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ADVANCING PRECISION AGRICULTURE: INTEGRATED APPLICATIONS OF GLOBAL NAVIGATION SATELLITE SYSTEM IN PRECISION FARMING

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ABSTRACT

The Global Navigation Satellite System (GNSS) is very important for precision farming because it gives precise position data that can be used to apply fertilizers, herbicides, and water in a specific way. This level of precision cuts down on waste, lowers the prices of inputs and labour, and increases agricultural yields, which enhances both profitability and economic sustainability. GNSS also provides valuable data for informed farm management. As satellite technology, AI, and machine learning get better, GNSS systems get more accurate and reliable. This helps people make better decisions and long-term sustainability. This study investigates the role and function of GNSS in precision agriculture and its potential to revolutionize farming through the integration of advanced technology.

Key words: Automatic Steering, GNSS, Livestock Monitoring, Precision Agriculture, Yield Monitoring

Introduction

Global Navigation Satellite Systems (GNSS) utilize a constellation of orbiting satellites to continuously transmit real-time positioning and timing signals to ground-based receivers, thereby delivering highly accurate geospatial information on a global scale (Píšová & Chod, 2015). This technology serves as a foundational component in the advancement of smart agriculture, where its integration facilitates precise field operations, resource optimization, and data-driven decision-making. The widespread availability and affordability of GNSS have revolutionized conventional farming practices by enabling the adoption of precision agriculture techniques across diverse agroecological zones. Leading agricultural machinery manufacturers now incorporate GNSS-enabled solutions to support site-specific crop management strategies, which are increasingly embraced worldwide (Shannon *et al.*, 2018).

GNSS-powered precision agriculture enhances operational efficiency, timeliness of interventions, agricultural productivity, and environmental sustainability. These systems provide sub-meter to centimetre-level positioning accuracy, which supports automated steering,

variable-rate input application, and spatially-resolved field monitoring (Fu *et al.*, 2022). By providing accurate direction, GNSS technology is essential to precision agriculture, helping to maximize field operations like planting, fertilizing, and harvesting (Pawar *et al.*, 2025). When integrated with advanced sensing technologies and Internet of Things (IoT) devices, GNSS facilitates real-time monitoring of key agronomic parameters such as soil moisture, canopy temperature, air humidity, and crop stress indicators. This synergy enables timely agronomic decisions, improves resource use efficiency, and reduces environmental externalities. Furthermore, GNSS provide location and dynamic tracking of agricultural machinery, equipment, livestock contributing to better planning of various operations like planting, harvesting, and herding and maintenance and overall operational logistics of machineries (Karunathilake *et al.*, 2023).

This study explores the diverse applications of GNSS across a wide range of agricultural operations, emphasizing their significance in improving precision, operational efficiency, and data-driven decision-making within modern farming systems. The applications of GNSS in agriculture can be broadly categorized as follows:

Tillage and Land Levelling Operations

Tillage refers to the mechanical manipulation of soil aimed at improving its physical condition for seedbed preparation, moisture conservation, and weed control. The integration of GNSS into tillage operations has significantly enhanced the precision, uniformity, and operational efficiency of these activities. By facilitating accurate path tracking and position control, GNSS technology ensures consistent tillage depth while minimizing overlaps and missed strips. This level of precision contributes to improved soil structure, reduced fuel consumption, lower operator fatigue, and optimized time and resource management (Karunathilake *et al.*, 2023; Sharma and Shivandu, 2024).

A notable early example of GNSS-enabled automation in tillage is the Robotra tillage robot, developed in Japan in 1997. This autonomous system features an advanced navigation and control architecture, wherein a central computer processes GNSS signals via an RS-232C bus. A dedicated vehicle controller interprets sensor feedback to generate precise control commands for steering, gear shifting, throttle modulation, and independent braking⁶. Field evaluations revealed that Robotra is capable of autonomously tilling up to 50 hectares with performance levels comparable to conventional manual methods (Yukumoto *et al.*, 2000).

Further advancements have led to the development of multi-functional autonomous systems. For instance, Shaik *et al.*, (2018), designed a multipurpose agricultural robot equipped with GPS and magnetometer-based navigation, capable of executing multiple tasks including ploughing, seeding, levelling, and irrigation with minimal human supervision. In another study, Manpreet *et al.*, (2019) proposed a GNSS/GPS-based topographic surveying and land levelling system (Fig. 1), which demonstrated substantial improvements in field uniformity.



Fig. 1: NSS/GPS-based topographic surveying and land levelling system.

Compared to traditional manual surveys, this approach resulted in a 74.0% reduction in earthwork and a 75.4% improvement in land levelness, outperforming conventional methods that achieved reductions of only 61.5% and improvements of 62.1%, respectively.

Moreover, the incorporation of GNSS with Real-Time Kinematic (RTK) systems has enabled high-resolution mapping of land surface features and assessment of land preparation quality. In particular, RTK-enabled GNSS systems have been employed to capture land levelness data following each land preparation operation. These data are used to calculate the levelling index, a quantitative indicator of field smoothness and grading accuracy, where higher values reflect better land preparation outcomes (Omar *et al.*, 2023).

GNSS-Enabled Precision Seeding and Planting Technologies

Global Navigation Satellite System (GNSS)-enabled precision seeding and planting have emerged as foundational components of modern precision agriculture, offering enhanced spatial accuracy in seed placement, optimized sowing depth, consistent crop density, and uniform row spacing. Among various implementations, Real-Time Kinematic (RTK)-GPS guidance systems integrated with seed planters and transplanters have demonstrated significant efficacy in geo-referencing the precise location of seeds and transplants during field operations. This spatial precision contributes to improved planting accuracy, reduced overlaps and misses, and better inter-plant spacing (Ehsani *et al.*, 2004; Sun *et al.*, 2010).

These GNSS-based systems not only minimize input wastage—such as seeds and fertilizers—but also promote uniform crop emergence and efficient resource utilization. Empirical studies have reported yield increases ranging from 10% to 30% compared to conventional seeding methods, primarily attributed to better plant stand establishment and reduced intra-row variability (Zhai *et al.*, 2014; Zhang *et al.*, 2012). Furthermore, the integration of GNSS with variable-rate technology (VRT) allows for adaptive seeding rates based on spatial variability in soil fertility, texture, and moisture, thereby enhancing field-level productivity and environmental sustainability (Schellberg *et al.*, 2008).

A critical determinant of uniform crop emergence is the consistency of seeding depth, which influences early seedling vigor and ultimately impacts crop yield. Addressing this need, Nielsen *et al.*, (2018) developed a GNSS-assisted coulter depth control system for a low-cost seed drill (Fig. 2), utilizing the BT-Q1000XT GNSS receiver (Qstarz, Taiwan) to map coulter depth variability across the field. The system, which incorporated coulter

position sensors and ultrasonic soil surface sensors, enabled real-time monitoring and adjustment of seeding depth. As a result, the system improved coulter depth stability and uniformity, leading to enhanced seeding performance and stand establishment under field conditions.

GNSS Enabled Variable Rate Application in Crop Input Management

Global Navigation Satellite System (GNSS) technology plays a pivotal role in enabling Variable Rate Technology (VRT), which facilitates the site-specific application of inputs such as fertilizers, pesticides, herbicides, and irrigation water. By correlating input application rates with spatial variability in field conditions, GNSS-based VRT reduces wastage, improves input efficiency, and minimizes the environmental footprint of agricultural practices. GNSS-integrated machinery can precisely modulate input delivery in real time, thereby enhancing fertilizer use efficiency, conserving fuel, and improving crop productivity.

Recent advancements have enabled the deployment of GNSS-guided systems in aerial as well as ground-based platforms. Song *et al.*, (2020) developed a UAV-mounted variable-rate granular fertilizer spreader that utilized GNSS coordinates to adjust application rates based on prescription maps. The system effectively regulated the rotational speed of a fluted roller motor through an optimized metering mechanism, ensuring spatially accurate and uniform fertilizer distribution.

Similarly, in orchard management, high-performance GPS (HPGPS) integrated with sensor-based decision systems has demonstrated utility in addressing site-specific disease control (Fig. 3). The developed precision fumigant applicator that employed HPGPS signals and inclination sensors to activate solenoid valves. The applicator delivered fumigants only when the shank was accurately positioned within the designated treatment zone, significantly improving the precision and efficacy of



Fig. 2: GNSS-assisted coulter depth control system for a low-cost seed drill.

chemical application in orchard replant disease management (Perez-Ruiz and Upadhyaya, 2012).

Despite challenges such as occasional signal degradation and limited satellite coverage, GNSS-based technologies continue to replace labour-intensive manual operations with automated and spatially responsive alternatives (Haneklaus *et al.*, 2016). The integration of GNSS with Unmanned Aerial Vehicles (UAVs) further expands the scope of precision agriculture. When combined with advanced positioning systems such as Real-Time Kinematic (RTK) and Post-Processed Kinematic (PPK) techniques, GNSS-equipped UAVs offer centimetre-level geolocation accuracy. This precision prevents off-target applications during aerial spraying, minimizes chemical drift, and enhances environmental safety (Biglia *et al.*, 2019). Furthermore, the automation enabled by GNSS improves flight path efficiency and overall UAV operational safety.

GNSS Based Site-Specific Weed Management System

Weeds not only compete with crops for vital resources such as nutrients, water, and light, but also serve as important reservoirs and vectors for plant pathogens, including symptomless carriers of vector-borne viruses. Effective weed management is therefore critical not only for maximizing crop yield but also for mitigating disease transmission. The advent of site-specific herbicide applicators has revolutionized weed control by enabling precise chemical application, thereby minimizing herbicide usage and reducing the carbon footprint associated with herbicide manufacturing and deployment (Tiwari *et al.*, 2019).

Real-Time Kinematic (RTK) Global Positioning System (GPS) technology further enhances the precision of weed control operations. By enabling centimetre-level positional accuracy, RTK-GPS supports targeted herbicide applications along crop rows without compromising the efficacy of intra-row chemical treatments. This approach has been shown to reduce

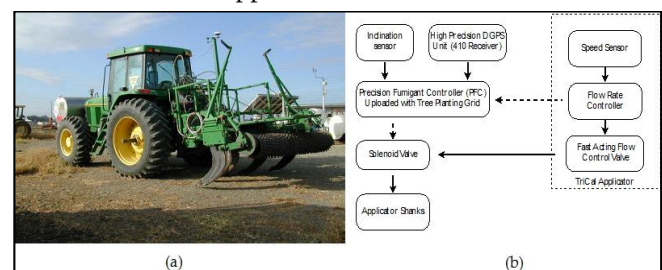


Fig. 3: A shank type fumigant applicator (a) retrofitted with a precision fumigant controller and a HPGPS positioning unit, (b) Schematic of the fine-tuned site-specific fumigant application system.

herbicide usage by up to 50%, resulting in lower input costs and reduced environmental contamination.

Innovative robotic systems are also being developed for real-time weed detection and control, integrating GNSS technology with mechanical actuators for site-specific intervention. A notable example is the automatic intra-row weeding system developed by the Department of Biological and Agricultural Engineering at the University of California. This system employs cultivator knives for mechanical weed removal and utilizes a high-precision RTK-GPS-based plant map generated during the transplanting stage to navigate the crop rows accurately. Field evaluations demonstrated that the system effectively removed intra-row weeds without damaging crop plants, even when operated at working speeds of 0.8 and 1.6 km/h (Pérez-Ruiz *et al.*, 2012).

The integration of GNSS and RTK technologies into automated weeding platforms offers a sustainable alternative to conventional blanket chemical applications. By enabling both chemical and mechanical site-specific weed management, these systems contribute to precision agriculture's broader goals of improving resource use efficiency and environmental stewardship.

Irrigation Management

Site-specific or variable rate irrigation (VRI) represents a critical component of precision agriculture, aimed at improving water use efficiency and crop productivity under diverse field conditions. By integrating Global Navigation Satellite System (GNSS) technology, modern irrigation systems can deliver water with spatial precision, ensuring that application is restricted to zones with actual water demand. This spatially adaptive approach not only conserves water but also supports sustainable agriculture by minimizing runoff, leaching, and waterlogging—key challenges in conventional uniform irrigation systems.

A notable advancement in GNSS-based irrigation monitoring is the MISTRALE project, an EU-funded initiative that pioneered the use of GNSS reflectometry to measure soil moisture from low-altitude Unmanned Aerial Vehicles (Anonymous, 2020). By analyzing the reflected GNSS signals from the soil surface, this technique provides accurate, non-invasive moisture measurements, offering farmers timely insights into irrigation requirements and enabling data-driven decision-making for irrigation scheduling.

Complementing GNSS-based monitoring, irrigation control systems incorporating Wireless Sensor Networks (WSNs) and real-time soil moisture sensing have demonstrated considerable potential for field-level irrigation optimization. These systems continuously

monitor in-situ soil water status and communicate data wirelessly to central controllers or mobile devices. As a result, they facilitate automated, site-specific irrigation management, ensuring timely and efficient water delivery while reducing manual intervention (Kim and Evans, 2009; Hedley *et al.*, 2011).

The integration of GNSS, UAV remote sensing, and WSN technologies represents a paradigm shift in irrigation management. It enables precision control of water inputs aligned with spatial and temporal variability in crop water demand, thereby enhancing water productivity, improving crop yields, and promoting environmental sustainability.

Yield Mapping and Harvest Automation

Among the various technologies driving precision agriculture, yield mapping and automatic guidance of agricultural machinery are among the most widely adopted and recognized by farmers (Dos Santos *et al.*, 2018). Yield mapping enables the continuous collection of site-specific yield data during harvest, allowing the spatial variability in crop production to be visualized and analyzed. This variability often reflects differences in soil properties, plant health, topography, and microclimatic conditions (Pérez-Ruiz and Upadhyaya, 2012). Understanding these patterns is fundamental to implementing site-specific crop management strategies that optimize input use and improve overall productivity.

GNSS-equipped harvesters facilitate real-time yield monitoring while maintaining accurate cutting paths, reducing crop losses, minimizing overlaps, and conserving fuel. Such precision is especially valuable in large-scale farming operations, where even minor inefficiencies can translate to significant economic and environmental costs. Major agricultural equipment manufacturers—including John Deere, CASE IH, New Holland, Fendt, and CLAAS—have integrated GNSS navigation systems and GPS compasses into their machines to determine the absolute position and orientation of vehicles during operation. Field evaluations have shown that these systems can achieve lateral navigation errors as low as 0.04 m and steering angle errors of approximately 2.6° (Zhao, 2017).

GNSS is also essential in robotic harvesting systems, where geolocation data is paired with computer vision to automate harvesting tasks. RGB cameras serve as core sensors, capturing high-resolution imagery for the identification and localization of mature fruits and vegetables (Karkee *et al.*, 2021). When integrated with GNSS, these systems enable autonomous harvesting robots to perform precise navigation and apply appropriate force during fruit detachment, thereby reducing damage and increasing harvesting efficiency.

Several notable developments underscore the advancements in GNSS-based automation. Guan *et al.*, (2021) proposed a tracing algorithm and control strategy for a crawler-type rice combine harvester, which achieved a steady-state navigation error of 6.4 cm and a harvest width efficiency of 91.9%. Similarly, Liao *et al.*, (2021) developed an integrated GPS/Inertial Navigation System (INS)/Vision Navigation System (VNS) for automatic rice transplanters, significantly improving navigation accuracy in structured field environments.

In the United States, GNSS-based automatic guidance systems have gained widespread adoption among peanut growers for both sowing and digging operations. Studies have demonstrated that these systems improve row alignment, reduce input overlaps, and increase operational efficiency, despite minor instabilities during field manoeuvres (Leidner, 2012; Vellidis *et al.*, 2014; Dos Santos *et al.*, 2018).

To further enhance field navigation, Han *et al.*, (2021) introduced a path-planning algorithm for autonomous tillage in polygonal paddy fields. The planner efficiently generated complete field coverage routes and optimized headland turnings, contributing to improved machine performance in irregular field geometries.

Long-term studies have also explored the linkage between yield variability and spatial soil properties. At the University of Córdoba, Spain, a study was conducted to investigate yield variability in a 6-hectare irrigated cotton field using a GNSS-equipped cotton harvester Agüera *et al.*, (2003). The system employed a PF3000 yield monitor (AgLeader Technology Inc.) calibrated with four optical cotton flow sensors and a Trimble AgGPS 132 receiver, receiving OmniSTAR differential corrections (Fig. 4 (a)). Site-specific soil sampling and analysis revealed that variations in soil texture were the primary determinant of spatial differences in yield (Bravo *et al.*, 2004). Kriged maps of soil properties and crop yield were developed using Surfer software, offering a detailed visualization of the field's productivity zones. The main cause of the spatial variability in cotton yield in this field was found to be due to the spatial variation in soil texture (in particular, the sand and clay percentages) as seen in Fig. 4(b).

Collectively, these examples demonstrate the central role of GNSS in enhancing the accuracy, automation, and analytical capacity of yield mapping and harvesting technologies in precision agriculture.

GNSS in Field Mapping, Soil Sampling, and Site-Specific Decision Support

Global Navigation Satellite System (GNSS) technology is integral to modern field boundary mapping

and soil sampling operations. By providing high-precision geospatial data, GNSS enables the generation of accurate field maps that are essential for informed input planning, continuous monitoring of field conditions, and effective long-term farm management. The spatial resolution offered by GNSS facilitates the development of yield maps that allow farmers to identify intra-field variability and manage site-specific differences in crop performance. These maps support targeted decisions in irrigation scheduling, pest and disease management and harvest planning.

Incorporating GNSS into field scouting operations enhances the precision of crop health assessment and pest infestation monitoring. GNSS-enabled handheld or mobile scouting devices allow for georeferenced data collection on crop anomalies and field observations. When combined with other geospatial datasets—such as yield maps, soil texture maps, and elevation models—GNSS data contributes to the generation of prescription maps. These maps are crucial for driving Variable Rate Technology (VRT) systems, which apply agricultural inputs such as fertilizers and pesticides at variable rates based on localized field conditions (Ammoniaci *et al.*, 2011). This data-driven approach improves resource use efficiency and minimizes environmental impacts.

A significant advancement in spatial soil analysis was achieved by researchers at the University of California,

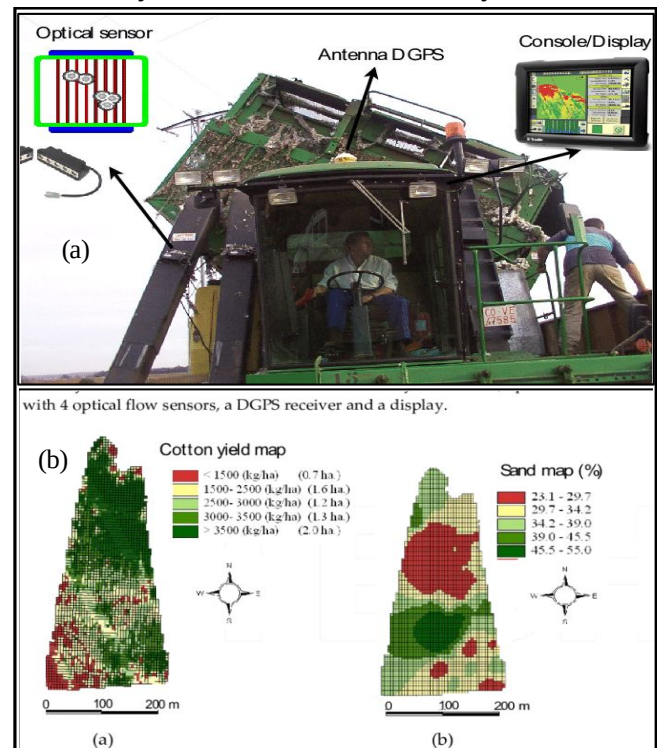


Fig. 4: Cotton yield monitor mounted with 4 optical flow sensors, a DGPS receiver and a display; 4.2: Kriged maps of: (a) cotton yield and (b) sand content in the test field.

who developed a soil compaction profile sensor capable of assessing within-field variability in subsurface physical conditions. The system includes five 5.1 cm long active cutting elements; each connected to individual octagonal load cells that measure soil cutting resistance ahead of the element. To georeferenced compaction data, the system integrates a Differential GPS (DGPS) receiver with sub-meter accuracy. Field trials revealed a strong spatial correlation between the soil compaction index and corresponding yield maps, indicating that localized subsurface resistance could be a key factor influencing crop performance (Andrade-Sanchez *et al.*, 2008).

Together, these technologies underscore the utility of GNSS in supporting precision field operations and site-specific agronomic decisions. By enabling spatially referenced data integration and decision-making, GNSS lays the foundation for efficient and sustainable agricultural practices.

Automatic Steering

As agriculture has become increasingly commercialized and capital-intensive, the efficient management of machinery services has become essential to avoid underutilization or excessive wear. The integration of Global Navigation Satellite System (GNSS) technology has emerged as a transformative solution in enhancing the effectiveness, precision, and efficiency of agricultural machinery operations. One of the most prominent applications is in automated steering systems for tractors and self-propelled machines. These GNSS-enabled systems minimize overlaps and skips common in manual operations, thereby optimizing input use, reducing labour requirements, and improving overall operational efficiency (Yandun *et al.*, 2017).

Modern GNSS-guided systems encompass a range of automation levels—from assisted steering to fully autonomous navigation. Auto-guidance (or auto-steering) systems utilize GNSS signals to align machinery paths with previously mapped tracks or predefined geographic coordinates, significantly reducing operator involvement during field operations (Easterly *et al.*, 2010). With the addition of Real-Time Kinematic (RTK) positioning, these systems achieve centimetre-level accuracy, making them suitable for a variety of field tasks including seeding, tillage, spraying, and harvesting (Rovira-Más *et al.*, 2015). GNSS-based guidance not only improves the accuracy of field operations but also conserves fuel, reduces machinery wear, and supports sustainable farming practices (Romano *et al.*, 2020).

From an ergonomic and human factors perspective, GNSS-assisted systems enhance operator comfort and safety. They allow machine operators to focus on overall

field supervision rather than constant manual steering, thereby reducing fatigue and the likelihood of musculoskeletal strain. Tractor cabins are typically equipped with user-friendly displays that visualize GNSS-based geolocated information, offering real-time guidance and alerts to prevent unnecessary overlaps and ensure optimal coverage (Jing *et al.*, 2019).

New-generation systems increasingly integrate GNSS with mechatronic components—such as electronic steering actuators, control units, and camera-based feedback loops—facilitating semi- and fully autonomous machine navigation. These technologies are driven by software capable of processing GNSS signals to generate precise guidance paths, while image processing and computer vision systems enhance environmental awareness and obstacle detection (Azmi *et al.*, 2020).

The practical implementation of GNSS-based navigation systems has been demonstrated in various applications. For example, Nugroho *et al.*, (2014) developed a GPS-based tracking system for evaluating tillage effectiveness with a four-wheel tractor. The system used GPS-based location acquisition (iGPSport) and trajectory analysis to measure field overlap, a key indicator of tillage efficiency. Similarly, the documented early adoption of GNSS for private agricultural vehicle guidance, noting its rapid uptake following public availability in 1995 (Lechner and Baumann, 2000).

Moreover, research continues to advance in combining GNSS with other technologies such as Inertial Navigation Systems (INS), Geographic Information Systems (GIS), and data transmission protocols like ISOBUS. These integrations are accelerating the transformation of agricultural equipment from conventional mechanical tools into intelligent, automated systems capable of data-driven decision-making (Lenz *et al.*, 2007; Shearer and Pitla, 2013). For instance, ISOBUS-enabled communication between sensors, actuators, and control terminals ensures seamless operation across different machinery platforms, while GNSS enhances spatial decision-making accuracy.

The continued convergence of sensing, communication, and automation technologies—powered by high-resolution GNSS navigation—underpins the evolution of smart, autonomous farming systems. These developments promise not only to improve farm-level productivity and profitability but also to advance sustainable and precise resource management across diverse agricultural landscapes.

GNSS-Based Monitoring and Management in Livestock Farming

Livestock farming presents multifaceted challenges, including health surveillance, feeding efficiency, reproductive tracking, and milking management. The integration of Global Navigation Satellite System (GNSS) technology into livestock systems has significantly improved pasture-based animal management by enabling spatially explicit monitoring of grazing behaviour, movement patterns, and physiological indicators. GNSS facilitates precision pasture management by optimizing the use of grazing areas and improving decision-making related to animal welfare, feeding schedules, and land use planning.

One of the most notable contributions of GNSS in animal husbandry is the ability to characterize animal movement and behavioural patterns across pastures. By collecting high-resolution positional data, farmers can track grazing paths, identify preferred foraging zones, and quantify grazing intensity and distribution. For instance, Sales-Baptista *et al.*, (2019) demonstrated the use of GNSS receivers to monitor grazing sheep, analysing variables such as movement trajectories and speed to gain insights into daily foraging behaviour and pasture utilization efficiency.

The use of GPS sensors has also advanced behavioural classification by distinguishing static and dynamic activities such as foraging, resting, and locomotion based on movement speed and trajectory. The study showed that activity differentiation based on GNSS-derived data enables a more nuanced understanding of animal behaviour, which is essential for developing targeted pasture rotation strategies and minimizing overgrazing (Andriamandroso *et al.*, 2016)

To further improve behavioural interpretation, posture monitoring systems using tri-axial accelerometers have been developed. When integrated with GNSS, these systems can precisely detect head positions (upward or downward) to classify feeding-related behaviours. It was reported that combining accelerometer and GNSS data collected at sampling frequencies of 4–10 Hz achieved classification accuracies exceeding 90%, with time windows as short as 5–10 seconds. Such real-time behavioural detection is valuable for assessing feed intake, animal health, and time budgets (Dutta *et al.*, 2014).

Reproductive management, particularly the detection of oestrus in grazing animals, also benefits from GNSS-enabled tracking. In a study, mixed-age Merino ewes were fitted with GNSS devices on neck collars, and behavioural observations were synchronized with location data (Fogarty *et al.*, 2014). Results indicated a significant increase in movement speed during early morning hours

on the predicted day of oestrus. These findings highlight the potential of remote GNSS-based tracking technologies to improve the detection of reproductive events in extensive livestock systems where direct observation is often impractical.

The advancement of autonomous monitoring tools combining GNSS, accelerometry, and data analytics represents a promising direction for livestock farming. Such systems not only enhance the efficiency of animal monitoring but also contribute to more sustainable and welfare-oriented management of ruminant species in pasture-based production systems.

Conclusion

Global Navigation Satellite System (GNSS) technology has become an integral component of precision agriculture, offering highly accurate geospatial data that supports the site-specific application of critical inputs such as fertilizers, pesticides, and irrigation water. By enabling spatially targeted management, GNSS enhances operational efficiency, reduces input waste, and ensures optimal resource utilization. These improvements translate into substantial cost savings for farmers through decreased consumption of agrochemicals and lower labor requirements, while simultaneously enhancing crop yield and quality—thereby boosting overall farm profitability.

Beyond immediate agronomic benefits, GNSS-based systems contribute to data-driven decision-making by providing detailed insights into field variability, equipment performance, and environmental conditions. This fosters long-term economic resilience and facilitates more sustainable land management practices.

Looking ahead, ongoing advancements in satellite infrastructure, signal processing, and positioning accuracy—particularly with the integration of Real-Time Kinematic (RTK) corrections—are expected to further enhance the precision and reliability of GNSS applications in agriculture. Moreover, the convergence of GNSS with emerging technologies such as artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT) will enable autonomous decision-making and real-time responsiveness. Together, these innovations will continue to transform conventional farming into a highly optimized, sustainable, and technologically advanced enterprise capable of meeting the growing global demand for food.

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Conflict of Interest The authors declare that there is no conflict of interest.

References

- Agüera, J., Pérez-Ruiz M., Gil J.A., Madueño A., Zarco-Tejada P. and Blanco G. (2003). Determining spatial variability of yield and reflectance of a cotton crop in the Guadalquivir Valley. In memory: 4th Conference on Precision Agriculture, 347-348.
- Ammoniaci, M., Kartsiotis S.P., Perria R. and Storch P. (2011). State of the Art of Monitoring Technologies and Data Processing for Precision Viticulture. *Agriculture*, **11**(3), 201; <http://dx.doi.org/10.3390/agriculture11030201>
- Andrade-Sanchez, P., Upadhyaya S.D. and Plouffe C. (2008). Development and Field Evaluation of a Field-Ready Soil Compaction Profile Sensor for Real-Time Applications. *Applied Engineering in Agriculture*, **24**(6), 743-750.
- Andriamandroso, A.L.H., Bindelle J., Mercatoris B. and Lebeau F. (2016). A review on the use of sensors to monitor cattle jaw movements and behavior when grazing. *Biotechnol. Agron. Soc. Environ.*, **20**(S1), 273-286.
- Anonymous (2020). Using GNSS Reflectometry to map soil moisture. European Commission, <https://doi.org/10.3030/641606>
- Azmi, M.A., Mohammad R. and Pebrian D. (2020). Evaluation of Soil EC Mapping Driven by Manual and Autopilot-Automated Steering Systems of Tractor on Oil Palm Plantation Terrain. *Food Research*, **4**(S5), 62-69.
- Biglia, A., Grella M., Bloise N., Comba L., Mozzanini E., Sopegno A. Pittarello M., Dicembrini E., Alcatrão L.E., Guglieri G., Balsari P., Aimonino D.R. and Gay P. (2022). UAV-Spray Application in Vineyards: Flight Modes and Spray System Adjustment Effects on Canopy Deposit, Coverage, and off-Target Losses. *Science of the Total Environment*, **845**, 1-17.
- Bravo, C., Giráldez J.V., Agüera J., Pérez-Ruiz M., González P., Ordóñez R. and Gil J.A. (2004). Assessing and modelling spatial variability of soil properties and association with the cotton yield map. Book of Abstracts. ISBN 90-76019-258. *AgEng Leuven*. 916-917.
- Dos Santos, A.F., da Silva R.P., Zerbato C., de Menezes P.C., Kazama E.H., Paixão C.S.S. and Voltarelli M.A. (2019). Use of real-time extended GNSS for planting and inverting peanuts. *Precision Agriculture*, **20**(1), 840 – 856. <https://link.springer.com/article/10.1007/s11119-018-9616-z>
- Dutta, R., Smith D., Rawnsley R., Bishop-Hurley G., Hills J., Timms G. and Henry D. (2014). Dynamic cattle behavioural classification using supervised ensemble classifiers. *Comput. Electron. Agric.*, **111**, 18-28.
- Easterly, D.R., Adamchuk V.I., Kocher M.F. and Hoy R.M. (2010). Using a vision sensor system for performance testing of satellite-based tractor auto-guidance. *Computers and Electronics in Agriculture*, **72**, 107-118.
- Ehsani, M.R., Upadhyaya S.K. and Mattson M.L. (2004). Seed location mapping using RTK GPS. *Trans. of the ASAE.*, **47**(3), 909 – 914.
- Fogarty, E.S., Manning J.K., Trotter M.G., Schneider D.A., Thomson P.C., Bush R.D. and Cronin G.M. (2014). GNSS technology and its application for improved reproductive management in extensive sheep systems. *Animal Production Science*, **55**(10), 1272-1280.
- Fu, J., Ji C., Liu H., Wang W., Zhang G., Gao Y., Zhou Y. and Abdeen M.A. (2022). Research Progress and Prospect of Mechanized Harvesting Technology in the First Season of Ratoon Rice. *Agriculture*, **12**(5), 620; <https://doi.org/10.3390/agriculture12050620>
- Guan, Z., Li Y., Mu S., Zhang M., Jiang T., Li H., Wang G. and Wu C. (2021). Tracing algorithm and control strategy for crawler rice combine harvester auxiliary navigation system. *Biosystems Engineering*, **211**, 50-62.
- Han, X., Xu L., Peng Y. and Wang Z. (2021). Trend of Intelligent Robot Application Based on Intelligent Agriculture System. In Proceedings of the 2021 3rd International Conference on Artificial Intelligence and Advanced Manufacture (AIAM), Manchester, UK, 205-209.
- Haneklaus, S.H., Lilienthal H. and Schnug E. (2016). 25 years precision agriculture in Germany—a retrospective. In Proceeding of 13th International Conference on Precision Agriculture, At: St. Louis, Missouri, USA.
- Hedley, C., Bradbury S., Watson E., Dalrymple H. and Wright J. (2011). Farm scale trials of variable rate irrigation to assess the benefits of modifying existing sprinkler systems for precision application. *Intl. J. of Agr. Mgt.*, **1**(2), 51-55.
- Jing, Y., Li Q., Ye W. and Liu G. (2023). Development of a GNSS/INS-based automatic navigation land levelling system. *Computers and Electronics in Agriculture*, **213**, 108187; <https://doi.org/10.1016/j.compag.2023.108187>
- Karkee, M., Zhang Q. and Silwal A. (2021). Agricultural Robots for Precision Agricultural Tasks in Tree Fruit Orchards. In *Innovation in Agricultural Robotics for Precision Agriculture: A Roadmap for Integrating Robots in Precision Agriculture*; Bechar, A., Ed.; Progress in Precision Agriculture; Springer International Publishing: Cham, Switzerland, 63-89. ISBN 978-3-030-77036-5.
- Karunathilake, E.M.B.M., Le A.T., Heo S., Chung Y. and Mansoor S. (2023). The Path to Smart Farming: Innovations and Opportunities in Precision Agriculture. *Agriculture*, **13**(8), 1593. <https://doi.org/10.3390/agriculture13081593>
- Kim, Y. and Evans R.G. (2009). Software design for wireless sensor-based site-specific irrigation. *Computers and Electronics in Agr.*, **66**(2), 159-165.
- Kondo, N., Monta M. and Noguchi N. (2011). Agricultural Robots: Mechanism and Practices. Trans Pacific Press, Balwyn North Victoria, Australia.
- Lechner, W. and Baumann S. (2000). Global navigation satellite systems. *Computers and Electronics in Agriculture*. **25**(1-2), 67-88.
- Leidner, J. (2012). Precision farming payoff in peanuts. *Southeastern Peanut Farmer*, **50**(5), 10-12.

- Lenz, J., Landman R. and Mishra A. (2007). Customized Software in Distributed Embedded Systems: ISOBUS and the Coming Revolution in Agriculture. *Agricultural Engineering International: The CIGR Ejournal. Manuscript ATOE 07*, **9**, 1-18.
- Liao, J., Zhou H., Zhu D., Yin J., Zhang S., Bi L. and Wang Y. (2021). An Integrated Navigation Method Based on an Adaptive Federal Kalman Filter for a Rice Transplanter. *Trans. ASABE*, **64**, 389–399.
- Manpreet, S., Sidhu H.S., Singh Y., Singh S.K. and Pandey H.S. (2020). Performance evaluation of automatic vis à vis manual topographic survey for precision land levelling. *Precision Agriculture*, **21**(2), 1-11; <https://link.springer.com/article/10.1007/s11119-019-09669-3>
- Nielsen, K.S., Munkholm L.J., Lamandéb M., Nørremarka M., Edwardsd G.T.C. and Green O. (2018). Seed drill depth control system for precision seeding. *Computers and Electronics in Agriculture*, **144**, 174–180.
- Nugroho, A.P., Shalij S.M., Purwantana B., Sutiarsa L., Radi., Markumminingsih S., Masithoh R.E., Yun J.H., Yeo K.U. and Lee D.G. (2014). Development of GPS-based Tracking System to Evaluate the Effectiveness of Tillage using Four-wheel Tractor. In Proceedings of IOP Conf. Ser.: *Earth Environ. Sci.*, **355**(1), 012014.
- Omar, M.F.Z., Mhd Bookeri M.A., Ahmad M.T., Abu Bakar B., Abdullah M.Z.K. and Wan Harun W.M.S. (2023). The Impact of Land Preparation Operations on the Land Leveling Index Status in a Rice Field. *Advanced and Sustainable Technologies*, **2**(2), 81-87; <http://dx.doi.org/10.58915/aset.v2i2.340>
- Pawar, A.T., Pathak S.V. and Shahare P.U. (2025). Application of GNSS In Agriculture and Horticulture. *International Journal of Agriculture, Environment and Biotechnology*, **18**(01), 67-73.
- Perez – Ruiz, M. and Upadhyaya S.K. (2012). GNSS in Precision Agricultural Operations. In *New Approach of Indoor and Outdoor Localization Systems* (ed. Fouzia Boukour Elbahhar and Atika Rivenq) 3-25.
- Pisova, P. and Chod J. (2015). Detection of GNSS Signals Propagation in Urban Canyons Using 3D City Models. *Information and Communication Technologies and Services*, **13**(1), 22-29; <http://dx.doi.org/10.15598/aeet.v13i1.1291>
- Romano, E., Bisaglia C., Calcante A., Oberti R., Zani A., Vinnikov D., Marconi A., Vitale E., Bracci M. and Rapisarda V. (2020). Assessment of Comfort Variation among Different Types of Driving Agricultural Tractors: Traditional, Satellite-Assisted and Semi-Automatic. *International Journal of Environmental Research and Public Health*, **17**(23), 8836; <http://dx.doi.org/10.3390/ijerph17238836>
- Rovira-Más, F., Chatterjee I. and Sáiz-Rubio V. (2015). The role of GNSS in the navigation strategies of cost-effective agricultural robots. *Comput. Electron. Agric.*, **112**, 172 – 182; <https://doi.org/10.1016/j.compag.2014.12.017>
- Sales-Baptista, E., Ferraz-de-Oliveira M.I., Lopes de Castro J.A., Rato L.M. and Cancela d'Abreu M. (2019). Pastoreio De Precisão: Monitorizar O Comportamento Dos Animais Para Adaptar a Oferta À Procura. In *Revista Portuguesa de Zootecnia; Associação Portuguesa de Engenharia Zootécnica (APEZ): Vila Real, Portugal*, 121–128. ISBN 0872-7098.
- Schellberg, J., Hill M.J., Gerhards R., Rothmund M. and Braun M. (2008). Precision agriculture on grassland: Applications, perspectives and constraints. *European Journal of Agronomy*, **29**(2-3), 59–71.
- Shaikh, K., Edwin P., Sujeshkumar B., Bonu M. and Reddy B.V. (2018). GPS based Autonomous Agricultural Robot. In proceeding of the International Conference on Design Innovations for 3Cs Compute Communicate Control. 100-105, <http://dx.doi.org/10.1109/ICDI3C.2018.00030>
- Shannon, D., Clay D.E. and Sudduth K.A. (2018). An Introduction to Precision Agriculture. In *Precision Agriculture Basics*, John Wiley & Sons, Ltd.: Hoboken, USA, 1–12.
- Sharma, K. and Shivandu S.K. (2024). Integrating artificial intelligence and Internet of Things (IoT) for enhanced crop monitoring and management in precision agriculture. *Sensors International*, **5**(1), 100292.
- Shearer, S.A. and Pitla S.K., (2013). Field production automation. In *Agricultural Automation: Fundamentals and Practices* (Ed. Q. Zhang and F. J. Pierce.) CRC Press, 97–124.
- Song, C., Zhou Z., Zang Y., Zhao L., Yang W., Luo X., Jiang R., Ming R., Zang Y. and Zi L. (2020). Variable-rate control system for UAV-based granular fertilizer spreader. *Comput. Electron. Agric.*, **180**(1), 105832.
- Sun, H., Slaughter D.C., Ruiz M.P., Gliever C., Upadhyaya S.K. and Smith R.F. (2010). RTK GPS mapping of transplanted row crops. *Computers and Electronics in Agr.*, **71**(1), 32-37; <http://dx.doi.org/10.1016/j.compag.2009.11.006>
- Tiwari, R., Vivek, Naresh R.K., Tyagi S., Shivangi and Kumar A. (2019). Evaluation of effective weed management strategy for enhancing productivity and profitability of chickpea (*Cicer arietinum* L.) under sub-tropical climate of western U.P. *International Journal of Chemical Studies*, **7**(5), 928-933.
- Vellidis, G., Ortiz B., Beasley J., Hill R., Henry H. and Brannen H. (2014). Reducing digging losses by using automated steering to plant and invert peanuts. *Agronomy*, **4**, 337–348.
- Yandun Narvaez, F., Reina G., Torres-Torriti M., Kantor G. and Cheein F.A. (2017). A Survey of Ranging and Imaging Techniques for Precision Agriculture Phenotyping. *IEEE/ASME Trans. Mechatronics*, **22**, 2428–2439.
- Yukumoto, O., Matsuo Y. and Noguchi N. (2000). Robotization of Agricultural Vehicles (Part 2) - Description of the Tilling Robot. *Japan Agricultural Research Quarterly*, **34**(2), 107-114.
- Zhai, J.B., Xia J.F., Zhou Y. and Zhang S. (2014). Design and experimental study of the control system for precision seed-metering device. *International Journal of Agricultural and Biological Engineering*, **7**(3), 13-18.
- Zhang, N., Wang M., and Wang N. (2012). Precision agriculture—a worldwide overview. *Computers and Electronics in Agriculture*, **36**(2-3), 113–132. [https://doi.org/10.1016/S0168-1699\(02\)00096-0](https://doi.org/10.1016/S0168-1699(02)00096-0).
- Zhao, T. (2017). Development of Automatic Navigation Method for Combine Harvester Based on Laser Scanner. Ph.D. Thesis, Northwest A&F University, Yangling, China.