due to soil types, electrical conductivity (EC), soil moisture content, pH, and nutrient availability. Further, the spatial variability of soil across the fields can be caused by topography, soil texture, and management practices such as cropping patterns, crop rotations, soil fertility programs, and soil compaction over the years. A “blanket approach” in applying inputs results in a portion of those inputs never being used by plants. This results in an increase in farm production costs while causing environmental pollution. Precision agriculture also addresses the issues of soil fertility and variability of the soil type, thus aiding in the improvement of the yield and the quality of the food and, at the same time, increasing the income of the farmers.

#### Limitations of precision Agriculture

Despite its potential benefits, precision agriculture also faces some challenges that hinder its adoption and implementation. One of the main challenges is the



Figure 3.2 Machine learning in agriculture allows farmers to process substantial amounts of Big data about climate change, crop and soil conditions, and other environmental variables.

## Machine Learning Methods

Machine learning methods work on the algorithms that are constructed to gain a self-learning property; thus, ML is categorized as a major area of artificial intelligence. “ML algorithms” differ from “conventional computer algorithms” that work strictly according to the program created by its developer. ML algorithms interpret and analyze the input as well as the output (results) so that the machine learning model increases accuracy with this progression. The advantage of these methods is that the model is less dependent on user instructions, unlike the conventional statistical methods. There are several different classes of machine learning algorithms, which can be broadly categorized based on the type of learning they perform: (1) Supervised learning algorithms, (2) Unsupervised learning algorithms, and (3) Reinforcement learning algorithms.

### Supervised Machine Learning

In supervised learning, the machine is taught by example. The operator provides the machine learning algorithm with a known dataset that includes desired inputs and outputs, and the algorithm must find a method to determine how to arrive at those inputs and outputs. While the operator knows the correct answers to the problem, the algorithm identifies patterns in data, learns from observations, and makes predictions. The algorithm makes predictions and is corrected by the operator—and this process continues until the algorithm achieves a high level of accuracy/performance. Supervised learning is divided into two categories: regression and classification. Regression is a technique that is used to find the relation between independent and dependent variables. Classification is

the process of dividing the data into specific and distinct classes where we assign a label to each class.

### Unsupervised Machine Learning

Here, the machine learning algorithm studies data to identify patterns. There is no answer key or human operator to provide instruction. Instead, the machine determines the correlations and relationships by analyzing available data. In an unsupervised learning process, the machine learning algorithm is left to interpret large data sets and address that data accordingly. The algorithm tries to organize that data to describe its structure. This might mean grouping the data into clusters or arranging it in a way that looks more organized. An unsupervised learning algorithm gives better output while performing complex tasks compared with supervised learning. It is more unpredictable, and also it helps to find the unknown pattern in data.

### Reinforcement Machine Learning

Reinforcement learning focuses on regimented learning processes, where a machine learning algorithm is provided with a set of actions, parameters, and end values. By defining the rules, the machine learning algorithm then tries to explore different options and possibilities, monitoring and evaluating each result to determine which one is optimal. Reinforcement learning teaches the machine trial and error. It learns from past experiences and begins to adapt its approach in response to the situation to achieve the best possible result.

#### AI in Predictive Analytics

One of the most significant contributions of AI in logistics is predictive analytics. Through machine learning algorithms, AI can forecast demand and supply trends accurately. These forecasts are based on a complex variety of data inputs, including weather conditions, market trends, historical sales data, and even social media activity. Farmers and distributors can use these insights to plan their operations more effectively, reducing the risk of overproduction or shortages. This predictive power leads to better inventory management and more strategic resource allocation.

## Machine Learning Algorithms

Several prevalent ML algorithms have emerged within the context of agriculture. Machine learning algorithms can ingest vast amounts of data and identify complex patterns that humans would struggle to discern. These models can predict future conditions, such as the likelihood of disease

signal and compare where the satellite says it is with orbit models showing where it should be. Operators at these stations can control the satellite’s position to correct or alter their orbital path, for example, if a satellite has drifted or needs to be moved to avoid debris collision. This process and monitoring of a satellite’s health ensure a baseline of accuracy in GNSS positioning. The third part of GNSS is the user segment, the GNSS receivers. A GNSS receiver is a device that records data transmitted by each satellite and then processes these data to obtain three-dimensional coordinates. There is a wide array of receivers and methods for determining position. Receivers are often handheld devices with screens and keyboards or electronic components mounted on cars and trucks, planes, or other objects. The satellite and control segments differ for each GNSS. Each GNSS positions its satellites, forming a constellation with a certain arrangement. Satellites are distributed in orbits, and the number of orbits can also change from system to system. Global positioning systems are designed to ensure that there is always a minimum number of satellites to calculate the position at any time and in any position on Earth. For example, GPS is designed to have a constellation with 24 satellites distributed in six orbits, with four satellites in each orbit.

### Types of Global Navigation Satellite Systems

A GNSS (Global Navigation Satellite System) is a general term for any satellite constellation providing positioning, navigation, and timing (PNT) data. The four main GNSS constellations are GPS (US), GLONASS (Russia), Galileo (EU), and BeiDou (China). Additionally, regional constellations like QZSS (Japan) and IRNSS (India) are worth noting. These systems transmit their signals using radio frequencies in the L-Band, but each constellation might use different frequencies or label them differently (Table 5.1). Together, these constellations are called the Global Navigation Satellite System (GNSS). Important to note there are satellite-based augmentation systems (SBAS), which provide global error corrections for

improved accuracy in GNSS applications. Many countries manage their own SBAS systems, and these are usually considered separate from traditional GNSS constellations.

## 5.2 Global Positioning System (United States)

Satellite navigation is based on a global network of satellites that revolve around the Earth in a precise orbit. The satellite constellation most people are familiar with is the United States Global Positioning System (GPS). At the time of this publication, the GPS constellation consists of 31 operational satellites that orbit the earth twice a day. These satellites are positioned so that a user can view at least four satellites from any location on Earth. Each satellite transmits a unique signal and orbital information that enable GPS devices to calculate your location by measuring the time it takes for the signal to travel from the satellite to the GPS receiver. The terms GPS and GNSS are often used synonymously; the main difference between the two systems is that the GPS receivers can only receive signals from U.S. satellites, while the GNSS receivers can receive signals from U.S. satellites and other worldwide satellite systems. Most new systems today have both GPS and GNSS capabilities—having the availability to acquire more satellites improves receiver accuracy and reliability. All GNSS receivers are compatible with GPS, but GPS receivers are not necessarily compatible with GNSS.

The GPS is a space-based satellite navigation system that provides users with highly accurate three-dimensional positioning information (longitude, latitude, and elevation) as well as time that allows GPS receivers to calculate their position. Having precise location information at any time allows soil and crop measurements to be mapped. The global positioning system technology is useful in performing tasks requiring high precision, such as crop mapping, automatically driven farm vehicles, soil sampling, and distribution of fertilizers and pesticides at variable rates. Today, many growers use GPS-derived products to enhance their farming operations. Combining GPS and

**Table 5.1 Major GNSS Systems**

System	Country/Agency	Satellites	Accuracy
GPS	USA	31	≈5m (Basic)
GLONASS	Russia	24	≈5-10m
Galileo	European Union	30	≈1m (civilian, ≈20cm (encrypted))
BeiDou	China	45	≈2-10m
QZSS	Japan	4 (planned: 7)	≈1m, (Better in Asia-Pacific)
NaviC	India	7	≈10m (regional coverage)

### Applications of Multispectral Remote Sensing in Precision Agriculture

The NIR and red edge bands are particularly helpful for studying vegetation, as plants reflect a large amount of light in these regions. Since the band placement for many multispectral sensors targets the biochemical components of vegetation, these sensors are frequently used for environmental applications such as crop monitoring, ecological restoration, and detecting invasive species. Vegetation indices (VI), ratios or linear combinations of spectral reflectance in two or more bands, are among the most used tools in multispectral remote sensing. Numerous VIs have been defined for various purposes, including the Normalized Difference Vegetation Index ( $NDVI = (NIR - Red) / (NIR + Red)$ ), which is the most distinguished index in remote sensing, derived from the combination of NIR and red bands. Multispectral imaging can be used to predict the potential yield of the crop. This information enables the farmer to make informed decisions regarding resource allocation. In addition, specific bands can be used to estimate nitrogen deficiency and other important traits based on various vegetative indexes.

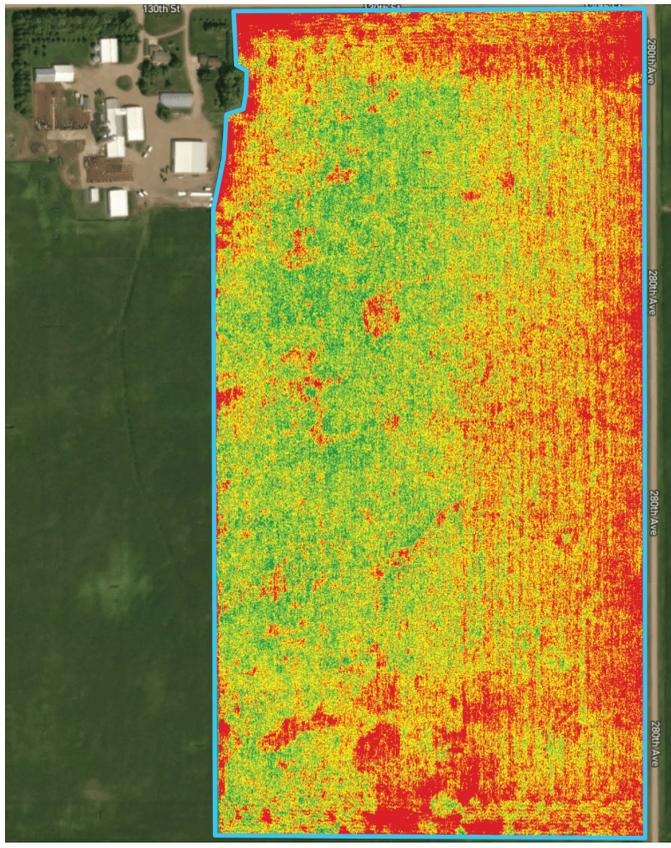


Figure 6.9 Farmland captured by multispectral imagery.

Hyperspectral imagers can capture spectral characteristic changes in crops when affected by insects and diseases, enabling detection and early warning before or at the onset

of insects and diseases. This assists farmers in promptly implementing preventive measures to reduce losses caused by pests and diseases. By analyzing spectral information from different bands, this technology can identify and classify various types of insects and diseases, including viruses, bacteria, fungi, and insects. This helps farmers accurately determine the type and severity of insects and diseases, providing a basis for precise control measures.

### Limitations of Multispectral Remote Sensing in Precision Agriculture

Multispectral sensors typically measure reflected energy in only a few broad bands (e.g., red, green, blue, near-infrared). They miss subtle variations in crop health or soil conditions that might be captured by hyperspectral sensors (which collect data in hundreds of narrow bands). Consequently, it is difficult to detect specific plant diseases, stress types, or nutrient deficiencies. They mostly capture the canopy surface. In addition, multispectral sensors have poor visibility of soil conditions or early-stage crops and have limited information on the root zone, subsurface moisture, or diseases affecting the lower parts of the plant. Multispectral sensors are more expensive than RGB sensors. They are heavy and require drones with significant payload capacities.

### Hyperspectral Remote Sensing

Multispectral images have been widely used in agriculture to retrieve various crop and soil attributes, such as crop chlorophyll content, biomass, yield, and soil degradation. However, due to the limitations in spectral resolution, the accuracy of the retrieved variables is often limited, and early signals of crop stresses (e.g., nutrient deficiency, crop disease) cannot be effectively detected in a timely manner. Hyperspectral sensors have emerged as a promising tool for precision agriculture (PA). Hyperspectral sensors, like multispectral imaging, cover a broad electromagnetic spectrum but can operate across tens or hundreds of much narrower bands. The electromagnetic spectrum can start with UV light, extend through the visible spectrum, and end in the near or short-wave infrared. The higher spectral resolution that characterizes hyperspectral sensors provides a precise digital “fingerprint” or spectral signature of the material or objects being imaged. This spectral signature provides more information compared to the few data points from a multispectral sensor, and the data can be analyzed more intensely to uncover the biophysical or chemical components of the material or object.

Hyperspectral imagery is typically described and presented as a hypercube because the tens or hundreds of bands can be conceptualized as a large stack forming a

known, fixed location to provide high-precision corrections to the UAV’s GPS—either in real-time (RTK) or through post-processing (PPK). The RTK system in drones comprises two main components: a mobile station (or rover) on the drone and a stationary base station with a known position. The base station plays a pivotal role in this setup; it continually measures satellite signals and calculates correction data based on its established location. This correction data, which compensates for errors due to atmospheric disturbances, satellite and receiver discrepancies, and orbital inaccuracies, is then transmitted to the mobile station in real-time.



Figure 8.5 RTK drone solution high precision GPS base station system for measuring satellite positioning mapping.

### RTK Base Station

To transmit data in real time, a stable communication channel (radio signal or mobile communication) between the base station and the mobile receiver is required. RTK allows sub-centimeter accuracy, but data quality depends on signal stability. Short-term accuracy deviations or data gaps may occur if the signal is lost. RTK systems can be expensive, especially if a stable connection to a mobile network or the use of radio modems over long distances is required.

### PPK Base Station

Post-processing kinematic (PPK) is a method of high-precision positioning using GNSS data with subsequent post-flight data processing. PPK is similar to RTK but differs in that the data is corrected after the flight rather than in real time. GNSS data is recorded by the base station and the rover and then combined and corrected in specialized software. This improves accuracy, but the data is only available after post-processing. PPK does not require real-time communication between the base station and the rover, making it less dependent on communication conditions, which is helpful in remote or challenging environments. PPK provides the same or even higher accuracy since the data is processed after the flight, and correcting all errors and distortions during recording is possible. PPK can be more reliable under challenging conditions since all data is available for analysis and correction.

### UAV Ground Control Stations

The ground control station (GCS) is a central hub that collects flight-related data and facilitates communication with the UAV control system. Sensors, both ground-based and onboard, contribute to data collection. Some UAVs incorporate collision avoidance systems, utilizing sensors to detect obstacles and enhance operational safety. These integrated systems collectively contribute to the UAV’s ability to operate autonomously or under human supervision across a diverse array of applications, from PA to surveillance and beyond. GCS are used for both manual and autonomous control of UAVs—depending on the mission type and operator preferences. For manual control, the ground control station acts as a live remote controller: the operator manually pilots the UAV via a joystick or touchscreen. For autonomous control, the flight plans (waypoints, altitudes, speeds) are uploaded to the control station, and the UAV is monitored as it autonomously follows the mission.

Table 8.2 Base Station Versus GCPs for Georeferencing

Aspect	Base Station (RTK/PPK)	Ground Control Points (GCPs)
Accuracy	2–5 cm horizontal, 5–10 cm vertical (RTK)	1–3 cm (if properly surveyed and placed)
Field Setup	Set up 1 base station + RTK drone	Place and survey multiple GCPs (5–10+) across AOI
Workflow Speed	Faster — minimal or no GCPs needed	Slower—needs surveying time for each GCP
Post-Processing	Less intense (especially RTK)	Essential for accurate photogrammetry
Best Use Case	Precision mapping with RTK UAVs, large AOIs	High-accuracy mapping with budget drones
Photogrammetry Support	Fully supported (e.g., Pix4D, Agisoft, DJI Terra)	Fully supported (requires manual input)
Dependency	Requires correction signal or PPK processing	Requires accurate GNSS survey gear (rover)

disease detection. Examples of active light sensors for soil include LightSpex Advanced Spectroscopy and Teralytic, which measure parameters like NPK, pH, moisture, and salinity. Examples of active light sensors for crops include Trimble GreenSeeker®, Holland Scientific Crop Circle™, and Yara N-Sensor. Each device utilizes slightly different algorithms to calculate an NDVI, allowing farmers to adjust fertilizer application rates based on the real-time plant health readings in the field; essentially, they all measure how much light is reflected from the plant at specific wavelengths, but the specific algorithms used to interpret that data differ between each sensor and can be influenced by factors like viewing angle and sensor design.

### Stationary Sensors

Continuous monitoring of a specific point can be achieved through stationary sensor systems that are linked together via a wireless network (Figure 9.1). For example, soil water content sensor networks have been used to monitor soil water over the entire season. Based on this information, the irrigation scheduling can be optimized and rates adjusted. Since these systems are stationary, they are generally used to track micro climatic parameters through time. Sensors measure temperature, humidity, wind speed and direction, and available water. They can also measure parameters such as solar radiation, light intensity, and amount of rain, which affect plant vigor. The sensors can be applied both in the environment in which the crop is developing for monitoring soil, air, and water conditions (extra-canopy) and at the plant level (intra-canopy) based on the concept of a “plant sentinel,” using single plants to estimate conditions for the surrounding crop. This modality essentially results in (spatial) mapping or (temporal) monitoring. While any mobile system can be used in a stationary mode, most stationary systems are intrusive, e.g., capacitance probes for measuring volumetric soil water status.



Figure 9.1 Soil moisture probe

### Mobile Sensors

Mobile proximal sensors measure soil properties and crop conditions while moving, or “on-the-go” or “stop-and-go.” On-the-go plant and soil sensors collect data in real-time while moving (e.g., mounted on a tractor, robot, or vehicle), while stop-and-go sensors require the operator to pause at each sampling point to take a measurement (Figure 9.2). On-the-go sensors offer the advantage of dynamic data collection during fieldwork, while stop-and-go sensors provide potentially more precise measurements when the device is stationary. Like the conventional sampling approach, these sensor systems provide detailed information on specific field locations defined by the user and typically have lower mapping density than on-the-go systems. An example of an on-the-go soil sensor was introduced by Veris® Technologies of Salina, Kansas, for EC mapping within the soil by ion-selective antimony electrodes. It measures EC at two depths (0 to 12" and 0 to 36") as the device is pulled across a field. Stop-and-go sensors usually collect information at a predefined location and then travel to the next point of investigation. A standard cone penetrometer (ASABE standard 5313.3) is an example of a stop-and-go sensor used to obtain data representing the soil profile at a given location. A cone penetrometer measures the soil's resistance to pushing a cone into the soil. When analyzed under specific physical conditions, these measurements provide information on soil compaction.



Figure 9.2 The Trimble® GreenSeeker® crop sensing system helps the farmer effectively and precisely manage crop inputs on-the-go. With GreenSeeker, the farmer can address field variability by applying the right amount of fertilizer in the right place at the right time.

## 11.3 Combine Harvester Components

### Yield Monitor Console

The yield monitor console (Figure 11.1) is a data collection unit and computer that records data from the yield sensor, moisture sensor, and DGPS receiver. The display is also used by the grower to input information, such as the header width, swath width, ground speed, field name, crop type, cultivar, and electronic flags manually set by the operator. For instance, the data collected from a field could all be tagged with, or referenced by, a user-supplied name such as “Field A” or “North Forty.” Electronic flags are often used to record the location of weeds (known to be highly correlated with yield reductions). These flags may locate and identify other problems or obstacles, such as rocks, terrace failures, standing water, etc. In addition to sensor inputs, the display console receives inputs from the combine operator. This permits the operator to provide data for which no sensor is installed (width of cut, for example) or field or load information to permit tagging or referencing of the yield and moisture data that is being collected.

The console may also monitor or record elevation, elevator speed, ground speed, swath width, header height (for switching the unit on and off) and electronic flags manually set by the operator. Electronic flags are often used to record the location of weeds known to be highly correlated with yield reductions. These flags may also help in managing other problems such as rocks, terrace failures, standing water, etc.

A yield monitor equipped with a DGPS receiver stores data in a format that includes position information. These spatially indexed data are later used to produce maps of yield, moisture, elevation, or any other information collected during harvest. Most yield monitors can display instantaneous readings of yield and moisture and provide statistics for loads or batches of grain from a field or within an area of a field.

Today, many combines can be purchased with factory-installed yield monitors. After-market yield monitors are also available for installation on late-model combines. The software on the computer is generally sold as part of a mapping software system with other precision agriculture solutions, such as John Deere’s Agricultural Management Solutions (AMS), Case IH’s Advanced Farming Systems (AFS), New Holland’s Precision Land Management (PLM), and AGCO’s Fuse® Technology. The resulting map can be further analyzed using the standard integrated system, or it can be imported into other mapping analysis software if preferred, such as Ag Leader’s SMS™ or ESRI’s ArcMap™. Combine manufacturers offer display options that come pre-installed with their systems, but other computer displays, such as the Ag Leader® Integra or Trimble® FmX®, are also available through third-party dealers. Computer displays and the GNSS receivers can be moved between harvesters and tractors used for other precision agriculture technologies, so they can be used for more than yield mapping.

### Data Collection and Storage

Yield monitors create files containing large amounts of spatial information, including the type of monitor, longitude, latitude, field name, object ID, track, swath width distance, elevation, header switch status, GPS

**FIGURE 11.1**

A yield monitor console is the operator interface for the yield monitoring system installed in a combine harvester. It displays real-time harvest data, including grain yield, moisture content, and field location, and is central to precision farming and harvest mapping.



The commonly used actuators in robotics are electric actuators. This actuator converts electric energy into linear or rotary motion. Hydraulic actuators use compressed oil to cause motion. They are most commonly used in heavy machinery, and they can generate very high force. Pneumatic actuators are very similar to hydraulic actuators. Instead of using compressed oil to cause motion, they use compressed air.

### End Effectors

The end effector, also known as an end-of-arm tool (EOAT), is a special tool at the end of the robot's arm, giving the robot its hands and fingers. It allows a robot to pick up, manipulate, and work with objects like your hand would. At present, a wide variety of end effectors have been developed, with fingers, attractors, needles, spray nozzles, scissors, and robotic arms, to grip, cut, attach, or press into crops to effectively perform all biological production processes, which include picking, harvesting, spraying, sowing, transplanting, shaping, and primary processing. Because end-effectors come into direct contact with the objects being manipulated (or being operated on), the end-effector efficiency greatly determines the performance of a robotic system.

The current robots (that are being developed around the world) are primarily utilized to harvest vegetable and fruit crops in greenhouses, orchards, and vineyards. Vegetables and fruit crops in greenhouses are characterized mainly by soft surfaces and small sizes. Peppers, for example, with their smooth, waxy surface, are well suited to be gripped by suction cups. Tomatoes are more fragile than peppers, so the robots use a soft-fingered gripper that twists the fruit as it is pulled to separate it from the plant. Strawberries are even more delicate, requiring extra care to harvest them. Fruit detaching methods directly affect fruit damage rate, harvest success rate, and cycle time. Many fruit detaching methods rely on stem detachment from the branch by exerting external force directly or indirectly on the stems. These can be categorized into four groups based on force application: grasping and stem cutting, vacuum suction and plucking, and twisting and pulling.

### Grasping and Stem-Cutting

At present, stem-cutting end-of-arm tools (EOATs) are mainly used for long-stem fruits such as strawberries, cucumbers, and tomatoes (Figure 14.2). Given that the fruit stem abscission layer is naturally formed when the fruits mature, EOATs acting on separating the fruit at abscission do not need an additional stem separation mechanism. These EOATs can separate the fruit through pulling, folding, and twisting while the fingers steadily hold the fruit. Stem cutting might cause disease infection

in plants. Therefore, thermal cutting provides an alternative that is considered a safe way to sever fruit stems.



Figure 14.2 Robots can harvest tomatoes by grasping and stem-cutting, using various mechanisms to ensure precise detachment and minimize damage.

### Vacuum Suction and Plucking

Vacuum grippers utilize suction to pick up and hold objects, making them suitable for delicate fruits and vegetables that can be easily damaged by mechanical grippers (Figure 14.3). Vacuum grippers can be designed with different suction cup shapes and sizes to handle a variety of produce types.



Figure 14.3 The robot operates using vision-guided suction cup end-effectors to harvest apples.

### Twisting and Pulling

Robotic end-effectors for harvesting often utilize twisting and pulling motions to detach fruit from plants (Figure 14.4). These motions are inspired by manual picking methods and are designed to efficiently and effectively detach produce while minimizing damage.

### Path Planning

Finding a continuous route for the robot to travel from the initial state to the target state/configuration is called path planning. The mobile system uses a known map of the

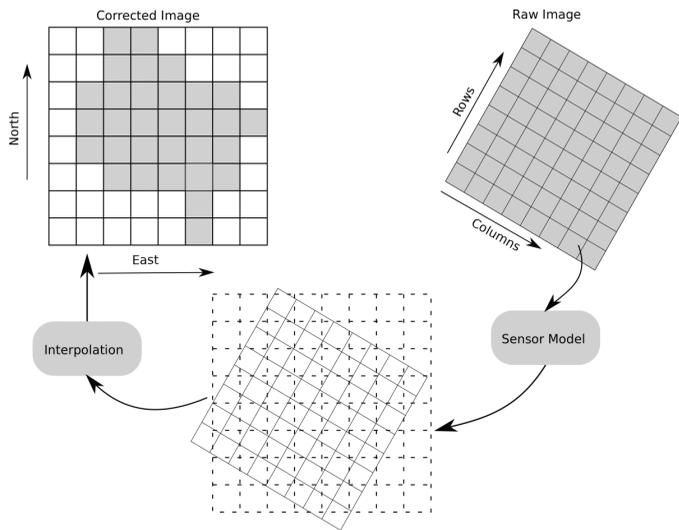


Figure 15.6 Rectified output image

images. The image, therefore, has a more “natural” look. Another relatively complex resampling method is cubic convolution. Cubic convolution uses a weighted average of values within a neighborhood that extends about two pixels in each direction, usually encompassing 16 adjacent pixels. Typically, the images produced by cubic convolution resampling are much more attractive than those of other procedures, but the data are altered more than are those of nearest-neighbor or bilinear interpolation, the computations are more intensive, and the minimum number of GCPs is larger.

### Orthorectification

Image data acquired by airborne systems is affected by systematic sensor and platform-induced geometry errors, which introduce terrain distortions when the sensor is not pointing directly at the nadir location of the sensor. Orthorectification aims to create a final product whereby every pixel in the image is depicted as if it were viewed at a nadir (or directly overhead), thereby removing the effects of hills, valleys, etc., on the data (Figure 15.7). Once data has been orthorectified, one can accurately compute distances, areas, and directions from the imagery. Orthorectification places image features in their true ground position while ensuring a uniform scale. A digital elevation model (DEM) performs image orthorectification to remove image distortions accurately.

### Image Registration

Image registration in digital image analysis is the process of geometrically aligning two or more images of the same scene, or different images of the same scene taken at different times, from different viewpoints, or with different sensors. The goal is to bring the images into spatial

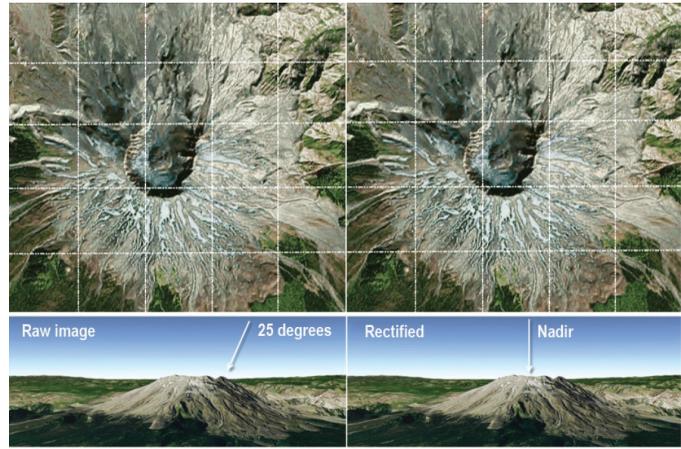


Figure 15.7 A view captured from an oblique angle (for example, 25°, left) must be corrected for relief displacement caused by terrain to generate the orthorectified view (looking straight down, right)

correspondence, allowing for meaningful comparison, analysis, or integration of the data. It is essential for change detection, image fusion, multi-temporal analysis, and classification.

Table 15.2 Types of Image Registration

Type	Description	Example
Multitemporal	Register images from different dates	Drought monitoring, crop stage analysis
Multisensor	Align data from different sensors	SAR + optical fusion
Multiview	Align images from different angles	3D reconstruction, UAV photogrammetry

### Image Mosaicing

Georeferenced (or orthorectified) images with different spatial resolutions, brightness histograms, and sizes can be digitally mosaicked (i.e., join two or more images with overlapping regions) with advanced image processing software (Figure 15.8). Image mosaicing is still one of the hot subjects, especially for remote sensing applications. The two primary steps for image mosaicing include (1) image alignment and (2) blending. In the alignment step, the common region of the overlapping images is used to align the images on top of each other using either the intensity-based methods, e.g., Normalized cross-correlation (NCC), that depend on the intensity of pixels, or the feature-based methods, e.g., scale-invariant feature transform (SIFT), that rely on some distinct or salient features such as edges and points. The blending methods can be classified into three groups: transition smoothing (weighted average of

Spatial databases can be more complex to set up, manage, and query compared to relational databases. The ecosystem of tools and applications that support spatial databases is often less mature than that of relational databases.

## 16.6 GIS Spatial Analysis

GIS spatial analysis in agriculture uses geographic information systems to analyze spatial data like soil maps, weather patterns, and crop health to optimize resource allocation, improve yields, and enhance sustainability. It enables farmers to make data-driven decisions about resource allocation, crop management, and overall farm operations. By integrating spatial data like land use, topography, climate, and soils, GIS helps optimize resource utilization, boost productivity, and promote sustainable practices. Spatial analysis in GIS uses location-based data (e.g., coordinates, polygons, raster grids) to uncover:

- Patterns (e.g., crop health zones)
- Relationships (e.g., proximity to water sources)
- Changes over time (e.g., land use)
- Optimal solutions (e.g., best site for planting)

### GIS Data Layers

GIS data layers, in the context of geographic information systems (GIS), refer to the thematic representation of spatial data that is overlaid on a map. These layers organize and display specific types of data, such as roads, land use, population density, or elevation, enabling users to analyze and visualize complex geographical information in a structured and coherent manner. Each layer can be manipulated independently or combined with other layers to produce comprehensive maps that reveal insights into spatial patterns and relationships.

Data layers are essentially the building blocks of any GIS application. They consist of spatial and non-spatial data that are stored in a digital format. Spatial data includes the coordinates and geometry representing geographic features on Earth, such as points, lines, and polygons. Non-spatial data, or attribute data, consists of the information associated with these features, such as names, categories, statistics, and other pertinent details.

In GIS, data layers can be visualized as transparent sheets stacked upon each other, each with unique information. For instance, a map might have separate layers for soil conditions, land use, crop conditions, and other relevant factors. By controlling the visibility and order of these layers, users can generate tailored maps that emphasize specific aspects of the data.

The use of data layers is crucial for spatial analysis and decision-making processes. By analyzing different layers together, GIS users can identify trends, assess management practices, manage resources, monitor changes over time, and solve spatial problems more effectively.

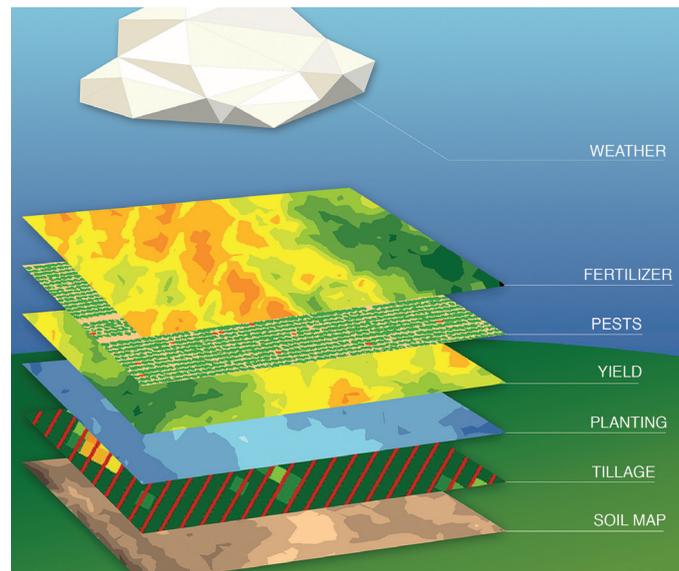


Figure 16.3 GIS data layers

### GIS Spatial Data Analysis Techniques

Spatial data analysis uses a large variety of techniques to uncover patterns, relationships and predictions that inform decision-making. These methods range from overlaying datasets to creating predictive models, offering tools for those in agriculture. Each approach provides a unique way to interpret data, solve problems and guide resource allocation.

- **Overlay Analysis.** Overlay analysis in GIS involves combining two or more spatial layers to create a new layer that combines the information from each input layer. This technique is widely used in agriculture to analyze spatial relationships between different factors like soil type, elevation, climate, and crop suitability.
- **Buffer Analysis.** In agricultural GIS analysis, buffering is a powerful tool for creating zones around geographic features to study spatial relationships and assess proximity. For example, a buffer around a river can help identify agricultural fields within a floodplain, aiding in land management and flood risk assessment. Buffers can also be used to create protected zones around sensitive areas like wetlands or endangered species habitats.
- **Proximity Analysis.** Proximity analysis, for example, helps farmers determine the ideal location for crops

# Precision Agriculture

Updated and revised to keep pace with developments, the third edition of *Greenhouse Management* is meant to be a stand-alone resource guide that describes all phases of greenhouse management. This book is written in a non-technical format designed to be practical and well-suited guide for growers, technical industry representatives, and university horticulture students.

## Key Features of the Third Edition:

- New chapters on greenhouse curtains and artificial intelligence in greenhouses
- A better introduction to greenhouse lighting
- Updated information on growing media
- Expanded coverage on irrigating greenhouse crops and micro-irrigation systems
- A dedicated chapter on greenhouse water treatment and filtration
- Revised and expanded information on fertigation
- Expanded coverage on plant nutrition of greenhouse crops
- Revised and expanded information on pesticide application
- A number of important appendices have been added

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