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Satellite to field: GIS and remote sensing in agriculture and allied sector

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Abstract
Agricultural production systems are extremely susceptible to changes in terrain, soil, and climate in various geographic locations. These factors must be examined spatiotemporally in order to ensure sustainable agriculture management. An innovative strategy for sustainable agriculture is represented by precision farming, which combines GIS, GPS receivers, continuous yield sensors, geo-statistics, and variable rate applicators. Information technology-based precision agriculture allows farmers to gather information for improved decision-making, reducing some of the inherent risks and variables in agriculture. The success of precision farming systems depends on integrating these technologies into a single farm-operable system. In the 1970s, GIS—a comprehensive application system created over the past 50 years and acknowledged as the third generation language of geography—started to be utilized globally in the field of agriculture. Since the 1990s, its use has broadened from surveys and assessments of land resources to in-depth and extensive management analysis of data related to agricultural resources. Assessing and managing these variables is greatly aided by advanced technology like geographical information systems (GIS), remote sensing (RS), and global positioning systems (GPS). In order to make tactical decisions about food security, import/export, and economic impacts, producers, managers, and policy planners need access to timely and accurate information on crop acreage, growth conditions, and yield estimation. Remote sensing and GIS techniques are useful for obtaining such regional information. GIS is important for agriculture on many levels, from local to global, and it has a big impact on site-specific or precision farming. This approach aims to optimize farm returns and minimize chemical inputs and environmental hazards by directing the application of seeds, fertilizers, pesticides and water within fields. Remote sensing and GIS are effective tools for generating essential information such as mapping agriculture crop areas, identifying potential cultivation zones and determining suitable locations for infrastructure development. Mapping natural resources at both the macro and micro levels has shown the value of these technologies. Using GPS devices whether built into smartphones or handheld devices allows for precise field mapping providing farmers with site-specific solutions. With applications in spatial decision support systems (SDSS), crop simulation models, yield estimate, food security analysis, pest management, livestock mapping, and potential site identification, GIS and remote sensing are being used in agriculture at a rapid pace.

Keywords: Precision farming, remote sensing, GIS, GPS

Introduction
Atzberger (2013) [1] identified five main applications of remote sensing in agriculture: estimating biomass and yield, tracking drought stress and vegetation vigour, evaluating crop growth, calculating crop acreage and mapping farmland, and identifying disturbances and changes in land use/cover. Precision farming and irrigation control are among these applications. Geographic information system (GIS) and remote sensing (RS) technologies have become more popular recently as a means of obtaining spatiotemporal meteorological and crop status data to supplement conventional methods. By offering rapid, comprehensive, economical, and repeatable information on the earth's surface, remote sensing data greatly improve monitoring (Justice *et al.*, 2002) [15].
With conventional methods, it is difficult to immediately analyse extreme weather events and crop development status under changing climatic conditions, including crop stress detection and damage assessment.

In such situations, geospatial technology including RS and GIS is highly effective for acquiring and managing extensive spatiotemporal data using satellite information, digital maps and simulation models. This technology provides decision-makers and policy planners with quick and repetitive data access, efficient analysis, and valuable information generation. Based on the biophysical characteristics of crops and soils, remote sensing technologies can completely change the way agricultural productivity is detected and characterized (Liaghat and Balasundram, 2010) [18].

Remote sensing satellite data can be utilized for yield prediction (Doraiswamy *et al.,* 2005) [12], crop phenological information (Sakamoto *et al.,* 2005) [24], stress scenario identification (Gu *et al.,* 2007) [14] and disturbance mapping. According to De Beurs and Townsend (2008) [11], remote sensing offers a financially viable substitute for gathering data across vast geographic regions. Combined with GIS, remote sensing helps to create spatiotemporal informational layers and generate useful integrated information by superimposing several basic layers. Numerous sectors, such as floodplain mapping, hydrological modelling, surface energy flux, land use changes, crop growth monitoring, stress detection, and urban development, can benefit from the application of this technology. Precision agriculture now uses remote sensing as a practical management tool for site-specific crop management (Casady and Palm, 2002) [7].

Concept

Precision agriculture holds the potential to boost productivity, increase yield, lower production costs and reduce the environmental impact. It envisions a future where farmers employ planning software that perfectly predicts crop growth alongside with computerized machinery that is precisely controlled by local sensors and satellites. This vision of technologically advanced farming is often referred to as the futuristic agriculture.

Management strategy

The majority of precision agriculture management techniques entail matching agronomic practices and resource applications with the varying soil conditions and crop needs at different site locations. Often known as site-specific or prescription application, these strategies typically include:

- **Soil Sampling:** Determining the variability and physical characteristics of soil across the field.
- **Variable Rate Application:** Precisely applying the right and required type and quantity of nutrients or chemicals to certain areas of the field.
- **Yield Monitoring:** Simultaneously documenting the location within the field and taking an accurate measurement of the crop production.

Even if each of these elements is essential, neither by itself nor in combination, do they completely characterize precision agriculture.

Precision agriculture

In the late 1990s, John Deere, among others, introduced precision agriculture (PA) by installing GPS sensors in its tractors and other machinery to facilitate information management. Precision farming is becoming more and more popular among scientists, engineers, and large-scale crop growers, and one of its key components is remote sensing technology (Liaghat and Balasundram, 2010) [18]. Precision farming employs information gathered by sensors on farm machinery to lower cultivation costs, increase control, and optimize resource use. The most advanced kind of precision farming is called variable rate technology (VRT), which uses sensors mounted on moving farm machinery to manage input applications using computer input recommendation maps and GPS data. With the rise of the Internet of Things (IoT), smart devices have become progressively interconnected through wireless networks, improving communication and interaction between all devices (Wolfert *et al.,* 2017; Porter and Heppelmann, 2014) [32, 21]. The gathering, handling, and utilization of data for decision-making constitute PA's primary focus (Pham and Stack, 2018) [20]. Computer-based decision support models for land evaluation have been developed as a result of advancements in information and communication technology (De la Rosa *et al.,* 1992; Shim *et al.,* 2002) [10, 27]. Geographic information systems (GIS) have been used to evaluate land through map analysis approaches (Burrough, 1989; Kalogirou, 2002; Baja *et al.,* 2002) [6, 16, 2]. In order to gather spatially referenced data, carry out spatial analysis, and make decisions while implementing variable rate treatments, many site-specific farming systems make use of GIS and related technologies (such as GPS receivers, continuous yield sensors, and remote sensing devices) (Usery *et al*., 1995) [30]. These cutting-edge technologies have many benefits at all sizes, from global to farm fields. They can quickly and economically produce and synthesize new information, document data sources and integration techniques provide diagnostics for error detection and assess accuracy, supply input data for a variety of crop yield and non-point source pollution models, and produce maps and tables that are customized to meet particular requirements.

Interactive computer-based systems known as Decision Support Systems (DSS) assist decision-makers in using models and data to address unstructured problems (Efraim, 1995) [13]. These technologies shorten the time and manpower required to analyse complex issues, thereby improving the performance of decision makers. Digitalized geo-referenced spatial databases are used by Spatial Decision Support Systems (SDSS) to focus on the spatial component. These geographical databases are managed using GIS, a relatively new information technology that enables the accurate and simultaneous study and analysis of a wide range of resources related to agriculture, including soil, weather, hydrology, and various socioeconomic characteristics. In addition to promoting the development of stable and sustainable dynamic agricultural technology, this simultaneous investigation in a GIS environment improves our understanding of how agricultural systems interact and function over time and space.

To foster holistic growth in the horticultural sector, it is crucial to create and update a comprehensive database covering all horticultural activities. Geographic information systems (GIS) and remote sensing are useful methods for producing this sort of data. Mapping natural resources at both the macro and micro levels has shown the value of these technologies. Compared to other regions, hilly states present unique challenges for agriculture in implementing new technologies because of their varied terrain, which ranges from low hills to high mountain ranges. Because precision farming necessitates more site-specific techniques than flat agricultural areas, it is especially crucial in mountainous terrain. Maintaining agriculture in these limited, targeted agricultural regions requires accurate field location identification. Farmers can acquire precise and site-specific solutions to their problems through field mapping that is made possible by GPS devices, whether they are handheld or built into smartphones. In addition to making field mapping easier, GIS and RS, when combined with other web-based

applications, offer strong tools for managing diseases and pinpointing disease hotspots, tracking crop stages, estimating yields, and mapping weeds and soils. Through the use of remote sensing space-borne sensors, geospatial technology provides repetitive coverage and synoptic observations of the spectral behaviour of crops as well as the soil and atmosphere of their growing environments. Applications for this data include monitoring crops and land, analysing site suitability, forecasting crop production, inventorying crop production, assessing drought and flood damage, irrigated fields, and monitoring and managing range (Sahai & Dadhwal, 1990) [3].

The GIS is an interdisciplinary information technology developed since the 1960s. Geographic science, surveying science, management science, space science, computer science, environmental science, and information science are some of the fields whose knowledge is integrated into GIS. Data collecting, storing, management, analysis, and display are all part of a comprehensive GIS. This method is applicable to the analysis of huge datasets, especially those containing spatial information. By combining the geographic location of numerous objects with related views, spatial query analysis, data mining, network analysis, digital terrain model (DTM) analysis, buffer analysis, neural networks, overlay analysis, and other techniques, GIS reorganizes information based on user demands. Today, GIS applications are used in every part of society, including forestry, agriculture, water conservation, environmental management, land management, and resource management. The planning of commercial and agricultural layouts, the management of natural resources, political and economic analysis, engineering design management, science and education, urban land planning, cultural and physical training, financial transportation, technology for national defence, and public facilities management are some examples of specific applications.

Importance of Precision Farming

Using technologies and principles to control temporal and spatial variability in all facets of agricultural production is known as precision farming. Precision farming has been improved during the last ten years by a number of technology developments. The integration and utilization of modern technology, such as advanced farm technologies and site-specific systems, are essential to the adaptability of PF. These technologies include things like faster connectivity to the internet and higher farmer awareness. The objective of PF, an integrated information and agricultural management system, is to reduce the negative environmental effects of chemical use while increasing farm production efficiency overall at a reasonable cost. Precision farming's primary focus is to collect extensive data on crop and soil conditions by capturing information at the spatial level.

Typically, the precision farming database contains the following information:

- Crop information, including nutrient needs, plant health, and different growth stages
- The chemical and physical characteristics of soil, such as texture, nutrient status, depth, soil temperature, toxicity, salinity, and potential productivity;
- Waterlogging conditions, surface and subsurface drainage;
- Seasonal and daily microclimatic data, including wind direction, canopy temperature, wind speed, and atmospheric humidity;
- Availability of water, irrigation facilities, and scheduling of additional inputs

Remote Sensing

Remote sensing has tremendous potential for PA by offering high-resolution monitoring of spatial and spectral changes throughout time, (Moran *et al.,* 1997) [19]. These spatiotemporal observations aid in the establishment of baselines for understanding variability across different periods. In regions like Himachal which experience diverse changes such as infrastructure development increased agricultural pressure on forest areas and competition for limited resources, integrating modern agricultural technologies into existing practices is crucial. RS is particularly advantageous for PA due to its ability to provide frequent updates (every 24-48 hours), high spectral and spatial resolution, high temporal resolution and cost-effective data (every 10-15 days).

Objectives

- **Inventory and Characterization:** Identify and catalog major crops within a selected district, categorizing these areas based on factors such as age, density, and health of the crop.
- **Expansion Mapping:** Determine potential areas for further crop expansion through site suitability studies and document the various crops present in the district.
- **Infrastructure Prioritization:** Identify optimal locations for postharvest infrastructure facilities through proximity analysis. This will help in pinpointing plantations that may need replacement or rejuvenation for improved management.

Basic aspects

Characterizing the biophysical properties of plants has become a more prominent focus of agricultural remote sensing in recent years. By offering high-resolution data on spectral and spatial changes over time without causing crop damage, this technique, which has been utilized for monitoring and assessing agricultural activities for a long time, offers significant advantages. Precision agriculture benefits greatly from this capability, which provides frequent updates and in-depth insights at an affordable price. The primary application of satellite remote sensing in India is for estimating crop acreage and yield. It has the potential to transform how agricultural productivity is assessed by examining biophysical attributes of crops and soils. Remote sensing data can be used for various applications including yield estimation, crop phenology and stress detection.

Agricultural applications

1. **Monitoring Vegetation Cover:** RS reduces the need for gathering large amounts of field data and precision of estimates is increased. Hyper spectral data in particular enhances the ability to characterize, model, discriminate and map crops and vegetation compared to traditional multispectral remote sensing.
2. **Crop Condition Assessment:** RS plays a crucial role in agriculture by providing timely spectral information that helps assess plant health. Changes in a plants physiological state due to stress can alter its spectral reflectance or emission characteristics making it detectable by remote sensing. Regular crop monitoring allows for timely interventions and helps understand the impact of factors such as planting date, air temperature, soil moisture and soil condition on crop productivity.
3. **Nutrient and Water Status:** RS and GIS are valuable for managing nutrient and water stress. By detecting nutrient

deficiencies these technologies enable site-specific nutrient management, reducing cultivation costs and enhancing fertilizer efficiency. Precision farming technologies, when paired with remotely sensed canopy air temperature data, drip irrigation can increase water use efficiency in semi-arid and arid settings by reducing percolation and runoff losses.

4. **Crop Evapotranspiration:** Productivity declines due to irregular rainfall and rising temperatures which reduce soil moisture. Drought defined as a long-term imbalance between precipitation and evapotranspiration is influenced by the timing and strength of the monsoon. RS especially with hyper spectral sensors aids in water management and integrates with GIS and GPS technologies for improved agricultural systems.
5. **Weed identification and Management:** Precision weed management is enhanced by remote sensing technologies which offer a promising alternative to labour-intensive ground surveys. RS can identify weeds based on their spectral reflectance differences from crops allowing for the creation of weed maps and the application of site-specific herbicides.
6. **Infestation of Pests and Diseases:** RS is crucial for tracking crop stress caused by diseases and pests. It helps in identifying insect breeding grounds and assessing damage by relating spectral responses to visual symptoms like chlorosis and leaf reduction. This information supports pest management decision-making and can be used to detect and map defoliation and other disturbances.
7. **Crop Yield and Production Forecasting:** Based on statistical relationships between yield and vegetation indices, crop yields are predicted using remote sensing. Reliable yield forecasts are crucial for national food policy planning and depend on various factors including crop variety, pest and disease impact, water and nutrient status and weather conditions.

Geographic information system (GIS)

Using computer-based tools, GIS organizes spatial data and visualizes collected data to highlight patterns and relationships. According to Burrough and McDonnell (2015) [8], GIS is a potent toolkit for gathering, storing, and retrieving spatial data as well as for modifying and presenting this data for specific purposes. For individuals in the farming industry, its capacity to evaluate and visualize agricultural environments and workflows has proven to be extremely helpful. To achieve profitability, farming inputs and outputs must be well balanced. Layers of spatial data are frequently used to depict topography or other environmental elements. GIS technology has become vital in order to include different map and satellite data sources into models that mimic the dynamics inside complex natural systems, In addition to producing maps, GIS can generate cartographic products, pictures, drawings, and animations. GIS is helping farmers increase yields, save costs, and manage land more efficiently from mobile GIS utilized in the field to in-depth scientific study at a farm manager office. GIS applications can improve understanding and management through crop yield estimations, soil amendment assessments, erosion detection, and remediation, even when natural inputs in farming are uncontrollable. For instance, in one study, a spatial crop model was developed by integrating GIS with the Environmental Policy Integrated Climate (EPIC) model. GIS allows for the overlay of various data layers such as ecological conditions, physiognomy and human impact indices. A vital tool for planning and management, this layer-based thematic system provides the flexibility to examine and assess changes at different sites.

Its components include

- Digital geospatial data storage.
- Management and incorporation of spatial data into the GIS system from a variety of sources.
- Retrieving and transforming spatial information into the required formats.
- Using data analytics to transform data into insightful information.
- Model development based on information gathered.
- Displaying models for making well-informed decisions.

Application of GIS in agriculture

1. **Application of GIS in Information Management of Agricultural Resources:** Various elements used in agricultural production or associated economic activities are referred to as agricultural resources. These resources include social and economic resources like labour, transportation, and the agricultural population, as well as natural resources like the atmosphere, waterways, land, and biological elements. The spatial information management capabilities of GIS, which integrate different agricultural resources with their geographic locations and clearly depict them on a map, can be used to manage the complexity of these resources efficiently. This makes it possible to describe the characteristics of their temporal and spatial distribution, their dynamic changes at various levels, as well as to digitize and automate agricultural resource archives. Consequently, resource management becomes more standardized, convenient, intuitive and scientific providing a foundation for sustainable agricultural resource development and classified management. Countries all around the world appreciate the use of GIS technology in agricultural information statistics, which makes it an essential instrument for gathering, analysing, and presenting data in agricultural censuses. One of the most effective GIS systems in use today, the TIGER system was developed and applied by the American Agricultural Census, which was first implemented by the Census Bureau. Apart from the US, other affluent nations have established extensive statistical geographic information systems and developing nations like India also employ GIS as a vital tool for agricultural statistical surveys.
2. **Application of GIS in Agricultural Climatic Zoning:** Based on the distinctive climate requirements of agriculture, agricultural climatic zoning is a spatial classification that establishes the relationship between climate and agricultural production. Typically, this zoning is determined by agro-climatic indices, which have a major impact on the development, growth, distribution, and yield of significant agricultural organisms. Specific zoning methods are used to split areas into different regional units based on using zonal and non-zonal climate distribution laws and the principle of agro-climatic similarity and difference. This process provides a scientific basis for decision-makers to develop agricultural zoning and development plans optimally utilize climate resources and mitigate climate-related disasters.
3. **Application of GIS in Preventing and Controlling of Agricultural Disasters:** Agriculture as a system closely linked to nature differs from natural systems in that agro-ecosystems are simple semi-natural ecosystems vulnerable to natural disasters. Severe natural disasters can pose

significant threats to agricultural production. Therefore assessing, providing early warnings and recovering from natural disasters are crucial in agricultural production and decision-making. This process involves many complex factors such as vegetation, landforms, hydrology, lakes and rivers and animal species, all closely related to space and time. GIS technology excels in processing these data, utilizing remote sensing, GIS and computer technology to assess major agricultural meteorological disasters comprehensively. It provides timely, effective and accurate decision-making information for government and relevant departments offering a scientific basis for disaster reduction, prevention and relief. This capability is vital for the stable development of agricultural production and the rural economy.

4. **Application of GIS in Management of Agro-Ecological Environment:** The agro-ecological environment underpins agricultural development. Despite the significant societal advancements driven by human industrial civilization, it has disrupted the natural ecological environment and degraded the agricultural ecological environment. GIS are extensively used in agro-ecological research including environmental monitoring, assessment, prediction and managing point and non-point source pollution. Utilizing multi-temporal remote sensing image dynamic monitoring and GIS technology researchers like Zhang W. *et al*. have extracted crop growth status and planting areas by monitoring and analyzing field conditions and crop growth. They have established an agro-ecological GIS platform and an agricultural resource management database, remote sensing data, managing spatial data and attribute data of agricultural resources.
5. **Application of GIS in Precision Agriculture:** Precision Farming involves the precise adjustment of various agronomic practices based on the environmental conditions of each field unit and the spatial and temporal differences in crop yields. The goal is to optimize the quality, quantity and timing of inputs like fertilizer, seeds, water and pesticides to achieve the highest yield and maximum economic benefits while protecting the agricultural ecological environment and natural resources. This modern agricultural technology which integrates information technology with agriculture aims to maximize both economic and social benefits. Numerous scholars have employed GIS technology for preliminary research in precision agriculture. For example, research by C. Palaniswami indicates that the spatial and temporal interplay between production and CCS will become a major area of study if the sugar industry uses GPS and GIS for selective harvesting. These techniques can assist with managing how sugarcane plantation and environmental preservation interact in sensitive coastal floodplain ecosystems. One reason for field differences in crop yield is soil heterogeneity, which can be improved with precision agriculture.
6. **Application of GIS for Crop Yield Estimation and Monitoring:** Precisely approximating and monitoring the yield of crops is essential for a nation to promptly comprehend crop productivity and for formulating import/export regulations and pricing. The majority of nations and the Food and Agriculture Organization (FAO) of the United Nations consider this work as priority. Estimating the crop planting area and establishing the yield model using remote sensing monitoring are the two primary components of crop yield estimation. These tasks can be performed precisely and efficiently by GIS. Remote sensing methods obtain images of crop growth which are then interpreted and analysed within GIS. Spatial data is used to identify crop types and calculate planting areas. Changes in crop growth and environmental conditions are analysed and GIS models are constructed to estimate crop growth and yields under various conditions incorporating all relevant factors to provide comprehensive yield and growth estimates for large areas.

Global Positioning System

The introduction of the Global Positioning System (GPS) has not only improved the ease and versatility of spatial data acquisition but has also expanded the ways it can be integrated with RS and GIS. In the late 1980s, GPS emerged as a valuable tool for spatial data acquisition. GPS devices have evolved from traditional handheld devices with an accuracy of around 10 meters to differential GPS (DGPS) with accuracy in centimetres. In hilly terrains like Himachal Pradesh, where field areas are very small, implementing precision farming can be challenging due to limited cropping options. However, in-field variability can be recorded by GPS technology as geographically encoded data, enabling continuous and accurate position recording. This technology provides a more detailed view of agricultural areas and fields resulting in a larger database for users. Accurate yield data can only be reported at only at locations where GPS position tracking occurs.

Yield monitor data can be spatially coordinated using GPS receivers and yield monitors, allowing yield maps to be made for each field. Field management strategies for chemical application, cultivation, and harvesting can be developed by integrating information gathered from different satellite data referenced with GPS (Liaghat and Balasundram, 2010) [18]. Combining GPS and GIS has enabled the development and implementation of site-specific farming, also known as precision agriculture. These technologies make it possible to combine accurate positional information with real-time data collecting, which makes it possible to manipulate and analyse vast amounts of geospatial data effectively. Precision farming uses GPS-based applications for crop scouting, farm planning, yield mapping, tractor navigation, soil sampling, field mapping, and variable rate applications.

Future prospects

Even on small farms, remote sensing proves to be highly effective in assessing a variety of biotic and abiotic stresses in crops and is particularly helpful in addressing crop problems. Establishing state- or district-level information systems based on remote sensing and GIS data is crucial to use crop information for economic improvement. Data from remote sensing can be used by governments to address national agricultural concerns and make well-informed policy decisions. Nanochips are being inserted into seed and plant tissue in an emerging application that allows for near-real-time crop monitoring. These and other cutting-edge techniques will highlight how important remote sensing is for upcoming agricultural studies.

Conclusion

Remote sensing, GIS, and GPS technologies have revolutionized agriculture by enhancing precision, efficiency, and data management. These tools enable detailed monitoring and analysis of crop health, yield prediction, and resource management, leading to optimized productivity and reduced environmental impact. By integrating these technologies, precision agriculture can overcome traditional limitations,

offering comprehensive, real-time insights that drive informed decision-making. As technology advances, the potential for further innovations, such as nanochips for crop monitoring, underscores the increasing importance of these tools in shaping the future of sustainable and efficient agriculture.

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