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Satellite Crop Monitoring : Precision Meets Sustainability

Sujoy Saha, Ratna Thosar and Sneha Bhosale*

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ABSTRACT

Satellite crop monitoring which is an amalgamation of precision farming (PF) and smart agriculture leverages technologies like Global Positioning System (GPS), Unmanned Aerial Vehicle (UAVs), satellite imaging and variable rate technology for site-specific crop management. It enhances productivity by optimizing input use while minimizing waste and environmental harm. Economically, it is capable of reducing input costs by up to 20% while improving yields while environmentally, it minimizes chemical runoff, reducing pesticide usage by 30% and conserving water through precision irrigation. Tools such as soil sensors, UAVs, GIS, and data analytics platforms aid decision-making and sustainability. Despite benefits, PF adoption faces challenges like high initial costs, data privacy concerns, limited technical knowledge and infrastructure constraints. Satellite based crop management plays a vital role in climate change mitigation by reducing carbon footprints, minimizing fuel use and promoting sustainable practices like no-till farming. In India, The method includes soil health sensors, precision irrigation and digital platforms which form the core theme of enhanced sustainability. Although promising, the technology requires policy support, cost reduction strategies, and widespread education for broader adoption in sustainable agriculture.

Key words : Precision farming, Tools, Challenges, Sustainable agriculture practices, Impact of PF

Introduction

The mechanization of agriculture in the twentieth century led to a significant transformation in farming practices, transitioning from labor-intensive to capital-intensive methods. This shift allowed farmers to manage larger plots, achieve high yield and increase land productivity (Martín-Retortillo and Pinilla, 2015). Green Revolution further enhanced productivity through the development of genetically improved crop varieties and the use of synthetic fertilizers and pesticides. However, while these advancements have enabled broad efficiency gains but also reduced the ability to address within-field variability, including factors like soil characteristics, nutrient needs and abiotic and biotic stresses (Zhang *et al.*, 2002). Precision farming (PF) or climate smart agriculture or satellite crop monitoring which began to emerge in the 1980s, is a cutting-edge approach to agricultural management that uses advanced

ICAR-National Research Centre for Grapes, Plant Pathology, P.B. No 3, Manjri Farm, Solapur Road, Pune, Maharashtra, India, 412 307; *Corresponding author: Sujoy Saha, Email Id: sujoyta@gmail.com

technology to monitor and optimize crop production.

PF leverages technology to optimize crop production, resource usage, and environmental stewardship. Key features of precision agriculture include real-time monitoring of crop health, targeted application of resources, and improved decision-making based on data. PF technologies, which became more commercially available in the 1990s, helped to address spatial and temporal variability, thereby combining the advantages of both large- and small-scale operations and site-specific management. This approach encompasses a wide range of diagnostic tools to gather real-time data on variables such as soil moisture, crop health and nutrient levels. These tools ranged from satellite imagery, unmanned aerial vehicles (UAVs), which enabled high-resolution monitoring of crop biomass and soil properties (Candiago *et al.*, 2015). Applications of PF included Global Navigation Satellite System (GNSS) and variable rate technology (VRT), enabling precise, automated adjustments in inputs such as fertilizers, seeds, and water across different zones within a field (Robertson *et al.*, 2012). The term 'Satellite Farming' is occasionally used in this context. The core idea behind precision agriculture is to ensure that crops receive exactly what they need for optimal growth, at the right time and in the right amount. This not only enhances productivity but also minimizes waste and reduces costs.

By 2050, India's agri-food industry will face an alarming situation, i.e. feeding over 1.7 billion people on limited cultivable land, water, and energy resources. Natural resources, notably soil and water, have degraded as agriculture has intensified. The current input application strategy is focused on common recommendations for a composite sample or visual symptoms of crops and does not account for intra-field variability. It denotes suboptimal or excessive input application, as the recommended mean values are rarely found in a certain field. It diminishes input efficiency and causes environmental damage. Thus, intensification of agriculture using modern tools/techniques is essential. Precision farming is one of the solutions for sustainable development of agriculture.

Economic and environmental impacts of precision farming

PF had a significant effect on agriculture by offering both environmental and economic benefits. Economically, PF enables resource-efficient practices, optimizing inputs like water, fertilizers and pesticides to reduce overall input costs. Studies suggested that PF can reduce fertilizer use by up to 20%, lowering expenses while improving yields by utilizing measures specific to field conditions (Koch *et al.*, 2003). Interestingly, most studies in the late 1990s and early 2000s focused on the precision nutrient management aspects of PF, logically so, because this was the first PF technology that was technically feasible. In the following years novel technologies and improved management techniques continued to accelerate the adoption of PF including precision auto guidance, lightbar, autopilot systems, active crop sensing precision irrigation systems and smart sampling. Griffith *et al.* (2013)

investigated the economics of using a lightbar and auto guidance Global Positioning System (GPS) navigation technologies and found that a high-precision real- time kinematic (RTK) GPS system was less profitable to operate compared with no GPS use on a farm However, when a farmer started using GPS, its profitability increased with the level of GPS precision.

Environmentally, PF significantly reduced chemical runoff ultimately minimizing the impact on nearby ecosystems. Research indicated that variable-rate applications can cut pesticide usage up to 30%, limiting the introduction of chemicals into water systems and lowering contamination risks. By adjusting inputs according to soil organic matter and spatial variability, PF can prevent excessive chemical leaching and soil degradation (Mulla *et al.*, 2013). Advanced irrigation systems within PF enabled efficient water usage by monitoring soil moisture and adjusting schedules as needed, potentially reducing water usage by up to 25% in drought-prone areas. Delgado *et al.* (2008) used the Nitrogen (N) Loss and Environmental Assessment Package (NLEAP) model in Colorado to show that N leaching in irrigated corn could be reduced using variable rate nitrogen (N) applications. Variable rate N applications were particularly effective at reducing N leaching losses in management zones with low crop productivity where crop uptake of N was limited (Whitley *et al.*, 2004). In autosteer technology, precision farming reduced excessive application of chemical inputs. All of these factors for improved environmental quality and sustainability.

Tools of Precision Farming

Precision farming relies on various advanced technologies to enhance the efficiency and sustainability of agricultural practices (Mehta and Masdekar, 2018). Below are some key tools used in precision farming :

1. Satellite based tools : Satellite-based tools, such as GPS, Geographic information system (GIS), and remote sensing, play a pivotal role in precision farming. GPS enables precise field mapping and navigation of equipment, ensuring accurate placement of seeds, fertilizers, and pesticides while minimizing waste. GIS aids in analysing spatial data to manage fields effectively by identifying patterns in soil conditions, crop growth, and topography. Remote sensing, using satellites or drones equipped with advanced cameras, provides real-time imagery to monitor crop health, detect plant stress, and assess soil moisture. Together, these tools enhance efficiency, sustainability, and decision-making in modern agriculture.

2. Advanced mechanical tools : Advanced mechanical tools revolutionize modern farming by enhancing efficiency and precision. Laser land levellers ensure uniform field slopes using guided laser beams, improving water management and crop uniformity. Drones and UAVs provide aerial views to monitor crop health, water distribution, and pest infestations, enabling data-driven decisions. Combine harvesters with yield monitors gather real-time data on crop yield and moisture levels, facilitating yield mapping when paired with GPS. Auto-guidance systems use GPS for automated steering, reducing human error and optimizing planting, spraying, and harvesting operations. Robotics and autonomous machinery, including automated tractors and seeders, streamline tasks with minimal labour. Automated irrigation systems, equipped with timers and sensors, manage water distribution efficiently and further advancing precision farming.

3. Internet based tools : Data management software, including analytics platforms, helps farmers process and analyze data from precision farming tools such as sensors, GPS, and remote sensing, providing detailed reports and actionable points. Internet-based tools, leveraging IoT devices, enable the connection of farm equipment and sensors to a central system, allowing real-time remote monitoring and control of field operations.

4. Miscellaneous tools : Miscellaneous tools like soil sensors, leaf-coloured charts, and weather stations play a crucial role in modern farming. Soil sensors provide real-time data on moisture, nutrients, pH, and temperature, enabling precise irrigation and fertilization. Leaf-coloured charts offer an instant, low-cost method for diagnosing nitrogen levels in crops. Additionally, local weather stations supply real-time weather data, such as temperature, humidity, rainfall, and wind speed, aiding in the optimization of irrigation, pesticide application, and other farm activities.

Together, these tools help farmers optimize inputs, increase yields, reduce environmental impact, and improve overall efficiency, making precision farming a key component of modern, sustainable agriculture.

Role of Precision Farming in Climate Change Mitigation

Efficient utilization of resources to minimize waste and environmental impact is the cornerstone of PF which is achieved by precisely customizing inputs such as water, fertilizers, and pesticides to match the specific needs of crops.

a. Input Management : Precision farming enhances sustainability by optimizing fertilizer use, improving water management, and reducing pesticide application. Technologies like VRT and soil sensors minimize over-application of fertilizers, thereby reducing nitrous oxide emissions. Smart irrigation systems and soil moisture sensors address water scarcity by ensuring precise water delivery, conserving resources. Additionally, drone-based spraying and targeted pesticide application reduce environmental contamination, volatile organic compound (VOC) emissions, and the ecological footprint of chemical use.

b. Management of Carbon Footprints : Precision farming minimizes carbon footprints by reducing fuel consumption through GPS-guided machinery and auto-guidance systems, lowering CO_2 emissions. It promotes no-till farming and cover cropping to enhance soil health, increasing carbon sequestration and transforming soils into effective carbon sinks. Additionally, practices like site-specific management and crop rotation prevent land degradation, reduce deforestation, and maintain productivity, thereby mitigating greenhouse gas emissions linked to unsustainable farming methods.

c. Adaptation to Changing Climate Patterns : With the help of predictive analytics and climate modelling, precision farming allows farmers to anticipate and adapt to changes in climate conditions. This includes adjusting planting schedules, selecting more resilient crop varieties, or altering irrigation plans to suit evolving environmental conditions. These adaptive strategies help to maintain productivity and reduce the negative impacts of climate change on food security.

Challenges in Precision Farming

1. **High Initial Costs :** The adoption of PF technologies involves additional costs, such as initial investment cost, annual subscription costs, maintenance and operating costs. Many farmers considered initial PF costs as too high when compared with returns. The high upfront cost could inhibit adoption, especially for financially constrained farmers. Financial factors also pose major constraints to most of the innovative firms (Balogh *et al.*, 2021).

2. **Data Privacy and Security Concerns :** Precision farming relies heavily on data collection, thereby raising concerns about data privacy and ownership. Farmers may be hesitant to share sensitive data related to crop yields, soil conditions, or farm practices, particularly when working with third-party service providers or technology companies. When PF practices were first introduced, data generated belonged to farmers. With the launching of the big data era, data are aggregated across many farms and can be used in analyses, services and products created without the knowledge of the farmer. As use of PF equipment or services often requires producers to agree with sharing data, data privacy is a valid concern.

3. **Compatibility :** The compatibility of PF technology with existing resources affects ease of use, which in turn affects PF adoption. Compatibility, either among different manufacturer brands, or between hardware and software, could also be a concern to producers. Technology not compatible with current practices, equipment or existing software will pose additional challenges for farmers to adopt, especially for operations that require expensive equipment and specialized procedures.

4. **Lack of knowledge :** Knowledge affects farmer adoption decisions. Successful handling of PF machinery and software relies on good information service and training. Many farmers face difficulties in analyzing and interpreting data, which hindered use of data and management decisions based on them (Castle *et al.*, 2016). Adoption can be constrained by poor user experience, limited access to information and technical assistance. Moreover, demonstration and exhibition events significantly affect adoption decisions. Farmers need to see successful PF applications on lands like theirs to understand the benefits (Balogh *et al.*, 2021). Limited broadband connectivity in some rural areas also poses a significant barrier to PF adoption and restrict the benefits of PF technologies (Weersink *et al.*, 2018).

5. **Infrastructure Limitations :** Proper infrastructure is essential to facilitate data processing, its storage, accessibility and timely product delivery at the user and provider levels. In many developing countries, poor infrastructure such as unreliable power supply, inadequate roads, or lack of maintenance facilities for high-tech machinery can limit the use of precision farming tools. Without the necessary infrastructure, farmers cannot take full advantage of the available technologies.

6. **Economic and Market Risks :** Precision farming can increase productivity, but fluctuating market prices for crops may reduce the financial returns from increased yields. Moreover, farmers may be hesitant to invest in new technologies if they are unsure of future profitability or concerned about the long-term viability of their investment.

Integration of Precision farming with sustainable agriculture practices

PF is an integral part of sustainable agriculture in India as the country strives to improve food security, resource efficiency, and environmental sustainability. Innovative practices of PF along with Government-backed initiatives, have started transforming traditional agricultural practices by enabling farmers to manage resources more effectively. PF aims to balance productivity with environmental stewardship which is the major points of sustainable agriculture. The varied domains of this integration is as follows :

Soil Health Management through Smart Sensors

In India, soil health is a critical concern due to years of intensive farming that have led to progressive nutrient depletion. PF practices that use soil sensors to monitor nutrient levels are helping to address this issue sustainably. For instance, farmers can use these sensors to analyze soil health and adjust fertilizer applications based on specific nutrient needs, and avoiding their overuse.

Water Conservation with Precision Irrigation

Precision irrigation technologies, such as drip irrigation and soil moisture sensors, enable farmers to conserve water by irrigating crops based on real-time soil moisture data. States like Maharashtra and Rajasthan, which face acute water shortages, have adopted drip irrigation extensively, supported by Government subsidies. These practices not only reduced water wastage but also prevented soil erosion and salinization which are the key components of sustainable agriculture. Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) promotes micro-irrigation systems to encourage water-use efficiency, thus supporting sustainable water management at the national level (NITI Aayog, 2021).

Drones and Remote Sensing for Pest Management

Precision farming in India is also utilizing drones and remote sensing technology for pest and disease management. Drones can monitor large areas of crop land, identifying pest-infested zones, and enabling targeted pesticide applications (Burton *et al.*, 2023). This approach is already in use in states like Punjab and Haryana which helped the farmers in reducing pesticide usage, safeguarding biodiversity and reducing chemical pollution. Initiatives like the National Mission on Sustainable Agriculture (NMSA) support integrated pest management (IPM), combining traditional methods with precision tools to ensure environmental and economic sustainability (Khanal *et al.*, 2017). India is the first country to control locust by using drones after finalizing the protocols and getting all statutory approvals (Anonymous, 2020).

Digital Platforms for Resource Optimization and Farmer Empowerment

Digital platforms and mobile applications are bridging the gap between precision farming technologies and Indian large population of smallholder farmers. Apps like “Kisan Suvidha” and “Krishi Portal” provided farmers with access to data on crop prices, weather, soil health, and pest management (NITI Aayog, 2021). By providing critical information and reducing dependency on intermediaries, these platforms empowered farmers to make sustainable choices regarding crop management, input usage, and market access. Digitalization supported precision farming and enhanced the socio-economic sustainability of agriculture in India by enabling self-reliant farming communities.

Impact of Precision farming :

A. Economic Impact

Precision farming can significantly boost yields and incomes by optimizing resource use and improving productivity, particularly in horticultural crops. Projects like the Tamil Nadu Precision Farming Project (TNPFP) reported yield increases of 33% to 200%, despite cultivation costs rising by 30% to 100%. Low-cost methods, such as the Customized Leaf Colour Chart (CLCC), reduced input costs, while advanced technologies like micro-irrigation and nitrogen sensors enhance efficiency and quality. However, high initial costs, limited adoption due to fragmented agricultural systems, and farmers’ hesitancy to invest in unfamiliar technologies remain as major bottlenecks. While precision farming shows potential for long-term economic gains, further cost-benefit analyses are needed to support widespread adoption and profitability (Anonymous, 2021).

B. Environmental Impacts :

1. Soil, Nutrients, and Water Management

Precision farming significantly enhances soil health and water-use efficiency by balancing resource application. Techniques like GPS-guided tractor movements and nitrogen sensors reduced fertilizer use by 10-20 kilograms per hectare, minimizing nitrogen leaching and soil structural damage. Patch spraying and variable-rate applications lower herbicide use by 50-75%, reducing environmental contamination. PF’s water management techniques, such as micro-irrigation and laser land levelling (LLL), save 30-70% of water in horticulture and improve water-use efficiency while mitigating risks like waterlogging and salinity. These methods also prevent runoff and optimize soil moisture, though further research is needed to assess their potential across diverse regions (National Agricultural Innovation Project, 2014, Anonymous, 2021).

2. Energy Conservation and Emission Reduction

PF technologies reduce energy consumption and greenhouse gas (GHG) emissions by optimizing farm operations. GPS systems minimize input overlaps, saving fuel, labor, and machine hours, while micro-irrigation and LLL lower irrigation energy needs, cutting electricity use by up to 755 kWh per hectare in rice-wheat systems. PF also reduces nitrous oxide (N, O) and carbon dioxide (CO,) emissions through precise fertilizer application. Laser leveling shortens cultivation time and mitigates climate impacts by reducing water pumping energy. Although PF shows potential for significant energy and emission reductions, further studies are needed to quantify long-term impacts.

Success stories: Indian perspective

I. Jain Irrigation Systems Ltd. (JISL), had been instrumental in integrating PF with sustainable practices, particularly among small and marginal farmers in India. JISL had helped farmers in water-scarce regions to maximize productivity while conserving essential resources. Their success illustrates how PF can be adapted to India's unique agricultural challenges and provides a replicable model for other regions. In Maharashtra, where JISL operates, farmers, especially smallholders, struggle with erratic monsoon patterns and limited access to irrigation facilities. In the past, this led to inefficient water use, high input costs, and fluctuating crop yields. These challenges prompted JISL to introduce "drip irrigation systems" combined with "real-time soil moisture sensors" to optimize water usage. Their system provided water directly to the plant roots at scheduled intervals, significantly reducing water wastage as compared to traditional flood irrigation. By incorporating soil moisture sensors, JISL enabled farmers to monitor soil health and manage water use efficiently. In addition to water management, JISL provided "nutrient management tools" through fertigation which allowed farmers to apply precise amounts of nutrients directly to crops, reducing fertilizer usage and improving crop health. Farmers reported water savings of up to 60% and fertilizer reductions of up to 30%, resulting in substantial cost savings. Moreover, these changes led to a 30–40% increase in crop yield, especially in high-value crops like bananas, onions and tomatoes.

II. Sula Vineyards, Nashik, Maharashtra had implemented PF to overcome three critical challenges in grape production viz., optimze water usage, disease prediction and controlled use of pesticides. It involved a network of wireless sensor nodes strategically placed across the vineyard. These nodes were equipped with advanced sensors to monitor essential environmental and plant parameters, including soil moisture, ambient temperature, relative humidity, and leaf wetness. Based on the on-field sensor data, the Evapo-Transpiration and infection index were computed.

III. The use of Variable Rate Technology (VRT) in Punjab, where farmers, supported by government initiatives, use drones and sensors to assess crop health and apply inputs like fertilizers and pesticides in a targeted manner. One group of farmers in the Moga district reported a 15% reduction in fertilizer use while achieving higher crop yields. This not only cut down costs but also reduced the environmental impact associated with excessive fertilizer application.

IV. The collaboration between Tata Trusts and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has been instrumental in providing smallholder farmers with affordable precision farming tools. Through this initiative, farmers are using GPS-enabled devices and smartphone apps to map their fields and make data-driven decisions, which have resulted in increased productivity and improved soil health.

Way Forward

- Low-cost sensors are required to monitor soil nutrients, soil moisture, pests and diseases. Wireless sensors will hold the key to precise nutrient and water applications. Indigenous manufacturing of such sensors needs to be promoted.
- UAVs (Drones) with appropriate sensors be used for a quick survey to identify within field variations in nutrient status, as well as pest infestation for timely action. This is cost-effective and eco-friendly. An appropriate power source for drones, however, needs to be defined.
- Precision Agriculture Service Providers or StartUps will be required in huge numbers for popularizing and scaling up Precision Farming. As PF utilizes new technologies, skill development must be a vital component, in addition to training (pilot license) on the operation of drones. Capacity building for collection of data be included in operationalizing Decision Support Systems. Some StartUps have already been providing drone services on custom hiring basis.
- Skilled human resource is required for implementing precision agricultural practices. The agricultural universities have to initiate HRD through specially designed training modules and course curricula for different levels of activities including teaching, training and research. This essentially requires exposure and training of faculty in advanced centres of excellence.
- The industry, scientists, technologists, academicians, and other stakeholders have to work in unison to develop Decision Support Systems for empowering farmers to take informed decisions in real time. Since it involves the use of artificial intelligence, IoTs, machine learning and big data analytics, a seamless merging and integration of multi-source data from remote sensing, GIS, GPS and sensors is essential. Basically, it implies moving from heuristics and experience to evidence and information for realtime decision making.
- Many agriculture-related activities can be easily done by robots. In India, their presence is barely noticeable, but these have a great future. IITs, NITs and other similar organizations have to perhaps

interact more with agriculture scientists and extension workers to identify farmers' needs to design robots to meet specific needs.

- A Network Project on precision Agriculture has been recently initiated by ICAR. This needs further strengthening with additional activities covering more institutions, and crops/animals, namely pig, poultry, goats and aquaculture. In a few years of its operation, the network can be considered upgradation to an All-India Coordinated Research Project so that Precision Agriculture Research is institutionalized to deliver innovative technologies and methods

Conclusion

PF represented a promising solution to balancing agricultural productivity with environmental conservation. Its ability to enhance crop yields, reduce input costs and minimize environmental harm makes it a valuable tool in the transition toward more sustainable agriculture. Despite challenges such as high costs and technical barriers, with appropriate support, satellite crop monitoring could become a standard practice, benefiting both farmers and the planet in the long run.

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