

AI-Powered Precision Agriculture: A Technical Review

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ABSTRACT

The agricultural industry is undergoing a transformative revolution through the integration of artificial intelligence and precision farming technologies. This technical review discusses a novel application of using computer vision and machine learning systems for precision weed management - specifically, sprayer technologies designed to revolutionize row crop agriculture. Modern precision agriculture technology utilizes complex AI-based systems using camera arrays in combination with convolutional neural networks to identify weeds in real-time and operate a targeted herbicide application accordingly. These implementations have very high classification accuracy across many species of crops and weeds while also functioning at speed across the field, even with unchanging environmental influences. The technology, used on the selective treatment principle, can recognize crops (desired) and weed species (unwanted) through complex pattern recognition and multispectral image processing. The newest implementations have additional edge computing capacity, with sophisticated sensor fusion and precision control for indicated spray application rates, and can respond very rapidly while remaining accurate at the targeted spatial scale of treatment. Based on economic considerations, it is likely to be more expected if new economies are kept at the level of farm operator rather than regional implications impacting the wider agricultural economy due to reduced costs, stable crop yields, and reduced resource costs. Environmental benefits are likely to be most considerable when all environmental dimensions are considered, which may include reducing chemical exposure to non-target beneficial organisms, and reduced overall chemical load on the environment, e.g., via risk to groundwater contamination. Future options will allow improved machine learning, expanded identification databases, and consolidation with broad field management platforms embracing autonomous farming systems.

Keywords: Precision agriculture, computer vision, machine learning, targeted herbicide application, sustainable farming

1. Introduction

The agricultural industry is in the midst of a technological shift as artificial intelligence and precision farming are poised to play a role in the future. Global food demand is estimated to increase significantly by 2050, and modern farming will continue to face tough challenges to meet food demand while minimizing environmental impact and production costs [1]. The precision agriculture industry is among the fastest-growing sectors in agriculture, where market valuations have reached astounding levels, and growth continues, primarily due to the adoption of AI-enabled technologies [1].

Traditional herbicide application methods, while using broad-spectrum herbicides, have some degree of effectiveness for weed management, but often lead to unnecessary product waste, increased cost, and potential environmental challenges. Current conventional herbicide spraying procedures involve applying herbicides over entire fields, which often results in herbicides that miss the weed targets, instead affecting non-target areas [2]. This method is not effective, resulting in millions of wasted dollars in herbicides applied annually across capital crop production systems. Farmers typically have a predetermined ratio of herbicides per acre, regardless of the weed density distributions in their fields.

This approach to spraying herbicides has led to the proliferation of herbicide-resistant weed populations, with many species of weeds worldwide with hundreds of documented cases of herbicide resistance, leading to large economic impacts in many crop-producing areas.

The advancement of AI-based precision agricultural technologies represents a significant move toward more sustainable and more economical farming practices. These technologies utilize complex computer vision algorithms with high recognition accuracy for differentiating crops from weeds and applying herbicides only when and where needed, providing the same level of weed control while using much less chemical [2]. Modern field sensors employed in these systems incorporate real-time field monitoring capabilities that allow users to detect and classify vegetation types in virtually real-time, regardless of environmental conditions (e.g., soil moisture, rain, crop growth phase) [2]. Early users of precision spraying technology report lower operational costs and improvements to environmental impacts related to chemical runoff and soil contamination [1].

This technical review documents the convergence of computer vision and machine learning technologies in precision weed control systems, specializing in sprayer technologies that are redefining row crop agriculture in corn, soybeans, and cotton production. The significance of computer vision algorithms for operationalizing machine learning classification and the development of precision application ability is the intersection of key new technologies designed to address the economic and environmental challenges facing agriculture today. Advanced sensor arrays combined with intelligent decision-making systems enable unprecedented precision in agricultural interventions, fundamentally changing traditional farming methodologies [2].

2. Technology Overview and System Architecture

2.1 System Design Principles

Modern-day precision agriculture technologies are advanced technological implementations that essentially transform traditional spraying practices. These AI-enabled technologies utilize advanced computer vision capabilities in combination with cutting-edge machine learning techniques to provide real-time weed detection and point herbicide application [3]. Today's precision spraying systems travel fast in the field and provide high detection capabilities across crop types and weed species, indicating the systems are at a technological maturity level [3]. Using multiple sensor types (high-frequency RGB cameras, near-infrared imaging systems, advanced ranging sensors), fully multi-sensor modalities facilitate the use of vegetation and growth assessment with significant degrees of spatial resolution [3].

The core technology is based on selective treatment. This works to use artificial intelligence to differentiate between desirable crops and what are undesirable weeds in agricultural fields. The advanced convolutional neural networks incorporated in these systems leverage multispectral images with a deep learning architecture to accomplish the necessary feature extraction and classification under changing environmental conditions [4]. This can help farmers apply herbicides in a more precise and targeted manner than previously possible, only treating the areas that require herbicide application without impacting crop areas. The intelligent decision-making algorithms can differentiate between numerous weed species and multiple crop varieties with exceptional classification confidence levels [3].

Machine learning models integrated within precision agriculture systems undergo continuous optimization through extensive field data collection, with training datasets containing vast quantities of annotated images representing diverse growth stages, lighting conditions, and seasonal variations [4]. The computational architecture supports real-time inference processing with minimal latency periods from image capture to spray activation, ensuring precise application timing during high-speed field operations. Contemporary implementations leverage edge computing capabilities to process

complex algorithms locally, reducing dependency on external connectivity while maintaining operational reliability in remote agricultural settings [3].

2.2 Operational Framework

The system's architecture is built around real-time image processing and decision-making capabilities, allowing for instantaneous responses to detected weed populations during field operations [4]. Contemporary precision spraying systems integrate distributed computing architectures featuring robust edge processing units capable of handling substantial data throughput rates while maintaining operational reliability across extreme environmental conditions typical of agricultural applications [4]. This technological foundation enables continuous processing of vast amounts of visual data while maintaining optimal operational speeds for large-scale farming applications.

The operational framework incorporates advanced spray control mechanisms featuring individual nozzle activation systems with rapid response times and precise application capabilities [3]. Modern implementations utilize sophisticated pulse-width modulation techniques for accurate spray volume control, enabling variable application rates depending on weed density and species requirements. The integrated positioning systems, typically employing high-precision satellite navigation technology, provide exceptional accuracy for precise georeferencing of treatment zones and comprehensive field mapping capabilities [4].

Contemporary precision agriculture platforms demonstrate remarkable operational efficiency metrics, achieving substantial field coverage rates while maintaining consistent detection and treatment performance across varying terrain conditions and crop growth stages [3]. The modular architecture supports scalable implementation configurations, accommodating various boom widths and integrating numerous individual spray nozzles per system for comprehensive field coverage. Advanced sensor fusion techniques combine multiple data streams to enhance decision-making reliability and reduce false positive detection rates under challenging field conditions [4].

System Component	Core Technology	Key Capabilities
Vision and Detection Systems	Multi-sensor modalities, including high-frequency RGB cameras, near-infrared imaging, and advanced ranging sensors	Real-time weed identification with high detection accuracy across diverse crop and weed species under varying environmental conditions
Machine Learning Processing	Advanced convolutional neural networks with deep learning architectures and edge computing capabilities	Continuous optimization through extensive field data collection, minimal latency processing, and exceptional classification confidence levels
Application Control Systems	Individual nozzle activation with pulse-width modulation and high-precision satellite navigation	Variable application rates, rapid response times, and comprehensive field mapping with a scalable modular architecture

Table 1: Technological Framework for Precision Spraying Systems: Core Components and Functions [3, 4]

3. Computer Vision and Machine Learning Components

3.1 Image Capture System

The technical implementation of precision agriculture systems relies on high-resolution camera arrays strategically mounted along sprayer boom assemblies. These camera systems continuously capture detailed images of the field during operation, creating comprehensive visual datasets for real-time

analysis [5]. Contemporary implementations typically deploy camera configurations with substantial resolution capabilities, operating at high frame rates to ensure adequate temporal sampling during high-speed field operations. The camera arrays are positioned at optimal heights above the crop canopy, providing exceptional ground sampling resolution across extensive boom widths [5].

Modern imaging systems are understood to use several spectral bands that extend beyond visible light, and the additional near-infrared wavelengths permit enhanced discrimination between types of vegetation in a range of illumination conditions. The optical systems comprise high-quality lenses with optimal focal lengths and aperture settings designed for agricultural field conditions to ensure as much image quality as practicable under widely varied lighting conditions over long operating periods [5]. Modern camera arrays integrate robust environmental protection systems, enabling reliable operation in dusty, humid, and temperature-varying agricultural environments across wide operational temperature ranges.

The image acquisition systems incorporate sophisticated synchronization mechanisms, utilizing advanced positioning technology and inertial measurement units to precisely correlate captured images with geographic coordinates at centimeter-level accuracy [5]. This precise spatial registration enables accurate mapping of weed distributions and treatment zones across large field areas, supporting comprehensive farm management data collection and detailed agricultural analysis capabilities.

3.2 Machine Learning Processing

Advanced machine learning algorithms form the analytical core of precision agriculture systems, processing captured imagery to perform accurate crop-versus-weed classification [6]. The computer vision components utilize sophisticated pattern recognition techniques to identify various weed species while distinguishing them from desired crop plants. Contemporary deep learning architectures employ convolutional neural networks with extensive layer configurations, processing multispectral image data through complex feature extraction pipelines containing substantial numbers of trainable parameters [6].

The differentiation capability is critical for ensuring selective herbicide application and preventing damage to valuable crops. Machine learning models demonstrate robust performance across extensive ranges of different weed species commonly encountered in major crop production systems, with specialized algorithms trained for specific crop-weed combinations across multiple agricultural applications [5]. The classification systems operate with minimal inference times per image frame, enabling real-time decision-making during field operations at substantial operational speeds.

Machine learning models undergo training on extensive datasets containing diverse crop and weed characteristics across various environmental conditions, growth stages, and field scenarios [6]. Training datasets typically comprise substantial numbers of labeled images representing multiple geographic regions, seasonal variations, and crop maturity stages. This comprehensive training enables systems to maintain high accuracy rates in weed detection even under challenging field conditions such as varying lighting, diverse plant density conditions, and multiple growth stages spanning complete plant development cycles [6]. The models incorporate advanced data augmentation techniques and sophisticated transfer learning methodologies to enhance generalization capabilities across different agricultural environments and varying farming practices.

3.3 Targeted Application Mechanism

When systems identify weeds through computer vision analysis, precise targeting mechanisms immediately trigger activation of individual spray nozzles positioned directly above detected weed locations [5]. This precise targeting mechanism ensures herbicide application is limited to specific areas requiring treatment, significantly reducing overall chemical usage compared to conventional broadcast spraying methods. Modern spray control systems feature rapid response times from weed

detection to nozzle activation, enabling accurate treatment of weeds during high-speed field operations [6].

The application mechanisms incorporate advanced pulse-width modulation control systems capable of delivering variable spray volumes, adjusted based on weed species, density, and size parameters [5]. Individual nozzle assemblies are strategically spaced along boom structures, providing overlapping coverage zones to ensure complete treatment of detected weed populations. The spray systems maintain optimal application pressures, generating droplet sizes optimized for herbicide efficacy while minimizing drift potential under varying environmental conditions [6].

Contemporary targeting systems achieve exceptional spatial accuracy relative to detected weed centers, utilizing advanced trajectory prediction algorithms that compensate for equipment motion, spray droplet ballistics, and environmental factors, including variable wind conditions [5]. The precision application mechanisms integrate with comprehensive data logging systems that record treatment locations, chemical application rates, and weed density distributions, providing detailed field maps for farm management optimization and regulatory compliance documentation [6].

System Component	Technical Implementation	Operational Capabilities
High-Resolution Camera Arrays	Strategically mounted camera systems with substantial resolution capabilities, multi-spectral imaging beyond visible light, including near-infrared wavelengths, and robust environmental protection systems	Continuous detailed field image capture during operation, exceptional ground sampling resolution across extensive boom widths, and reliable operation across wide temperature ranges
Machine Learning Processing	Advanced convolutional neural networks with extensive layer configurations, sophisticated pattern recognition techniques, and complex feature extraction pipelines with substantial trainable parameters	Accurate crop-versus-weed classification across extensive weed species ranges, minimal inference times enabling real-time decision-making, and robust performance under challenging field conditions
Precision Targeting Systems	Individual spray nozzle activation with advanced pulse-width modulation control, strategic nozzle spacing for overlapping coverage zones, and advanced trajectory prediction algorithms	Rapid response times from detection to activation, variable spray volumes adjusted for weed parameters, and exceptional spatial accuracy compensating for equipment motion and environmental factors
Data Integration Systems	Sophisticated synchronization mechanisms with advanced positioning technology, comprehensive data logging systems, and integration with farm management platforms	Precise geographic correlation at centimeter-level accuracy, detailed treatment location recording, and comprehensive field mapping for optimization and compliance documentation

Table 2: Machine Learning and Imaging Technologies in Precision Weed Management Systems [5, 6]

4. Performance advantages and Sustainability Impacts

4.1 Operational efficiency

The application of agricultural technology with AI-powered precision agriculture has seen astounding performance gains, both in operational efficiency and environmental sustainability. The targeted application methodology achieves substantial reductions in herbicide usage compared to traditional broadcast spraying methods, with documented reductions across different crop systems and geographic regions [7]. Contemporary precision spraying systems demonstrate exceptional field operation efficiencies during critical application windows, significantly improving upon conventional equipment reliability metrics [7].

Research studies have quantified the economic and environmental benefits of this precision approach across multiple agricultural sectors. In soybean production, the technology has shown considerable potential for reducing post-emergence herbicide expenditures, translating to substantial cost savings per hectare depending on regional chemical pricing and weed pressure intensities [8]. Similar economic benefits have been documented in corn production systems, where precision application technologies achieve significant herbicide cost reductions, resulting in substantial annual savings across major corn-producing regions when extrapolated to full adoption scenarios [7].

This dramatic reduction in chemical usage translates to significant cost savings for farmers while simultaneously reducing the environmental footprint of agricultural operations. Labor efficiency improvements have been documented through reduced application passes and simplified weed management protocols [8]. The precision systems enable farmers to cover substantially more field area per operational day compared to conventional spraying methods, largely due to reduced time requirements for tank mixing, equipment cleaning, and multiple application passes. Additionally, the technology has demonstrated notable fuel consumption reductions per hectare treated, contributing to overall operational cost decreases and reduced carbon emissions from agricultural machinery [7].

Advanced precision agriculture systems also provide comprehensive data collection capabilities, generating detailed field maps with high-resolution weed density information, enabling data-driven decision making for crop rotation, seed placement, and nutrient management strategies [8]. The integration of precision application with farm management software systems has resulted in substantial planning efficiency improvements and reduced administrative burden for regulatory compliance documentation [7].

4.2 Environmental Benefits

The sustainability benefits extend beyond mere cost reduction, encompassing comprehensive environmental protection across multiple ecological dimensions. By applying herbicides only where needed, the system minimizes chemical exposure to beneficial soil organisms, reduces groundwater contamination risks, and decreases overall environmental chemical load compared to broadcast application methods [8]. This targeted approach supports biodiversity preservation in agricultural ecosystems while maintaining effective weed control, with documented increases in beneficial arthropod populations in treated fields compared to conventional management systems [7].

Soil health improvements have been quantified through reduced chemical stress on microbial communities, with precision-treated fields showing enhanced soil organic matter content and increased microbial diversity indices after extended implementation periods [8]. The selective application methodology also reduces herbicide residue levels in soil samples significantly, decreasing persistence times and potential carry-over effects to subsequent crops or groundwater systems. Water quality assessments in watersheds with precision agriculture adoption have documented substantial reductions in herbicide detection frequencies in surface water monitoring, with concentrations notably lower than areas utilizing conventional broadcast spraying [7].

Additionally, the reduced herbicide usage contributes to slower development of herbicide-resistant weed populations, helping preserve the long-term effectiveness of chemical control methods [8]. Resistance evolution modeling studies indicate that precision application strategies can substantially extend the effective lifespan of current herbicide technologies compared to broadcast applications, representing considerable value preservation in avoided resistance management costs. This resistance management aspect represents a crucial advantage for sustainable agricultural practices, maintaining diverse weed control options for future farming generations [7].

The technology also contributes to reduced atmospheric emissions through decreased herbicide volatilization, with precision systems achieving substantial reductions in off-target chemical drift compared to conventional boom sprayers [8]. Carbon footprint analyses demonstrate overall greenhouse gas emission reductions per unit of crop production in systems utilizing precision agriculture technologies, primarily through reduced fuel consumption, decreased chemical manufacturing energy, and improved soil carbon sequestration [7]. These environmental benefits compound over time, with long-term studies showing progressive improvements in ecosystem health metrics, including pollinator abundance, aquatic invertebrate diversity, and native plant species richness in agricultural landscapes [8].

Benefit Category	Key Performance Improvements	Sustainability Outcomes
Operational Efficiency	Substantial herbicide usage reductions across crop systems, exceptional field operation efficiencies during critical windows, and substantial cost savings per hectare with simplified management protocols	Reduced environmental footprint through decreased chemical usage, notable fuel consumption reductions, and reduced carbon emissions from agricultural machinery
Environmental Protection	Minimized chemical exposure to beneficial soil organisms, substantial reductions in herbicide detection in surface water, and enhanced soil organic matter content with increased microbial diversity	Biodiversity preservation with increased beneficial arthropod populations, reduced groundwater contamination risks, and progressive improvements in ecosystem health metrics
Economic and Resource Benefits	Comprehensive data collection enabling data-driven decision making, substantial planning efficiency improvements, and reduced administrative burden for compliance	Extended effective lifespan of herbicide technologies through resistance management, reduced atmospheric emissions, and overall greenhouse gas emission reductions per unit of crop production

Table 3: Performance Advantages and Environmental Benefits of AI-Powered Precision Agriculture Systems [7, 8]

5. Economic Impact and Future Implications

5.1 Economic Analysis

The economic implications of AI-powered precision agriculture extend well beyond individual farm operations, creating substantial macroeconomic benefits across agricultural regions. Regional analyses have indicated substantial aggregate cost savings potential, with statewide implementations projected to generate significant annual economic benefits for farming communities [9]. Economic modeling studies demonstrate that full-scale adoption of precision agriculture technologies could generate substantial aggregate savings across major agricultural regions when considering reduced input costs, improved yield stability, and enhanced resource efficiency. The technology adoption rate

has accelerated significantly, with precision agriculture implementation growing at considerable annual rates, reaching substantial penetration rates among large-scale farming operations and notable adoption among medium-scale producers [9].

Return on investment analyses indicate that precision agriculture systems typically achieve reasonable payback periods, depending on farm size, crop types, and regional economic conditions. The economic benefits compound over time, with multi-year net present value calculations showing substantial returns for early adopters [9]. Economists describe substantial economic value in both harvesting benefit and operational costs with precision spraying alone to reduce operating costs annually on a per-hectare basis while obtaining higher yields and improving crop yield due to weed control performance, as well as crop damage performance as related to over-application.

The trend of adopting these technologies signifies a larger push towards precision agriculture and data-driven farming practices, which provide significant indirect incremental economic value [10]. The systems generate a wealth of field-level data that allows for further agricultural decision making, such as accessing a system to gather and evaluate historical planting pattern data, irrigating, and optimizing harvest timing. The incremental economic value of precision agriculture data provided can have a large economic effect, with more effective decision-making being had. Labor productivity improvements have been documented extensively, with precision systems reducing the need for skilled applicator operators while enabling less experienced personnel to achieve professional-level application results [9].

Regional economic impact assessments indicate that precision agriculture adoption generates multiplier effects throughout agricultural communities, with investments in precision technology generating substantial total economic activity through equipment manufacturing, technical services, data analytics, and related support industries [10]. The technology sector supporting precision agriculture has created a considerable number of high-skilled jobs across engineering, software development, and technical support roles, contributing substantially to regional economies [9].

5.2 Future Development Trends

Future developments in this technology sector are likely to incorporate enhanced machine learning capabilities, expanded crop and weed identification databases, and integration with other precision agriculture systems [10]. Technology roadmaps project that next-generation precision agriculture platforms will achieve exceptional weed identification accuracy in the coming years, compared to current systems operating at high accuracy levels. The integration of advanced sensor technologies, including hyperspectral imaging, advanced mapping systems, and soil assessment sensors, is expected to enable comprehensive field assessment capabilities with significantly improved spatial resolution [9].

The potential for combining weed management with nutrient application, pest control, and crop monitoring systems presents opportunities for comprehensive field management platforms [10]. Market projections indicate that integrated precision agriculture systems will capture substantial portions of the precision farming market in the coming years, representing a shift from single-function to multi-purpose agricultural robotics. Development investments in artificial intelligence for agriculture have reached substantial levels annually, with significant portions focused on machine learning algorithm improvements and sensor technology advancement [9].

With advancements in AI and machine learning technologies, an even greater level of precision in crop management applications is expected. Adding better algorithms, additional sensors, and improved real-time processing will continue to optimize the balance between increasing agricultural productivity and environmental stewardship [10]. Edge computing capabilities are projected to enable substantial field-based processing of agricultural data per season, reducing dependency on cellular connectivity and enabling real-time optimization of farming operations.

Emerging technologies, including quantum computing applications, advanced robotics integration, and satellite-based monitoring systems, are expected to revolutionize precision agriculture capabilities within the next decade [9]. Research and development spending in agricultural technology is projected to reach substantial levels, with significant allocations to AI and automation technologies. The successful implementation of AI-powered precision agriculture solutions demonstrates the significant potential for technology to address fundamental challenges in modern farming, providing a pathway toward more sustainable, efficient, and economically viable agricultural practices for future generations [10].

Autonomous farming systems integrating multiple precision agriculture technologies are anticipated to achieve commercial viability in the coming years, with projected adoption rates among large-scale operations within reasonable timeframes. These comprehensive systems are expected to reduce overall production costs substantially while improving environmental sustainability metrics compared to conventional farming methods [9].

Impact Category	Current Economic Benefits	Future Development Projections
Regional Economic Benefits	Substantial aggregate cost savings potential across agricultural regions, significant annual economic benefits for farming communities, and multiplier effects generating total economic activity through equipment manufacturing and technical services	Full-scale adoption projected to generate substantial aggregate savings across major agricultural regions through reduced input costs, improved yield stability, and enhanced resource efficiency
Technology Adoption and ROI	Considerable annual growth rates with substantial penetration among large-scale operations, reasonable payback periods with substantial returns for early adopters, and reduced operational costs while improving crop yields	Market projections indicate integrated precision agriculture systems will capture substantial portions of the precision farming market, representing a shift to multi-purpose agricultural robotics
Advanced Technology Integration	Substantial development investments in artificial intelligence, with significant portions focused on machine learning improvements and sensor advancement, creating high-skilled jobs across engineering and software development	Enhanced machine learning capabilities, expanded identification databases, and integration of hyperspectral imaging, advanced mapping systems, and soil assessment sensors for comprehensive field assessment
Emerging Autonomous Systems	Labor productivity improvements reduce the need for skilled operators while enabling less experienced personnel to achieve professional-level results, with comprehensive data collection enabling data-driven agricultural decisions	Autonomous farming systems integrating multiple precision agriculture technologies are anticipated to achieve commercial viability, with quantum computing applications, advanced robotics, and satellite-based monitoring revolutionizing capabilities

Table 4: Economic Benefits and Future Development Trends in AI-Powered Precision Agriculture [9, 10]

Conclusion

The utilization of AI-powered precision agriculture represents a guiding forward leap in sustainable and economically sound agricultural practices that tackle some of the major obstacles faced in contemporary agriculture. These technologies show impressive performance improvements through selective usage approaches that significantly reduce the amount of herbicide used while still providing equivalent weed control. With advancements in computer vision algorithms combined with on-the-fly learning, these technologies allow for unprecedented precision for agricultural practices and represent a complete departure from traditional farming. Current precision agriculture platforms can achieve wide degrees of field coverage while experiencing little performance variability in detection and treatment across field conditions and growth stages. The environmental benefits are accumulative, and include notable improvements in ecosystem health indicators (which include: increased biodiversity retention, lower chemical toxicity, and slower rates of herbicide-resistant weed populations). Recent economic modeling shows full implementation would provide significant aggregate savings across several agricultural regions when accounting for reduced inputs (over time), better tailoring operational efficiency, and resource use. Technology outlooks predict that ongoing machine learning, sensor, and autonomous systems advancements will optimize the eco-balance between agricultural production and environmental outcomes. Achieving successful precision agriculture solutions will fully demonstrate the capacity to tackle global food security sustainably. Future innovations associated with quantum computing applications, continued integration of advanced robotics, and comprehensive field management protocols and systems will further enhance agricultural agriculture and develop new avenues for producing a sustainable crop system that benefits agricultural communities and environmental stewardship.

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