Agri Articles

(e-Magazine for Agricultural Articles)

Volume: 06, Issue: 01 (JAN-FEB, 2026)

Available online at http://www.agriarticles.com

©Agri Articles, ISSN: 2582-9882

Precision Weed Management Using Drones, Sensors and AI (Artificial Intelligence)

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Precision weed management is a focused, resource-efficient approach to mapping, identifying, and managing weeds in agricultural fields using state-of-the-art technologies. New developments in drone platforms, sensor systems, and artificial intelligence approaches have made it possible for farmers to apply variable-rate, site-specific herbicide treatments rather than mass herbicide spraying. When this is combined with prescription maps and, if needed, automated or robotic spraying and weeding machines, precision weed management can boost yields, cut costs, reduce chemical use and lessen environmental harm. The mechanical arms will chop the weed crops or uproot the weeds, while the drone will identify the weed crops using high resolution. In place of chemical weed management, we can use mechanical weed management by drones, artificial intelligence, and sensors will help to increase soil fertility. This review article emphasizes the precision weed management using drones, sensors and AI.

Keywords: Precision Weed Management, UAV and Drone Technology, Spectral Imaging (Multispectral & Hyperspectral), AI and Deep Learning in Agriculture, Site-Specific and Sustainable Weed Control

Introduction

Weeds remain one of the most persistent problems in agricultural production systems, mainly because they compete with crops for basic growth resources such as sunlight, water, nutrients, and space. When weed growth is not properly controlled, it can lead to considerable yield losses and reduced crop quality, ultimately affecting farm income. As a result, weed management has always been an essential component of crop production practices. In most farming systems, weed control is still largely dependent on conventional methods, particularly the uniform or blanket application of herbicides across entire fields. Although this approach is easy to adopt and widely practiced, it is often inefficient and unsustainable in the long term.One of the major limitations of blanket herbicide application is that weeds are rarely distributed evenly within a field. In many cases, herbicides are sprayed even in areas where weed pressure is low or completely absent. This results in unnecessary chemical usage, increased production costs, and negative impacts on soil and environmental health. Moreover, the repeated and indiscriminate use of herbicides has contributed to the rapid development of herbicide-resistant weed species, which has become a serious concern in modern agriculture. These challenges clearly indicate the need for more precise and resource-efficient weed management strategies. In this context, the concept of Precision Weed Management (PWM) has emerged as a promising alternative to conventional weed control practices. Precision weed management is based on the principle that weed infestations vary spatially within a field and therefore require site-specific treatment rather than uniform application. Instead of treating the entire field in the same manner, PWM focuses on detecting the exact location, type, and intensity of weed populations and applying control measures only where they are needed. Over time, this concept has evolved alongside the broader development of precision agriculture, which emphasizes optimized input use and improved decision-making based on field variability. Recent advancements in digital technologies have significantly accelerated the adoption of precision weed management. The emergence of drones or Unmanned Aerial Vehicles (UAVs), coupled with advanced sensing technologies and artificial intelligence, has transformed weed detection and monitoring processes. Drones provide rapid and flexible access to high-resolution aerial images of agricultural fields. Sensors such as multispectral, hyperspectral, thermal, and near-infrared sensors are capable of capturing subtle differences in plant reflectance and physiological characteristics. Artificial intelligence and machine learning algorithms further enhance these technologies by processing large volumes of image data and accurately distinguishing weeds from crops. When used together, drones, sensors, and AI enable timely, accurate, and site-specific weed control decisions. The objective of this review paper is to provide a clear understanding of the importance of precision weed management and to examine the role of emerging technologies such as drones, sensors, and artificial intelligence in modern weed control. The scope of this review includes an overview of the limitations of conventional blanket herbicide application, the evolution of precision weed management concepts, and recent technological developments in this field. By synthesizing existing research findings, this review aims to highlight the potential of technology-driven weed management approaches to reduce chemical inputs, lower production costs, and promote sustainable agricultural systems.

Concepts and Principles of Precision Weed Management

Precision Weed Management (PWM) refers to a site-specific approach to weed control that aims to detect, map, and manage weeds based on their actual distribution within agricultural fields rather than applying uniform control measures across the entire area. The core concept of PWM is that weed populations are spatially and temporally variable and therefore require differential management strategies instead of blanket treatments (Gerhards and Christensen, 2003; Stafford, 2000). Unlike conventional weed management, which relies on uniform herbicide application regardless of weed presence, precision weed management focuses on identifying weed-infested zones and applying control measures only where necessary, thereby improving efficiency and sustainability (Blackmore et al., 2007). Site-specific weed management involves collecting detailed information on weed species, density, and location through field scouting, sensor-based measurements, or remote sensing technologies, which enables accurate weed mapping and targeted interventions (Christensen et al., 2009).

Conventional weed management, precision weed management, and smart weed management differ mainly in their level of technology integration and decision-making capability. Conventional systems apply uniform treatments with minimal field-level information, while precision weed management uses spatial data and decision-support tools to optimize input use (Stafford, 2000). Smart weed management represents an advanced stage of PWM, where artificial intelligence, real-time sensors, and automated machinery enable adaptive and autonomous weed control with minimal human intervention (Peteinatos et al., 2020). A fundamental principle underlying all precision and smart weed management approaches is the recognition of spatial and temporal variability of weed populations. Weed distribution varies not only across different locations within a field but also over time due to changes in cropping systems, soil conditions, weather patterns, and management practices (Heijting et al., 2007). Understanding and managing this spatial and temporal variability is essential for designing effective site-specific weed control strategies and forms the scientific foundation of precision weed management systems (Thorp and Tian, 2004)

Drone/Uav-Based Weed Management Technologies in Precision Agriculture

Types of Drones Used in Weed Management

Multirotor drones (Quadcopter, Hexacopter): Multirotor drones are the most commonly used UAVs in precision weed management due to their ability to hover, take off and land vertically, and fly at low altitudes. These drones are highly suitable for capturing high-resolution images required for accurate weed detection and mapping in small to medium-sized fields (Zhang and Kovacs, 2012).

Fixed-wing drones: Fixed-wing drones are designed for long flight duration and large-area coverage. They are mainly used in extensive agricultural fields where rapid field-level weed surveillance is required. However, their inability to hover and lower image resolution compared to multirotor drones limits their use for detailed weed identification (Colomina and Molina, 2014).

Hybrid drones: Hybrid UAVs combine the vertical take-off capability of multirotor drones with the long endurance of fixed-wing systems. These drones are increasingly explored for agricultural monitoring as they offer both flexibility and extended coverage (Villa et al., 2016).

Sensors Mounted on Drones for Weed Detection

RGB (Red, Green, Blue) cameras: RGB cameras are widely used for basic weed detection and visual field assessment. They provide high spatial resolution images that are useful for identifying visible differences between crops and weeds, especially at early growth stages (Peña et al., 2013).

Multispectral sensors: Multispectral sensors capture images in a few discrete spectral bands, including visible and near-infrared regions. These sensors are effective for differentiating weeds from crops based on vegetation indices such as NDVI and are widely used in precision weed mapping (Mulla, 2013).

Hyperspectral sensors: Hyperspectral sensors record data in hundreds of narrow spectral bands, allowing detailed analysis of plant reflectance characteristics. This enables accurate weed species identification and improved crop–weed discrimination, though high cost and data complexity limit widespread adoption (Thorp and Tian, 2004).

Near-infrared (NIR) sensors: NIR sensors are particularly useful for assessing plant vigor and biomass. Differences in NIR reflectance between crops and weeds help in detecting weed infestations under dense crop canopies (Hunt et al., 2013).

Thermal sensors: Thermal sensors measure canopy temperature and are used to detect plant stress caused by water deficiency or competition. Although not directly used for weed identification, thermal data support weed analysis by indicating stress patterns within fields (Zarco-Tejada et al., 2014).

Drone-Based Weed Mapping

Image acquisition: Drones equipped with appropriate sensors capture high-resolution, georeferenced images of crop fields at different growth stages to detect weed presence and distribution (Zhang et al., 2019).

Image processing and analysis: Acquired images are processed using image segmentation and machine learning algorithms to identify weed patches, estimate weed density, and classify weed species (Peña et al., 2015).

Generation of weed maps: Processed data are converted into spatial weed distribution maps, which highlight weed-infested zones within the field and provide the basis for site-specific weed management decisions (Christensen et al., 2009).

Drone-Emitted Weed Control Technologies

Site-specific herbicide spraying: Drones equipped with spraying systems apply herbicides only in weed-infested areas identified through weed maps, reducing chemical usage and minimizing environmental contamination (Huang et al., 2018).

Spot spraying and micro-dosing: UAVs enable precise spot spraying and micro-dosing of herbicides, which lowers input costs and reduces the risk of herbicide resistance development (Lan et al., 2017).

Operation in difficult field conditions: Drone-based spraying systems are particularly useful in wet fields, uneven terrains, and areas inaccessible to ground machinery, ensuring timely weed control (Xiongkui et al., 2017).

Ground and Proximal Sensing Technologies for Precision Weed Management

Optical sensors

Optical sensors are widely used in ground-based and proximal weed detection systems to identify weeds based on differences in colour, shape, and spectral reflectance between crops and weeds. These sensors operate mainly in the visible and near-infrared regions of the electromagnetic spectrum and are commonly mounted on tractors, sprayers, or handheld devices (Thorp and Tian, 2004).

Active optical sensors, such as those emitting their own light source, can function under varying light conditions and are effective for real-time weed detection during field operations. They are often used in spot-spraying systems to trigger herbicide application only when weeds are detected (Timmermann et al., 2003).

Passive optical sensors rely on ambient sunlight and are useful for collecting detailed spectral information under controlled lighting conditions. These sensors support accurate crop–weed discrimination but may be affected by changes in illumination and shadows (Mulla, 2013).

LiDAR and Ultrasonic Sensors:

LiDAR (Light Detection and Ranging) sensors use laser pulses to measure distances and generate three-dimensional information about plant structure and canopy height. In precision weed management, LiDAR sensors help differentiate weeds from crops based on height, biomass, and spatial structure, especially in row crops (Andújar et al., 2013).LiDAR-based systems are particularly useful for detecting weeds that protrude above or grow between crop rows, providing structural information that complements optical data and improves detection accuracy (Shendryk et al., 2020).

Ultrasonic sensors measure distance by emitting sound waves and recording their reflections from plant surfaces. These sensors are commonly used to estimate canopy height and biomass and have been applied in real-time weed detection and variable-rate spraying systems (Sui et al., 2008).Although ultrasonic sensors are relatively low-cost and simple, their accuracy can be influenced by plant density, wind conditions, and sensor positioning, limiting their standalone use for detailed weed identification.

Soil and Environmental Sensors

Soil sensors play an indirect but important role in precision weed management by monitoring soil properties such as moisture, temperature, electrical conductivity, and nutrient status. These factors strongly influence weed emergence, growth patterns, and spatial distribution within fields (Corwin and Lesch, 2005).

Soil moisture sensors help identify zones with favourable conditions for weed germination, enabling preventive or timely weed control measures (Gebbers and Adamchuk, 2010).

Environmental sensors, including temperature, humidity, and radiation sensors, provide real-time data on microclimatic conditions that affect weed growth dynamics. Integrating environmental sensor data with weed detection systems improves decision-making and supports adaptive weed management strategies (Pierce and Nowak, 1999).

Role of Artificial Intelligence (AI) in Precision Weed Management

Artificial Intelligence for Weed Detection and Classification: Artificial Intelligence (AI) plays a central role in modern precision weed management by enabling automated detection, identification, and classification of weeds from image and sensor data. Machine learning and deep learning algorithms analyze visual and spectral features of plants to distinguish weeds from crops with high accuracy (Thorp and Tian, 2004). Convolutional Neural Networks (CNNs) are widely used for image-based weed recognition due to their ability to learn complex patterns related to leaf shape, texture, colour, and canopy structure. These models have shown strong performance under varying field conditions and growth stages (Sladojevic et al., 2016). AI-based weed classification systems reduce dependency on manual scouting and improve the speed and reliability of weed detection, making real-time and large-scale applications feasible (Kamilaris and Prenafeta-Boldú, 2018).

Decision Support Systems (DSS) in Weed Management: Decision Support Systems (DSS) use AI-driven models to assist farmers and agronomists in making informed weed management decisions. These systems integrate weed detection outputs with agronomic knowledge to recommend optimal control measures, such as the type, timing, and rate of herbicide application (Pierce and Nowak, 1999). AI-based DSS can incorporate historical field data, weather information, soil conditions, and crop growth stages to predict weed emergence and competition dynamics. This predictive capability improves the effectiveness of weed control while reducing unnecessary chemical use (Gerhards and Christensen, 2003). By supporting site-specific and timely interventions, DSS enhances the economic and environmental sustainability of weed management practices.

Data Fusion in Precision Weed Management Data fusion refers to the integration of data from multiple sources, such as drone imagery, ground-based sensors, soil sensors, and environmental sensors, to improve the accuracy and robustness of weed detection and decision-making processes (Gebbers and Adamchuk, 2010). AI algorithms play a critical role in data fusion by combining spatial, spectral, and temporal datasets into a unified analytical framework. This approach allows more reliable weed identification than relying on a single data source (Mulla, 2013). Fusing drone-based remote sensing data with proximal sensing information helps capture both large-scale spatial patterns and fine-scale weed characteristics, leading to more precise weed mapping and control strategies (Peña et al., 2015).

Integration of Drones, Sensors, and AI

- The integration of drones, sensors, and AI represents a key advancement in precision weed management systems. Drones collect high-resolution spatial data, sensors provide detailed spectral and environmental information, and AI processes these datasets to generate actionable insights (Zhang and Kovacs, 2012).
- AI-driven systems enable real-time analysis of drone and sensor data, supporting automated weed mapping, variable-rate herbicide application, and autonomous weed control operations (Peteinatos et al., 2020).
- Such integrated systems reduce human intervention, improve operational efficiency, and support smart weed management approaches that align with sustainable and climate-smart agriculture goals.

Applications of Precision Weed Management in Different Cropping Systems

Cereal Cropping Systems (Rice, Wheat, Maize)

- In cereal crops, weeds cause severe yield losses due to early-stage competition and dense crop stands. Precision weed management has been effectively applied in rice, wheat, and maize systems to identify weed-infested zones and apply site-specific control measures (Gerhards and Christensen, 2003).
- Drone-based imagery combined with AI algorithms is used to distinguish grassy weeds from cereal crops, particularly during early growth stages when visual similarity is high. This approach supports variable-rate herbicide application and reduces excessive chemical use in cereal-based systems (Peña et al., 2015).
- In maize and wheat, row-based weed detection using sensors and machine vision enables inter-row and intra-row weed control, improving weed management efficiency and crop safety (Thorp and Tian, 2004).

Pulse and Oilseed Cropping Systems

- Pulse and oilseed crops such as soybean, groundnut, sunflower, and mustard are highly sensitive to early weed competition. Precision weed management helps in early detection of weed patches and timely intervention, which is critical for yield protection in these crops (Blackshaw et al., 2005).
- Multispectral and hyperspectral sensors are used to detect weed stress and spatial variability in pulse and oilseed fields, allowing targeted weed control instead of uniform herbicide spraying (Mulla, 2013).

- AI-based weed classification models have shown promising results in differentiating broad-leaved weeds from pulse and oilseed crops, supporting site-specific spraying and reducing herbicide load (Kamilaris and Prenafeta-Boldú, 2018).

Vegetable Cropping Systems

- Vegetable crops are often characterized by high crop value and intensive weed pressure, making precise weed management particularly important. Precision weed management technologies are used to detect weeds at early growth stages and apply localized control measures to minimize crop damage (Andújar et al., 2013).
- Ground-based sensors, machine vision systems, and AI-driven robotic weeders are increasingly used in vegetable fields to perform real-time weed detection and mechanical or chemical weed control (Slaughter et al., 2008).
- The integration of drones and proximal sensors allows continuous monitoring of weed dynamics in vegetable cropping systems, improving decision-making and reducing labour dependency.

Plantation and Orchard Cropping Systems

- In plantation crops and orchards such as tea, coffee, coconut, and fruit orchards, weeds mainly occur in inter-row and basin areas. Precision weed management enables accurate identification of weed-infested zones, allowing targeted control while protecting perennial crops (Zhang et al., 2019).
- Drones are used to monitor large plantation areas and generate weed distribution maps, while ground-based sensors support localized weed control operations (Colomina and Molina, 2014).
- Site-specific herbicide application and mechanical weed control in orchards help reduce chemical exposure to trees and improve soil and environmental health.

Cotton and Commercial Cropping Systems

- Cotton and other commercial crops often face prolonged weed competition due to longer crop duration. Precision weed management systems help monitor weed emergence over time and support timely, site-specific interventions (Gerhards et al., 2012).
- AI-based decision support systems integrate temporal weed data, weather information, and crop growth stages to optimize weed control strategies in cotton-based systems (Peteinatos et al., 2020).
- The use of drone-guided spot spraying in cotton fields has shown potential in reducing herbicide usage while maintaining effective weed control.

Mixed and Intercropping Systems

- In mixed cropping and intercropping systems, weed identification is more complex due to crop diversity and variable canopy structure. Precision weed management technologies help differentiate weeds from multiple crops using advanced sensors and AI algorithms (Mulla, 2013).
- Data fusion approaches combining drone imagery, ground sensors, and environmental data improve weed detection accuracy in complex cropping systems and support adaptive weed management strategies (Gebbers and Adamchuk, 2010).

Benefits of Precision Weed Management

Reduction in Herbicide Use

- One of the most significant benefits of precision weed management is the substantial reduction in herbicide usage through site-specific application. By targeting only weed-infested areas instead of applying chemicals uniformly across the entire field, unnecessary herbicide application is minimized (Gerhards and Christensen, 2003).
- The integration of drones, sensors, and AI-based weed detection systems enables accurate identification of weed patches, supporting spot spraying and variable-rate herbicide application. This targeted approach not only reduces chemical input but also helps slow down the development of herbicide-resistant weed populations (Peña et al., 2015).

Cost Effectiveness and Labour Savings

- Precision weed management improves cost efficiency by reducing expenditure on herbicides, fuel, and machinery operations. Since inputs are applied only where required, overall weed control costs are significantly lowered compared to conventional blanket spraying methods (Stafford, 2000).
- The use of automated technologies such as drones, ground-based sensors, and AI-driven decision support systems reduces dependence on manual labour for weed scouting and control. This is particularly beneficial in regions facing labour shortages and rising wage costs (Gebbers and Adamchuk, 2010).

Ecological and Environmental Benefits

- By minimizing excessive herbicide application, precision weed management reduces chemical residues in soil and water bodies, thereby protecting non-target organisms and overall ecosystem health (Mulla, 2013).
- Targeted weed control practices also help preserve beneficial soil microorganisms and promote biodiversity within agricultural systems. Reduced spray drift and lower environmental contamination contribute to safer and more environmentally responsible farming practices (Zarco-Tejada et al., 2014).

Improved Crop Yield and Sustainability

- Effective and timely control of weeds through precision weed management reduces crop–weed competition, allowing crops to utilize available resources more efficiently. This leads to improved crop growth, higher yields, and better crop quality (Blackshaw et al., 2005).
- Precision weed management supports long-term agricultural sustainability by optimizing input use, lowering environmental impact, and promoting climate-smart farming practices. The integration of advanced technologies ensures consistent weed control while maintaining soil health and farm profitability (Peteinatos et al., 2020).

Constraints and Challenges of Precision Weed Management

High Initial Investment Cost

- One of the major constraints limiting the adoption of precision weed management is the high initial investment required for advanced technologies such as drones, sensors, AI-based software, and automated spraying systems. The cost of acquiring and maintaining these technologies can be prohibitive, especially for small and marginal farmers (Stafford, 2000).
- In addition to equipment costs, expenses related to software subscriptions, data processing, and system maintenance further increase the overall financial burden, slowing large-scale adoption (Gebbers and Adamchuk, 2010).

Technical Complexity and Skill Requirements

- Precision weed management systems involve complex technologies that require technical knowledge and specialized skills for operation, calibration, data interpretation, and decision-making. Limited technical expertise among farmers and extension personnel remains a significant challenge (Pierce and Nowak, 1999).
- The effective use of drones, sensors, and AI tools often requires training in data analysis, software handling, and equipment maintenance. Inadequate access to training programs and skilled manpower restricts the practical implementation of these systems, particularly in developing regions (Mulla, 2013).

Data Availability and Model Generalization

- The performance of AI-based weed detection and decision support systems depends heavily on the availability of large, high-quality, and diverse datasets. In many cropping systems, especially in developing countries, such datasets are limited or inconsistent (Kamilaris and Prenafeta-Boldú, 2018).
- Another major challenge is the generalization of AI models across different crops, weed species, growth stages, and environmental conditions. Models trained under specific

conditions may perform poorly when applied to new regions or seasons, reducing their reliability and scalability (Thorp and Tian, 2004).

Weed Resistance and Sustainability Aspects in Precision Weed Management

Weed Resistance Management

- Herbicide resistance has emerged as a serious global challenge due to the repeated and indiscriminate use of the same herbicides under conventional blanket application practices. Continuous exposure to uniform herbicide doses exerts strong selection pressure on weed populations, leading to the survival and spread of resistant biotypes (Heap, 2014).
- Precision weed management plays an important role in mitigating herbicide resistance by reducing overall herbicide usage and avoiding unnecessary applications in weed-free zones. Site-specific and spot spraying approaches lower selection pressure on weed populations and help delay the development of resistance (Gerhards and Christensen, 2003).
- AI-based decision support systems further contribute to resistance management by enabling diversified weed control strategies, such as rotating herbicide modes of action and integrating chemical and non-chemical control measures based on weed density and distribution (Norsworthy et al., 2012).

Sustainability Aspects of Precision Weed Management

Sustainability is a key objective of modern agricultural systems, and precision weed management supports this goal by optimizing input use and minimizing environmental impact. Targeted weed control reduces chemical load in soil and water resources, thereby protecting ecosystem health and biodiversity (Mulla, 2013). The integration of drones, sensors, and AI enables efficient resource utilization, including reduced fuel consumption, lower labour requirements, and precise application of agrochemicals. These factors contribute to improved energy efficiency and reduced carbon footprint in farming systems (Gebbers and Adamchuk, 2010). Precision weed management also promotes long-term agronomic sustainability by maintaining soil health, reducing chemical residues, and supporting integrated weed management (IWM) approaches. By combining technological tools with agronomic practices, PWM enhances crop productivity while ensuring environmental and economic sustainability (Blackshaw et al., 2005).

Conclusion

Weed management remains one of the most critical challenges in crop production, and conventional blanket herbicide application has increasingly shown its limitations in terms of efficiency, cost, environmental safety, and herbicide resistance. Precision weed management represents a significant shift from uniform, input-intensive practices toward site-specific, knowledge-driven approaches that recognize the spatial and temporal variability of weed populations. The integration of advanced technologies such as drones, ground and proximal sensors, and artificial intelligence has made it possible to detect, map, and manage weeds with greater accuracy and timeliness. Drone- and sensor-based data acquisition, combined with AI-driven image analysis and decision support systems, enables targeted weed control through spot spraying, variable-rate application, and automated interventions. These technologies not only reduce herbicide use and labour requirements but also contribute to ecological sustainability by minimizing environmental contamination and preserving soil and ecosystem health. Moreover, precision weed management plays an important role in delaying the development of herbicide-resistant weed populations by reducing selection pressure and supporting diversified weed control strategies. Despite challenges related to high initial investment, technical complexity, data availability, and model generalization, continued advancements in sensing technologies, machine learning algorithms, and data integration frameworks are expected to improve the feasibility and adoption of precision weed management systems. With appropriate policy support, farmer training, and interdisciplinary research, precision weed management has the potential to become a key component of sustainable and climate-smart agriculture. Overall, the adoption of precision weed management offers a promising pathway to achieve efficient weed control, improved crop productivity, and long-term agricultural sustainability.

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