International Journal of Environment and Climate Change

Volume 13, Issue 10, Page 3559-3567, 2023; Article no.IJECC.105926
ISSN: 2581-8627
(Past name: British Journal of Environment & Climate Change, Past ISSN: 2231–4784)

Transformative Role of Remote Sensing in Advancing Horticulture: Optimizing Sustainability, Efficiency and Resilience

Ram Kumar Rai [a], Makhan Singh Karada [b*], Riya Mishra [c], Dheer Agnihotri [d], Kamal Kishor Patel [e], Satyendra Thakur [f] and Deepak Singh [a]

[a] Department of Horticulture, Jawaharlal Nehru Krishi Vishwavidyalaya, Jabalpur – 482004, Madhya Pradesh, India.
[b] Department of Forestry, Jawaharlal Nehru Krishi Vishwavidyalaya, Jabalpur – 482004, Madhya Pradesh, India.
[c] Department of Plant Breeding and Genetics, Jawaharlal Nehru Krishi Vishwavidyalaya, Jabalpur – 482004, Madhya Pradesh, India.
[d] Silviculture, Forest Management and Agroforestry Division, Tropical Forest Research Institute, Jabalpur – 482004, Madhya Pradesh, India.
[e] Department of Soil Science and Agricultural Chemistry, Jawaharlal Nehru Krishi Vishwavidyalaya, Jabalpur – 482004, Madhya Pradesh, India.
[f] Department of Plant Physiology, Jawaharlal Nehru Krishi Vishwavidyalaya, Jabalpur – 482004, Madhya Pradesh, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJECC/2023/v13i103026

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/105926

Review Article

Received: 08/07/2023
Accepted: 12/09/2023
Published: 19/09/2023

**Corresponding author: E-mail: makhansinghkarada1408@gmail.com;*

ABSTRACT

The field of horticulture, vital for addressing global challenges like food security and sustainable agriculture, has been revolutionized by remote sensing technology. This comprehensive review explores the transformative impact of remote sensing on horticulture, emphasizing its role in optimizing resource utilization, promoting environmental sustainability, and mitigating the effects of climate change. Remote sensing, encompassing a range of sensors, satellites, and data analysis techniques, enables the collection of critical information from a distance, providing insights into crop health, soil conditions, water availability, and more. Precision agriculture, including the use of GPS and GIS, is integrated with remote sensing to enhance agricultural efficiency while minimizing environmental impacts. Site-Specific Crop Management (SSCM) is highlighted as a key component of precision agriculture, enabled by geospatial technologies, including remote sensing. It discusses how remote sensing systems, with their multispectral and multi-temporal capabilities, support various horticultural applications such as crop yield estimation, abiotic and biotic stress management, crop classification, canopy measurement, crop area estimation, and even crop insurance validation. The use of Geographic Information Systems (GIS) and the Global Positioning System (GPS) in tandem with remote sensing is explored in the context of spatial analysis, mapping, and precise navigation.

Keywords: Precision agriculture; horticulture; remote sensing; GPS and GIS.

1. INTRODUCTION

Remote sensing has ushered in a new era of precision and efficiency in the field of horticulture, fundamentally altering the way we perceive, analyze, and manage crop systems and their surrounding environments. Horticulture, the art and science of cultivating fruits, vegetables, ornamental plants, and high-value crops, holds paramount importance in addressing global challenges such as food security, nutritional diversity, and sustainable agriculture. Horticulture, the art and science of cultivating plants, faces a myriad of complex challenges in today's world. From the efficient use of resources to the imperative of environmental sustainability and the pressing need to mitigate the impacts of climate change, horticulturists, farmers, and researchers find themselves navigating a complex landscape. However, amidst these challenges, there emerges a powerful ally: remote sensing technology [1,2]. Remote sensing technology has rapidly evolved into an indispensable tool for those involved in horticulture [3]. These tools provide a unique vantage point, allowing us to acquire critical insights into crop health, soil conditions, water availability, pest infestations, and various other factors that influence horticultural outcomes [4]. Armed with this information, stakeholders can make data-driven decisions that not only boost crop yields but also foster sustainable practices, conserving resources and contributing to global food security [5,6]. Precision agriculture, also known as precision farming, encompasses a range of technological components, including the Global Positioning System (GPS), Geographic Information Systems (GIS), and remote sensing. This integrated system aims to enhance the overall efficiency of agricultural production while simultaneously mitigating the adverse environmental impacts associated with excessive chemical use [7,8,9]. Site-Specific Crop Management (SSCM) serves as a valuable instrument in achieving precision agriculture. It encompasses various elements such as spatial referencing, monitoring crops and weather conditions, mapping attributes, employing decision support systems, and implementing targeted actions based on differentials [10,11]. Conducting Site-Specific Crop Management (SSCM) requires the utilization of geospatial technologies, which consist of four distinct tools. Among these tools, remote sensing holds a crucial role, alongside geographic information systems (GIS), global positioning systems (GPS), and information technology or data management [12,13,14,11]. The implementation of Site-Specific Crop Management (SSCM) in horticultural crops such as fruits and nuts has the potential to significantly enhance productivity while optimizing the efficient utilization of resources [15,11]. The application of spatial technology in orchard delineation offers supplementary data that proves valuable in making informed management decisions. This data aids in determining when and how much irrigation is needed, deciding on pesticide usage for pest and disease control, optimizing fertilizer application, and calculating fruit yield [10].

2. UNLOCKING INSIGHTS FROM AFAR: REMOTE SENSING

Remote sensing is the scientific practice of acquiring information regarding objects or regions remotely, often utilizing aircraft or satellites (NOAA). It involves the detection and observation of physical attributes of a specific area by gauging the radiation reflected and emitted from that area, all from a considerable distance. In the realm of Remote Sensing Systems, there are four fundamental elements employed to collect and document data about a location remotely. These elements encompass the energy source, the pathway of transmission, the designated target, and the satellite-based sensor [16,11,17,18]. Precision agriculture benefits significantly from this technology, as it can readily provide field parameter data. Typically, we observe sunlight's reflection, which encompasses ultraviolet wavelengths, visible light (including Red, Green, and Blue), and infrared rays. Information regarding the earth's surface and various specific objects is derived from the reflection, dispersion, or refraction of light. When the objects are exposed to the electromagnetic spectrum (comprising the Visible, Near-Infrared, Short-Wave Infrared, and microwave regions), they react differently. This differentiation allows for the identification of soil, vegetation, water bodies, and other elements found on the earth's surface [19,3,18]. Remote sensing systems offer precise databases on the spectral characteristics of crops and their surrounding environment, including soil and atmospheric conditions. This is made possible due to their regular, comprehensive, multispectral, and multi-temporal coverage of specific areas. These systems find diverse applications, such as crop inventory, assessment of crop health and condition, forecasts of crop production, evaluation of fruit quality, measurement of parameters like leaf area index and crown cover, monitoring the growth and well-being of horticultural crops, assessing damage from droughts and floods, as well as overseeing and managing rangelands and irrigated lands [20,21,22]. The mapping of orchards and spatial assessment through geospatial technology can offer supplementary insights for effective implementation of site-specific crop management (SSCM). This includes the identification of orchard boundaries and utilizing spatial analysis to enhance decision-making processes. It aids in determining fruit yields, accurately quantifying and scheduling fertilizer and irrigation requirements, as well as optimizing the application of pesticides for pest and disease control. All of these applications have the potential to boost net returns and optimize resource utilization in orchard management [23,15,22].

3. GIS TECHNOLOGY: MAPPING AND SPATIAL ANALYSIS

A Geographic Information System (GIS) is a pivotal system comprising a meticulously organized ensemble of computer hardware, software, geographic data, and personnel. Its primary purpose is to efficiently acquire, store, update, manipulate, analyze, and present various forms of geographically referenced information [8]. The domain of GIS encompasses both data management and modeling, thereby facilitating a transition from conventional mapping to spatial reasoning. Within GIS, there exists a foundational base map that encompasses vital geospatial details such as topographical features, soil classifications, nutrient levels, soil moisture content, pH levels, fertility status, and maps indicating weed and pest intensities. Furthermore, GIS has the capacity to seamlessly integrate diverse datasets and interface with other decision support tools. This integration allows for the utilization of these maps and information in the application of recommended rates of nutrients or pesticides, contributing to informed agricultural practices [18].

4. GLOBAL POSITIONING SYSTEM (GPS): A PRECISION NAVIGATION TECHNOLOGY

GPS, or the Global Positioning System, comprises a network of satellites perpetually transmitting coded data, enabling the precise identification of Earth-based locations by measuring the distance from these satellites. It involves determining positions through digital satellite data [24]. GPS technology serves as a highly accurate positioning system for implementing variable rate technology in the field. The evolution of these diverse positioning systems represents a significant technological leap that has transformed the concept of precision agriculture into a tangible reality. It enables the precise control of input application, pinpointing the exact location of agricultural equipment with near-inch accuracy, thereby facilitating the tailored prescription of fertilizers and pesticides based on soil characteristics. In GPS, all positional data is efficiently stored and disseminated through a singular system housed within a central vehicle, often a tractor, streamlining various tasks [25,18]. The primary advantage of this centralized system lies in its ability to calculate position data in alignment with specific applications and deliver them directly to the relevant point of use [26,18].

5. UTILIZATION OF REMOTE SENSING IN HORTICULTURE

India stands out as a nation that effectively harnesses the combination of space technology and ground-based observations to routinely produce updated statistics on crop production, contributing significantly to the promotion of sustainable agricultural practices. The inaugural application of remote sensing technology in India can be traced back to the coconut wilting experiment conducted in 1970 [27,11]. Since that time, Indian researchers have made substantial contributions to the advancement of digital image processing and the creation of proprietary software solutions. These applications have spanned a wide array of fields, including the development of horticulture, the estimation of crop acreage and production, the implementation of precision farming, the analysis of cropping systems, the management of agricultural water resources, the assessment and monitoring of drought conditions, watershed development, mapping of soil resources, forecasting potential fishing zones, studying the impact of climate on agriculture, and many more [28,29,30]. Some of the applications are listed below:

6. REMOTE SENSING FOR CROP YIELD ESTIMATION

While remote sensing has been employed to estimate yields for numerous annual crops, there has been relatively scant research conducted regarding yield estimation for fruit trees and vegetables [31,32,33,22]. Remote sensing methodologies have the potential to furnish growers with precise assessments of final crop yields, enabling them to discern variations in yield with a high degree of accuracy across fields or orchards. The growing adoption of harvester-mounted yield monitors has facilitated the collection of comprehensive yield data from fields, and remote sensing imagery enhances the accuracy of data evaluation. Presently, commercial yield monitors are in the developmental stages for only a limited number of crops, such as citrus, pistachio, and tomato crops [22].

7. REMOTE SENSING FOR ABIOTIC STRESS MANAGEMENT

Remote sensing is a potent method for observing, identifying, and quantifying how plants react to various stresses, such as temperature fluctuations, drought conditions, flooding, salinity issues, mineral toxicity, or infections. It's important to note that a single stress factor can have a cascading impact on a multitude of physiological processes. For instance, drought not only triggers the closure of stomata but also diminishes the rate of photosynthesis, stunts growth, causes wilting of leaves, and may result in the loss of essential pigments like chlorophyll. All of these reactions can be utilized as indicators for diagnosing plant stress [22,11]. In recent times, notable focus has been directed towards advancing multi-sensor imaging techniques for facilitating stress identification and surveillance. These methodologies encompass a spectrum of approaches, including the basic fusion of thermal and reflectance sensors, the integration of sensors measuring visible reflectance and fluorescence [34], as well as the amalgamation of fluorescence, reflectance, and thermal imaging sensors [35,36,37]. A relatively recent development in India is the establishment of the Mahalanobis National Crop Forecast Centre (MNCFC) under the purview of the Department of Agriculture & Cooperation within the Ministry of Agriculture. This marks the formal institutionalization of remote sensing applications in India. The institute plays a pivotal role in implementing two major programs of the Indian Space Research Organization (ISRO), namely crop forecasting and drought assessment, in addition to other initiatives aimed at evaluating agricultural activities [38,11].

8. REMOTE SENSING FOR BIOTIC STRESS MANAGEMENT

In the horticultural industry, production losses and subsequent economic setbacks primarily result from pest infestations and diseases. Remote sensing has demonstrated its efficacy as a valuable tool for the early detection of diseases and the identification and management of pests and nematodes. This is achieved by detecting alterations in plant pigments, recognizing the damage caused by pests through leaf skeletonization, and pinpointing susceptible plant areas [22,11]. For instance, an airborne multispectral digital imaging system was developed to assess crop canopy reflectance and density under varying degrees of phylloxera stress. In another study, the seasonal progression of the southern root knot nematode and soilborne fungi complex in kenaf was monitored through multi-temporal NIR videography [39]. Similarly, when citrus canker lesions appeared on citrus leaves, there were observable changes in the spectral reflectance of leaves within the wavelength range of 600-700nm [40]. In 1999, Hahn devised a prediction model for mango anthracnose and late blight disease in tomatoes using NIR (Near Infra-Red) bands. Remote sensing (RS) proves to be a faster and more cost-effective means of mapping weeds compared to traditional ground survey techniques. RS is particularly well-suited for mapping extensive geographical areas. Remote sensing enables a quicker and more cost-effective mapping of weeds compared to conventional ground survey techniques. Weeds with distinct biological features that can be easily differentiated from the surrounding vegetation are ideal candidates for mapping using lower spectral resolution imagery. On the other hand, weeds that closely resemble the spectral characteristics of the surrounding vegetation require higher spectral resolution imagery for accurate mapping [22]. A real-time selective herbicide application technique was developed, employing a texture-based weed classification method that utilizes Gabor wavelets and neural networks [41].

9. REMOTE SENSING FOR CROP CLASSIFICATION

Remote sensing data can effectively distinguish major physiognomic vegetation types, including forests, woodlands, scrublands, grasslands, and mixed vegetation, as they capture and record the distinctive spectral traits of these types of vegetation cover. In the case of horticultural crops, which consist of bushes, shrubs, or trees with green foliage, their spectral signatures closely resemble those of other healthy vegetation. For instance, in Kerala, India, coconut plantations often coexist with various other fruit crops such as jackfruit, mango, bael, and banana. Researchers found that multispectral photography proved valuable in clearly distinguishing each of these species from one another based on their unique color patterns [42]. An unsupervised clustering technique for image segmentation is another method that can be used to differentiate fruit and nut trees from forest vegetation that may have similar spectral characteristics, particularly in regions with unexpected land cover [15,22,11].

10. REMOTE SENSING FOR CROP CANOPY MEASUREMENT

Canopy volume holds significant importance in the precise management of horticultural crops, playing a pivotal role in the accurate application of fertilizers, irrigation, chemical treatments, and health assessment. Additionally, it correlates directly with crop yield in the case of tree crops [43,44]. For horticultural crops, understanding their growth stage, size, and water requirements is particularly crucial, as many of these crops thrive in water-limited environments and rely on irrigation. The rapid determination of mineral nutrition levels in fruit trees is imperative for precise orchard fertilization management. In this regard, a multispectral imaging system was developed for measuring the leaf nitrogen content of fruit trees [45]. Although remote sensing techniques have been employed for years to estimate canopy cover in major crops, there has been a noticeable gap in the coverage of horticultural crops [46]. Recent findings, however, have demonstrated that remotely sensed Normalized Difference Vegetation Index (NDVI) is correlated with canopy cover in major horticultural crops across commercial fields with varying planting configurations and stages of maturity [46].

11. REMOTE SENSING FOR CROP AREA ESTIMATION

Horticultural crops often experience significant fluctuations in both production and consumption, resulting in a highly volatile market and price structure. This unpredictability underscores the critical need for reliable statistics regarding the area and production of horticultural products, essential for effective market planning and the export of these produce. Remote sensing plays a pivotal role in assessing the supply scenario. For instance, when it comes to crops like potatoes, which are grown in extensive contiguous fields, remote sensing can estimate their area and production with an accuracy exceeding 90% [47]. However, estimating the area under mango orchards, particularly those with trees older than five years, is relatively straightforward using remote sensing. In contrast, for younger mango trees, the process is more complex due to spectral signature overlaps [22]. Similarly, mulberry exhibits spectral signatures early in the season that closely resemble those of other vegetable crops. However, as the season progresses, there is a noticeable distinction in these signatures [47,11].

12. REMOTE SENSING FOR CROP INSURANCE

The effects of global warming and climate change have made the climate increasingly erratic and destructive. In such uncertain conditions, crop insurance serves as a crucial safeguard for farmers who may suffer crop losses due to abrupt weather changes. However, it's important to acknowledge that instances of insurance fraud do exist. To counteract this issue, insurance companies can employ satellite images, specifically the red and infrared bands, in conjunction with the Normalized Difference Vegetation Index (NDVI). This approach allows them to validate seeded crops and identify potential instances of fraud [11].

13. REMOTE SENSING FOR CROP HEALTH MONITORING

Remote sensing proves to be a valuable tool for assessing crop conditions through the use of the Normalized Difference Vegetation Index (NDVI). Near-infrared radiation is employed to detect healthy vegetation in horticulture. Healthy vegetation has the characteristic of reflecting green light while absorbing red and blue light. NDVI is sensitive to changes in green biomass, chlorophyll levels, and canopy water stress. This system is straightforward to implement and particularly effective in predicting soil properties, especially when the vegetation is not densely packed, and soil areas are visible within the vegetation. The standard formula for calculating NDVI is expressed as follows:

$$NDVI = (NIR - RED) / (NIR + RED),$$

Where NIR and RED represent spectral reflectance measurements in the near-infrared and red or visible regions, respectively. This vegetation index exhibits a very strong correlation with vegetation parameters, as it captures radiation absorbed by photosynthetically active vegetation, contributing to its reliability [48,49,50]. Furthermore, hyperspectral reflectance data obtained from canopy reflectance can provide highly precise information for estimating crop production, as indicated by research [51,52].

14. CONCLUSION

In conclusion, remote sensing technology has revolutionized horticulture, offering precise Solutions to complex challenges in farming. By providing critical data on crop health, soil quality, and environmental factors, remote sensing empowers horticulturists and farmers to make informed decisions that boost yields, conserve resources, and contribute to global food security. Its role in site-specific crop management is pivotal, and its applications in horticulture are vast, from yield estimation to pest management. In a world where sustainable agriculture is paramount, remote sensing technology emerges as an essential tool for a more productive and environmentally friendly future in horticulture.

ACKNOWLEDGEMENT

We would like to express our sincere gratitude to the National Agricultural Higher Education Project, - Consortium for Agricultural Science and Technology - Centre for Sustainable Development in Agriculture (NAHEP-CAASTCSDA) for funding this research project. We would also like to extend a special thanks to the project PI, Dr. R.K. Nema, for his valuable guidance and support throughout the project.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/105926