Chapter

Precision Agriculture for Sustainable Soil and Crop Management

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Abstract

Precision agriculture (PA) transforms traditional practices into a new world of production of agriculture. It uses a range of technologies or diagnostic tools such as global navigation satellite system (GNSS), geographic information systems (GIS), yield monitors, near-infrared reflectance sensing, and remote sensing in collecting and analyzing the in-field spatial variability data, thereby enabling farmers to monitor and make site-specific management decisions for soils and crops. PA technology enables visualization of spatial and temporal variations of production resources and supports spatially varying treatments using variable rate application technologies installed on farm agricultural field machinery. The demand for PA is driven by recognition within-field variability and opportunities for treating areas within a field or production unit differently. PA 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 making, for example, site-specific deep tillage to remove soil compaction. PA technology ensures optimal use of production inputs and contributes to a significant increase in farm profitability. By reducing crop production inputs and managing farmland in an environmentally sensible manner, PA technology plays a vital role in sustainable soil and crop management in modern agriculture.

**Keywords:** farm profitability, GNSS, GIS, precision agriculture, remote sensing, site-specific management, soil and crop management, sustainability

1. Introduction

Soil and water are essential resources for food production and sustaining human life. These resources are under pressure given the expansion of urban areas and the effect of climate change. Global food demand increases with population growth and improvement in the quality of life. The world must increase food production to feed more than an estimated 9 billion people by 2050 [1] with its limited arable land and natural resources. The advent of new technologies such as precision agriculture (PA) will significantly impact our ability to improve agricultural productivity in a sustainable manner on a global basis. PA is described as “the science of improving crop yields and assisting management decisions using high technology sensor and analysis tools” [2]. It is the art and science of utilizing advanced technologies such as global navigation satellite systems (GNSS), geographical information system (GIS), remote sensing, spatial statistics, and farm management information.
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systems (FMIS) for enhancing efficiency, productivity, and profitability of agriculture while reducing environmental pollution [3, 4]. Further, PA management coupled with genetic improvements in crop traits could play a vital role now and in the future in meeting global demands for food, feed, fiber, and fuel [5]. By adapting and managing production inputs within a field, PA allows better use of resources to enhance the sustainability of the food supply while maintaining environmental quality [6].

Currently, PA technologies are evolving at a relatively faster pace given the affordability of onboard computer power. It contains different types of new technologies, such as GNSS, sensors, geo-information systems, geo-mapping, robotics, and emerging data analysis tools. To evaluate crop health and performance in situ sensors, spectra radiometers, machine vision, multispectral and hyperspectral remote sensing, thermal imaging, and satellite imagery are used by researchers and innovative farmers [7–11]. Undoubtedly, the idea behind using these technologies is to make farming systems more efficient, profitable, and sustainable. Sensing tools help in evaluating crop biomass, weed competition, nutrient status and soil properties, and provide valuable data required for site-specific management (SSM) [8].

Current field machinery has great potential to revolutionize PA due to its ability to collect more data at a higher resolution and offer an increased capacity for detailed management of crops [12]. These machinery can be operated with the help of navigation geographic information systems, which is a system that combines both GNSS and GIS systems [10]. This system includes components not limited to i) map display, ii) path planning, iii) navigation control, iv) sensor system analysis, v) precision positioning and data communication [10]. The use of auto-steering GNSS-controlled tractors optimizes path planning while reducing overlap. Map-driven seeding operations facilitate matching plant populations and crop genetics with the soil landscape based on historical crop yield as assessed from yield monitor data. Further, the same historical yield data can be used to enhance nutrient management and irrigation scheduling, thereby simultaneously enhancing productivity and profitability for farmers. Modern agriculture has also coined the term “Smart Irrigation”, which is essentially an Internet of Things (IoT) application in PA. The system senses soil moisture levels and manages irrigation scheduling in real time along with providing a record of field conditions and applied water to supplement farm management records [13].

PA tools can save farmers money as they enhance the efficiencies of commercial cropping systems [14]. Research conducted in the U.K. shows that a positive yield response over 20–30% of a 250-ha farm when using variable rate technology (VRT) to spatially manage nitrogen (N) management with concomitant increases in crop yield from 0.25 to 1.10 Mg ha\(^{-1}\) [15, 16]. Three years of study conducted by Longchamps and Khosla [17] showed that VRT can increase N use efficiency while simultaneously maintaining productivity and decreasing overall N introduction to the environment. Besides, PA reduces overall production cost while achieving at least equal crop yields when compared with conventional practices [18]. Variability driving the adopting of PA arises from variations in field topography, soil properties, soil nutrients, crop canopy, crop density and biomass, water content and availability, rainfall distribution, weeds, pest and disease infestations, tillage practice, crop rotation, and other factors [8, 19–22]. Low variance of soil parameters such as pH, phosphorus (P), or potassium (K) can be easily managed compared with substantial variations such as insect and disease infestation [23]. Variability within fields is typically measured by soil sampling, field scouting, physical measurements, soil survey, and yield monitoring [24]. However, the success of PA depends on the evaluation and management of spatial and temporal patterns in crop production. A graphical overview of PA technology is shown in Figure 1.
Sustainable soil and crop management are essential to improve the sustainability of agriculture [25]. Researchers consider pursuing the aim of agricultural sustainability through precision farming [25, 26], sustainable intensification [27], climate-smart farming [28], and integrated soil management [29], and many more. However, to achieve this, the cumulative use of best management practices (BMPs) of the agroecosystems is required, where i) optimum utilization of resources will be ensured, ii) soil health and quality will be maintained, and iii) environment and social benefits will be guaranteed at present without compromising the future [30–33]. Several studies showed that PA technologies could ensure the best utilization of resources, reducing variable costs and increasing farm productivity and income concurrently while decreasing the environmental impact [24, 26, 34–36].

2. Precision agriculture

PA is an innovative production system that is accomplished through the measurement of crop production variables coupled with the application of information technologies. Multiple terms have been coined by researchers to describe the application of PA practices to modern farming. The application of PA practices is sometimes termed “precision farming,” “site-specific farming,” “site-specific management,” “spatially variable crop production,” “grid farming,” “technology-based agriculture,” “smart farming,” “satellite farming,” and so on. The National Research Council [37] defined PA as “a management strategy that uses information technologies to bring data from multiple sources to bear on decisions associated with crop production.” According to Olson [32], who proposed a complete definition of PA is “the application of a holistic management strategy that uses information technology (IT) to bring data from multiple sources to bear on decisions associated with agricultural production, marketing, finance, and personnel [32].” More simply defined, PA is a farming concept that utilizes GIS to map in-field variability to maximize the farm output via optimal use of inputs [34].

Figure 1. A brief diagram of precision agriculture indicates concerns due to spatial and temporal variability, possible solutions/importance of PA, and a set of technologies encompassing PA and decision support systems.
PA encompasses the integrated use of GIS and GNSS tools to provide detailed information on crop health and soil variability [38]. It combines sensors, IT tools, machinery, and informed management decisions to enhance and optimize agricultural productivity by accounting for in-field variability and uncertainties within agricultural systems [6]. The primary goal of PA is to enhance sustainable soil and crop management of the farm by utilizing resources to increase food production and long-term profitability while reducing variable costs and environmental contamination. The specific purposes of PA are, therefore, to i) increase farm profitability, ii) enhance production, iii) reduce investment, iv) reduce soil erosion, v) reduce the environmental impact of fertilizer and pesticides, and vi) manage large farms in an environmentally sensible manner [32, 39]. PA has mainly three major components, namely: i) information, ii) technology, and iii) management (Figure 2). Thus, PA can be accomplished by recording data at an appropriate scale and frequency, proper interpretation and analyses, and finally, generation of actionable management decisions to implement at an accurate scale and time [37].

Several “Rs” (R stands for right) are recognized in PA, especially for nutrient stewardship that optimizes maximum crop yield and reduces nutrient losses. PA encompasses the optimum management of production inputs by implementing three “Rs”: the Right time, the Right amount, and the Right place [40]; four “Rs” [41] which includes an additional R, the Right source and five “Rs” [42] which described an additional R, the Right manner in addition to the earlier four “Rs”. The “Rs” applied to nutrient stewardship in PA directs farmers to place optimum nutrients in the root zones and make them available for crops when needed. PA involves better management of crop production inputs such as fertilizers, seeds, pesticides, herbicides, and machinery fuel by implementing the right management practice at the right place and time [43].

3. Importance of precision agriculture

PA is an approach for managing farms with the help of IT that improves the efficiency, productivity, and profitability of agriculture. PA can maximize land use, reduce the usage of inputs, and optimize crop management, resulting in healthier
crops and increased crop yield [35]. Technological advances are transforming agriculture as producers see many benefits from its innovation. Technologies such as GNSS guidance, autonomous tractors, agricultural drones, GIS, sensors, and software are assisting farmers to be more efficient than ever before [12, 38, 44, 45]. These technological advances help farmers specify the exact inputs and quantities, and precisely where to apply, to produce better crops, more food, and save resources. Robert [46] alluded that “PA is not just the injection of new technologies, but it is rather an information revolution, made possible by new technologies that result in a higher level, a more precise farm management system.”

Precision technologies precisely control various field operations required for crop production. PA advocates the need for precise agricultural input management in an environmentally sensible manner, which is consistent with the long-term sustainability of production agriculture [5, 24, 36]. Nevertheless, a farmer’s understanding of the within-field variability is essential. In conventional farming systems, farmers generally apply inputs such as fertilizer and pesticides uniformly to the whole field. They rarely think about spatial variations due to soils types, electrical conductivity (EC), soil moisture content (MC), pH, and nutrient availability. Further, the spatial variability of soil across the fields can be caused by land topography, soil texture, and historical management practices such as cropping patterns, crop rotations, soil fertility programs, and soil compaction over the years [47]. The use of “blanket doses” of valuable inputs results in a portion of those inputs never being used by plants. This results in an increase in production costs of the farm while causing environmental pollution. In the U.K., considerable differences in the spatial patterns and magnitudes of crop yield variation were reported even in uniformly managed fields due to soil variability, rainfall, and field operations [15]. PA technologies assist in quantifying and managing spatial variability of soils by developing site-specific management zones (SSMZs), which subdivide the field by treatment regiments. Therefore, precise crop input management enhances nutrient use efficiency, especially environmentally sensitive macro- and micronutrients, particularly N [24, 48]; while maximizing farm output and profitability [32, 39].

4. A brief history of precision agriculture

The historical development of current PA technologies spans a period of over 40 years. A brief history of PA technologies is warranted to given that adoption in some areas have lagged. The following discussion is divided between two rather distinct areas—pre-GNSS (before 1980) and post-GNSS (1980s and beyond).

4.1 Before the 1980s

Early in the twentieth century, research focused on topics such as field heterogeneity, spatial variability, and site-specific agriculture was concentrated mainly on crop nutrient management [49–51]. Soil sampling at 15 cm depth on a 0.4 ha grid was reported as the first known recommendation to address these concerns [50], including works focused on developing statistical tools and methods [52]. The mechanization of agriculture, including tractors and fertilizer applicators in the 1930s, increased food production and farm efficiency [53]. Melsted and Peck [54] considered visionaries, helped build the foundation for successful variable-rate fertilizer application using a soil sampling on a 24.3-m grid pattern around 1961 [51]. The Green Revolution that occurred during the 1950’s and 1960’s increased agricultural production worldwide, particularly in the developing world [55], and saved over a billion people from starvation. The main components of the “Green
Revolution” included high-yielding cereals, fertilizers and agro-chemical application, irrigation, and improved management practices and mechanization. The U.S. Department of Defense first developed a satellite-based radio-navigation system, the global position system (GPS), in the 1970s, but it was confined for military uses until 1980, when encryption was partially eliminated, thereby encouraging civilian use [56]. However, the GPS usage was prevalent in agriculture did not occur until 1993, given the lack of available correction to improve the horizontal accuracy of coordinates (< 2.0 m) [57]. GPS served as a model for other countries to develop similar radio-navigation systems today, and when combined, is now known as GNSS.

4.2 1980–1990

PA farming practices were largely believed to originate in the early 1980s [43, 58] linked with the advent of the GIS and later GPS into the agricultural sector [59, 60]. The vision began to materialize for what a personal computer coupled with a GIS and a GPS could mean for agriculture [11]. In the late 1980s, research activities in PA continued with the development of yield monitors, grid soil sampling, soil sensors, GNSS receivers and differential correction capabilities, and VRT, more so in the United States and Europe than in other countries [58]. Both academic (university) and industries were dedicated to improving practical and cost-effective implementation of these systems. The main thrust was to adapt IT software and hardware along with appropriate communications technologies to agricultural settings. The value of the geographically positioning capabilities supported the collection of field data and observations and later produced different derivative products such as yield and VRT maps. However, the main obstacles during this time included lack of understanding, lack of support, evolving equipment, lack of standardization, inefficiencies of design, and many more [57, 60].

4.3 1990–2000

PA has been practiced in the mid-1990’s [43]. Equipment manufacturers introduced more accurate GNSS receivers, yield monitors, and software packages. By the early 1990s, yield monitors and VRT controllers became commercially available [58]. A significant step in making the PA possible was the invention of the on-the-go crop yield monitor in 1993 [61]. John Deere developed their first GPS receiver integrating satellite control into their product line in 1996 [62]. The evolving GNSS assisted farmers in tracking the coordinates of material applications or harvested biomass across a field. Popular laptop computers and handheld devices such as personal digital assistants (PDAs) with appropriate software contributed to significant advances in PA. These systems allowed PA to within-field locations, trace field boundaries, and record crop health observations. However, companies utilized numerous proprietary wiring, devices, and file formats for recording and transferring data. Hardware and software incompatibilities along with steep learning curves presented major hurdles for early adopters during this decade [11]. Many companies emerged with solutions for productive agriculture. In fact, industry, agribusiness managers, and farmers have played a significant role in the development of PA [63]. The agricultural community witnessed rapid growth and progress of PA technologies since the mid-1990s with the advances in GNSS, GIS, sensors, and remote sensing technologies [58]. Some equipment companies worked with growers, while others worked with retailers, distributors, crop consultants, and university extension personnel to engage growers. Several international conferences have been held, such as the 1992 First International Precision Agriculture...
Conference in Minnesota and Biannual European and Asian conferences in 1997 and 2005, respectively [58], and so on. “Precision Agriculture,” a new journal launched in 1999, and PA research have become a popular topic in this and other academic journals on a global scale.

4.4 2000–2010

PA services became more mainstream and profitable during this decade. The widespread use of tablet computers and cell phones, and smartphones and their ability to access the Internet aided the immediate and more effective implementation of PA activities. The introduction of flash drives and cloud computing fostered the aggregation and analyses PA data exchanged between the field and data repositories. Several books on this topic have been published, including *Handbook of Precision Agriculture: Principles and Applications* [64], *The Precision-Farming Guide for Agriculturists* [65], and more. The conferences, proceedings, journals, and books provide effective forums for disseminating original and fundamental research and experiences in the fast-growing area of PA [58].

4.5 2010–2020

PA became even more mainstream during the 2010s decade. Larger and small companies alike came forward as partners integrating with the larger companies. These companies offered new technologies or solutions to growers at scale. There was growing competition among companies to either provide PA products or services. The unprecedented growth of PA has been observed in countries such as the United States, Canada, Germany, Australia to Zimbabwe, and others [5, 66]. In contrast, the rest of the world has seen relatively slow to embrace PA technologies [5, 66]. During this decade, the use of GNSS guidance systems dramatically increased in the Midwest and Southern regions of the U.S., estimating the current adoption rates of greater than 50% [67]. Emerging tools, such as satellite imagery and unmanned aerial vehicles (UAV) to support crop production systems, were reportedly used on 18% and 2% of crop production acreage, respectively [63, 67]. The use of UAVs alone increased from 2 to 16% by 2018 [63, 67]. Information gathering and analysis services such as grid/production zone soil sampling, UAV imagery, and yield map analytics increased substantially. The embrace of IoT applications in agriculture began to appear at the end of this decade in the Midwest U.S. [68].

4.6 2020s–current

The current decade marks the transition from PA to decision agriculture [11]. The earlier learning for technical skills and data solutions becomes a requirement for involvement in PA. Customers desire an integrated PA program and decision support system (DSS). It is the integration of technology, skill, and knowledge that will fuel complete solutions. Today’s growers desire a single system that integrates production decision making, BMP adoption, and risk management under one umbrella. The envisioned systems will aid framers to optimize their operations while improving the stewardship of farmland. The integration of PA technologies to include artificial intelligence, IoT, and cloud computing is becoming more common place in recent years. However, PA innovations will be continued to emerge similar to other technology-oriented industries. These will undoubtedly create new opportunities and also challenges given the complex and changing nature of global agriculture. It is expected that crop management decisions will increasingly be guided by the analyses of historical and real-time data collected from agricultural crop fields [68].
5. Applications of PA for sustainable soil and crop management

Modern agricultural practices, mainly forms of PA, are now mostly driven by efficiency, economic, and environmental considerations. PA offers solutions to select and deploy BMPs for producing crops in the agricultural field settings. The technological skills and knowledge associated within PA technologies will drive the implementation of sustainable soil and crop management practices. Some of the key aspects of PA that align with the sustainability of soil and crop management include soil sampling, geostatistics and GIS, farming by soil, site-specific farming, management zones, GPS, yield mapping, variable rate-nutrients, rate-herbicides, rate-irrigation, remote sensing, automatic tractor navigation and robotics, proximal sensing of soils and crops, and profitability and adoption of precision farming [45, 69–72]. A brief description of PA, including technologies for site-specific crop management, is shown in Figure 3.

Further, the key technologies and approaches for PA applications have been briefly described next.

5.1 Geospatial applications

The term “geospatial technologies” is used to describe the range of tools to produce geographic mapping and analysis of the Earth’s surface and human activities. Different types of geospatial technologies include remote sensing, GIS, GNSS, and Internet mapping technologies. GIS can assemble geospatial data that include information on its precise location on the Earth’s surface, also called geo-referenced, into a layered set of maps. GIS is a suite of software tools, which enables mapping and analyzing these geospatial data. The use of automated field machinery to accomplish crop production field operations is inevitable for modern...
agriculture [75]. These machines can be operated with the help of GIS and GNSS along an optimal path to perform field works precisely as per the positioning information provided to it. The success of geospatial technology depends on the collection of accurate data and their proper analyses and interpretations. Remote sensing technology is used to collect imagery and data on Earth’s surfaces and human activities. It shows detailed images at a resolution of 1 meter or less area, and helps monitor and address the problems and needs. Software programs such as Google Earth and web features, such as Microsoft Virtual Earth, facilitate changing the way the geospatial data are viewed and shared.

In PA, remote sensing technology facilitates dividing of large fields into smaller management zones [76]. Each zone aggregates specific crop management needs and production limitations. GIS and GNSS are central to the PA technologies for dividing cropland into small management zones. These divisions are accomplished mainly based on a) soil characteristics such as soil types, soil pH, soil EC, soil MC, nutrient availability, and soil compaction; b) crop characteristics such as i) crop canopy and density, insect and disease infestations, fertility requirements, hybrid responses, crop stress; and c) weather predictions. Observation made using remote sensing technology are geo-referenced within a GIS database. Therefore, much of PA relies on remote sensing imagery data, for example, to determine the chlorophyll content of plants as it relates to growth, yield, and productivity of different management zones [77]. A brief illustration of the GIS data-based soil map is shown in Figure 4. Datasets are recorded using remote sensing imagery data and can easily be converted into spatial data using GIS techniques and tools such as the “Kriging method” [77]. GIS software is used to develop digital maps that transform spatial information into digital format. These spatial data reflect and delineate all management zones within the farm.

5.2 Remote sensing

Remote sensing technology is used to collect image data from space- or airborne cameras and sensor platforms. Aerial remote sensing platforms such as sensors
on-board satellites and aircraft, including UAVs, have recently seen an increase in use. These technologies can be used to estimate and quantify many soil properties by integrating geo-referenced field data (soil and crop) with spectral properties of soil acquired by sensors. Khanal et al. [79] reported that integration of remotely sensed data and machine learning algorithms offers a cost-and-time-effective approach for spatial prediction of soil properties and corn yield compared with traditional methods [79]. Remotely sensed images can overcome such limitations and improve spatial and temporal coverage of data on soil and the yield of crops. Aerial and ground-based drones can be used for soil and field analysis, crop planting, applying pesticides, crop monitoring, irrigation, and health assessment [72]. Recently a startups company developed a UAV-based seeding system that reduces costs by 85% [72]. Sensors gather data on soil water availability, soil fertility, soil compaction, soil temperature, crop growth rate such leaf area index, leaf temperature, pest, and disease infestation. A typical example of remote sensing technology’s components is shown in Figure 5.

5.3 Site-specific soil and crop management

According to Robert et al. [40], “site-specific crop management is an information and technology-based agricultural management system to identify, analyze, and manage site-soil spatial and temporal variability within fields for optimum profitability, sustainability, and protection of the environment.” The most general approach to address such soil property spatial variability is the creation and management of SSMZs or sub-zones [84, 85]. These production level SSMZs or sub-regions are homogenous and have similar characteristics and yield-limiting factors with equal productivity potential [84, 86]. Khosla and Alley [86] optimized a soil sampling grid method using homogenous management zones in a large field. Fleming et al. [87] developed nutrient maps based on production management zones for VRT nutrient application. The delineation of soil property spatial variability can also be accomplished by identifying location spatially coherent areas within the field [88]. The delineation of management zones of a large field can facilitate managing variability
among the different zones [89]. A recent study suggested that a 50-m soil sampling interval can be considered an optimal interval for delineating production management zones in medium- and small-scale farmlands [90].

Wells et al. [91] reported that precision deep tillage varying depth compared with deep tillage at 400 mm in one site out of three locations enhanced crop yield and farmers’ benefits. Adoption of control traffic farming technology [92–94], reducing tire inflation pressure systems [25, 30, 95–99], and site-specific deep tillage [25, 88, 91, 100] are becoming viable methods for reducing soil compaction and enhancing the productivity and sustainability benefits in many cropping systems. These benefits can be triggered and expedited by adopting PA technologies. With the advances in PA and application of remote sensing tools, soil compaction assessment and mapping, modeling, and possible management can also be accomplished [9, 25, 101]. A recent study in the USA showed the adoption rates of grid sampling practice linked with site-specific lime and fertilizer application have been adopted on 40% of cropland (two out of five crop acres) [67]. On the other hand, the adoption of GNSS-assisted yield monitors for site-specific lime and fertilizer application was 43 and 59%, respectively [67]. Studies in the U.K. showed that autonomous equipment for PA is technically and economically feasible; and, if adopted, offers the potential to minimize costs for many farms [12].

5.4 Variable-rate technology (VRT)

PA is often misinterpreted as a complex technological intervention to agriculture in the developed world [5]. It is, however, shown to be profitable in less-developed regions in the world. For example, micro-dosing of nutrients to nutrient-starved soils in Africa showed an increase in crop grain yields [102]. Several case studies demonstrated that managing in-field variability benefited farmers in China [103]. Geostatistical methods are used to evaluate the spatial distribution of soil properties of a farm [104]. A detailed understanding of the spatial distribution of soil properties facilitates the SSM for maintaining crop and soil productivity while minimizing costs and decreasing the environmental impact [105–107].

Sustainable soil nutrient management, that is, site-specific nutrient management with a complete understanding of in-field soil and spatial variability, performs well in avoiding soil degradation and improving crop productivity [25, 108]. It is well known that soil physical and chemical properties are spatially variable and can be affected by farming practices such as irrigation and fertilization [48, 88, 109], so VRT application is crucial in the management of in-field soil variability. N is the most mobile and dynamic nutrient [86] and plays a vital role in maximizing crop yields and returns to farmers. These soil properties and management practices can affect N dynamics and the mechanisms of its losses from the soil. Remote sensing and GIS tools allow identifying, measuring, and developing maps of these changes across the field landscape. It has shown that VRT N management can potentially improve the N use efficiency by better adjusting N rates to crop needs [17]. A recent study demonstrated that site-specific P and K management could optimize target crop yield and save 21 kg ha$^{-1}$ and 30 kg ha$^{-1}$ of P and K, respectively, compared with conventional farming [90]. Therefore, the application of the correct products in the correct place at the correct rate is recognized as one of the key benefits of PA, which is generally accomplished with the use of VRT [67].

5.5 Yield monitoring and mapping

Today, modern combine harvesters are sold with integrated yield monitors as standard equipment, presenting a powerful tool for grain production. It allows
farmers to assess and delineate the effects of weather, soil properties, and management on grain production [71]. Shearer et al. [71] reported that there are three key benefits of the yield monitors: i) an operator can quickly view crop performance during harvest, ii) yield data can be transferred to a computer and summarized on a field-by-field or total-farm basis, and iii) this information can be geographically referenced to generate yield maps for year-to-year comparisons of high- and low-yielding areas of a field. However, proper installation, calibration, and operation are necessary to ensure the accuracy of these devices. Soil sampling followed by laboratory analyses provides detailed soil health information while yield monitors help in understanding the spatial variability in crop yield [79]. An example of different components of the yield monitoring and mapping system and yield map is shown in Figure 6a and b.

PA promotes the better use of information to improve the management of in-field soil and spatial variability on the farm [111]. The yield maps are central to the management of arable management [111]. Yield mapping and soil sampling tend to be the first stage in implementing precision farming [59]. The yield monitoring

![Figure 6](image_url)

**Figure 6.**
Different components of yield mapping system (a) and yield map (b) [110]. Red color indicates low-yielding areas, and green indicates higher than average crop yield.
system allows the collection of geo-referenced yield data and generation of yield maps for visualizing crop performance variability. Several interpolation techniques such as the inverse of distance, inverse of square distance, and ordinary kriging are commonly used in developing yield maps [112].

5.6 Agricultural robots

Robotics is reshaped agricultural practices beyond recognition. Robotic applications in agriculture, forestry, and horticulture are continuing to evolve [113]. Refinement of crop production management resolutions to the individual plant level will require the deployment of autonomous and robotic technologies. Autonomous tractors, drones, crop harvesting robots, seeding machines, and robotic weeding are some of the emerging technologies that make the PA more meaningful. Autonomous platforms can be used from field preparation to harvesting of crops and provide more benefits than conventional machines [114]. These platforms reduce the overall environmental impact of crop production through the targeted application of pesticides and fertilizers, reduced energy requirements, and lower vehicle weights while reducing soil compaction [115, 116]. Recently, robotic weeding and scouting and applying crop production inputs via UAV/drone are garnering more confidence in their potential among producers, retailers, and dealers in the Midwest United States [117]. Crop growth monitoring using a robot is shown in Figure 7.

6. Challenges and future trends

Future trends and challenges in the development and adoption of PA practices will demand new technical skills and knowledge, and a different mindset among farmers and end users. From the current user perspective, the adoption of PA is difficult as farmers are comfortable with tried and true historical production practices. Hightower [119] indicated that this mindset creates challenges, and it is difficult to overcome such mental barriers to adopt PA. High cost, lack of perceived benefits, and skills, expertise, and capability required for farmers or end users are considered
barriers to the adoption of PA [120]. The potential barriers to PA adoption are often not fully understood or treated seriously enough by the front-line agriculture professionals [121]. The large-scale adoption of PA requires the timely acquisition of low-cost, high-quality soil and crop yield maps [79]. While the benefits of autonomous crop equipment are many, and have the potential to revolutionize PA, its widespread adoption will be less likely unless farmers find them profitable [12]. PA in many developing countries is still considered a concept. Therefore, it is vital to promote the public and private sectors’ concomitant role and strategic support in promoting its rapid adoption. PA adoption is dependent on access to large amounts of reliable data; however, it is crucial to limit the gap between acquiring this information and utilizing it effectively in making management decisions for production agriculture [39].

Today, the trend toward PA applications in other domains includes precision animal/live-stock management, precision turf management, precision pasture and range management, and precision tree management [46]. During recent years, the agricultural community has become familiar with application of the new technologies from other industries. For example, IoT, artificial intelligence, and cloud computing are beginning to appear as part of PA services and applications.

IoT describes the interconnection of different physical objects through the Internet or other communications networks. In IoT, objects are embedded with sensors, onboard processing capabilities, software, to transfer data via the network without human interaction [122]. The application of IoT in agriculture was reported in the greenhouse setting [123], while other uses have also been reported for precision farming and farm management systems [13, 124]. The application of IoT in agriculture helps farmers to manage agricultural activities, control their farms remotely, minimize human efforts, and save time while increasing crop yields and benefits [123–125]. Further smart UAVs coupled with IoT and cloud computing technologies, support the development of sustainable smart agriculture [126]. Another concern is the security and privacy of data and information produced by the PA technologies given its economic value to farmers [127]. Therefore, it is important to assign ownership to these data and work products, so that those entities responsible for this information share in value creation [57]. This is one of the major concepts to be sorted out to ensure the successful implementation and adoption of PA.

7. Conclusions

PA transforms traditional production practices to intensive production practices with spatially and time-varying data. It is quickly becoming a vital component of successful farming operations in continually evolving agroecosystems. PA encompasses a set of related technologies that aim to conduct and increase the precision of cultivation practices, increase the efficacy of crop inputs, and increase higher soil and crop productivity. Like most other technology-oriented industries, PA has evolved through multiple phases in a relatively short period of time. Fields and sectors deploying PA technologies such as GIS, GNSS, and remote sensing continue to grow. With the use of remote sensing, GNSS, and GIS, farmers now routinely measure, map, and manage the spatial variability of their farms. The ability to visualize this variability has given rise to SSM decision making, which optimizes input use efficiency, yield, and profitability while reducing environmental contamination. However, PA requires technical skills, knowledge, and expertise to handle the range of technological tools now available to agricultural producers. High-tech field machinery coupled with appropriate sensing and control technologies can be capital intensive. Therefore, it is essential for producers to select and implement
PA technologies that offer the best return on investment for their unique situation. Alternatively, government entities may wish to consider incentives that encourage farmers to adopt PA technologies that have significant environmental benefits but may be at the margin of profitability for their operations. Strong linkage among researchers, extension workers along with industry partners, and farmers are vital to the continuing evolution and adoption of PA technologies.

Conflict of interest

The authors declare no conflict of interest.
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