Evaluation of an AI-driven High-precision Spraying System (Ecorobotix ARA) for Targeted Weed Control in Onions

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Abstract: Weeds are a persistent challenge in the Vidalia onion production region, where limited herbicide options make placement and selectivity critical. AI-based high-precision spraying systems may reduce herbicide use and crop injury by targeting only weeds and non-crop areas. This study compared the Ecorobotix ARA high-precision sprayer operating in an all-but-the-crop mode with a conventional broadcast application for weed control, crop phytotoxicity, and onion yield. A field trial was conducted at the Vidalia Onion and Vegetable Research Center in Lyons, Georgia, USA, using three treatments: (i) Ecorobotix ARA "all-but-the-crop" without a safety zone with Prowl® H2O and Goal® 2XL, (ii) conventional broadcast application of the same herbicides, and (iii) an untreated control. Application occurred on January 6, 2025, 15 days after transplanting, at 90,000 plants per acre. Both ARA and broadcast treatments targeted 26.7 gallons per acre with 32 oz/ac of both Prowl® H2O and Goal® 2XL. Chemical usage, phytotoxicity, weed counts, bulb size, and yield were assessed after application. Phytotoxicity and weed counts were measured at 14, 30, and 44 days after application within three randomly selected 10 ft^2 areas per 100 ft plot. Yield was assessed as gross onion weight from 15 ft harvest sections after undercutting, and bulb size from 30 randomly selected bulbs per plot. The experiment followed a randomized complete block design with three replications. The ARA system reduced chemical use by 59% compared with broadcast application. ARA showed lower phytotoxicity at 14 DAA while maintaining weed counts equivalent to broadcast across all evaluation dates; the untreated control had higher weed counts. Marketable yield was 50,595.3 lb/acre for ARA, 47,963.3 lb/acre for broadcast, and 28,667.7 lb/acre for the control. Average bulb sizes were 3.4, 3.3, and 2.9 in, respectively. No significant statistical differences were observed between ARA and broadcast for yield or bulb size, although yields differed by approximately 2,600 lb/acre. In transplanted onions, ARA achieved weed control and phytotoxicity comparable to full-rate broadcast application while using only 41% of the spray mixture, with a trend toward higher yield. Further research should test additional herbicide programs, split applications, performance across production environments, including direct-seeded onions, and economic impacts per acre.

Keywords: *Allium cepa*, computer vision, site-specific weed management, sustainability, Vidalia onions.

1. Introduction

Weed interference remains a major and costly challenge for onion (*Allium cepa L.*) growers, especially in southeastern Georgia's Vidalia region, where managing cool-season weed communities is difficult with just one method. Field tests near Lyons, Georgia, showed that integrated weed management strategies are often necessary because relying solely on chemical or mechanical controls can be ineffective under typical commercial Vidalia onion conditions (Johnson et al. 2017). Onions are particularly vulnerable to weed competition due to their slow early growth, narrow upright leaves, limited canopy coverage, and shallow roots. Studies comparing different weed-management systems in onions found that poor control during the early, weed-sensitive stage can lower bulb yield and compromise quality (Brown and Gallandt 2018).

The dominance of sandy and loamy sand soils in this production area introduces additional management difficulties. However, herbicide behavior in the environment should not be solely linked to soil texture, as factors like organic matter content, pH, rainfall, irrigation, herbicide formulation, and the physicochemical properties of active ingredients also influence leaching, retention, and degradation (de Medeiros et al. 2024). Thus, while reducing herbicide quantities can be environmentally advantageous, the actual risk of off-site movement must be assessed separately for each herbicide-soil pairing.

Current onion weed management relies on a limited set of pre-emergence and early post-emergence herbicides, such as pendimethalin and oxyfluorfen. Controlling weeds early in the season is critical because post-emergence options may only be selective after onions reach a certain growth stage, leaving them vulnerable during establishment (Loken and Hatterman-Valenti 2013). Herbicide selectivity is also greatly affected by application timing and crop development; studies have shown that residual herbicides used early in onion growth can vary significantly in phytotoxicity, and some can cause notable injury if applied before the crop is fully developed (Olescowicz et al. 2022).

Traditional broadcast spraying disperses a uniform herbicide dose across the entire field, regardless of spatial weed and crop distribution. Conversely, integrating computer vision, AI, and individually controlled spray actuators allows Site-Specific Weed Management, where images are processed to identify vegetation, guide targeted control measures on individual plants, weed patches, or specific zones (Singh, Zhao, and Shi 2025). These advancements are especially helpful in high-value vegetable crops, where crop injury, input costs, and application accuracy are critical.

Research on maize shows that herbicide spot spraying based on high-resolution weed maps can significantly lower treated areas while maintaining satisfactory agronomic results, with effectiveness depending on weed distribution, mapping accuracy, and sprayer response (Allmendinger et al. 2024). Similarly, targeted applications in soybean using machine vision achieved at least 93% control of key weeds, with results differing by no more than one percentage point from broadcast treatments (Avent et al. 2024). However, the link between chemical savings and weed control efficacy depends on the detection threshold set by the operator; higher thresholds can reduce sprayed areas but may also increase missed weeds, especially small or partially obscured ones (Barnhart et al. 2025).

Although targeted spraying has rapidly advanced in broadacre cropping, its effectiveness must be validated in specific crop structures and environments. Research in Vidalia onion indicates that dense cool-season weed infestations can be hard to control and may impair crop performance if control measures fail to suppress weeds throughout the season (Johnson et al. 2017). The narrow, upright onion architecture may also influence crop recognition and spray placement, requiring direct testing under commercial conditions.

This study aimed to compare a high-precision sprayer operating in an "all-but-the-crop" mode with conventional broadcast application, evaluating weed control, onion phytotoxicity, herbicide-use reduction, crop development, and marketable yield in Vidalia onion production.

2. Materials and Methods

The research was conducted at the Vidalia Onion and Vegetable Research Center located in Lyons, Georgia, USA (Figure 1). The field trial was established using a Randomized Complete Block Design (RCBD) with three replications. Each experimental unit (plot) measured 30.48 m in length. The onion population was approximately 222,394 plants per hectare. The three treatments evaluated were: (1) Ecorobotix ARA + Prowl® H2O + Goal® 2XL (All But The Crop mode); (2) Conventional Broadcast Prowl® H2O + Goal® 2XL; and (3) Control (not sprayed).

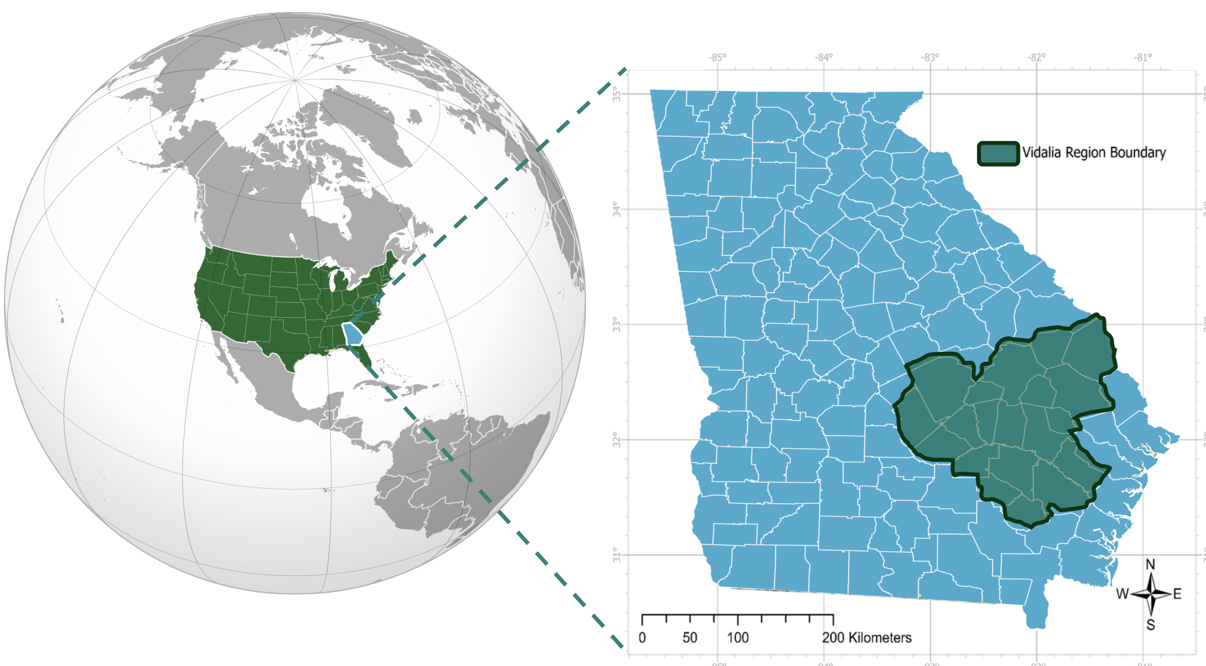

Figure 1. Map showing the extent of the Vidalia onion production region in southeast Georgia, USA, where the study was conducted.

The treatment applied was the Ecorobotix ARA spot-spray. (Ecorobotix, Yverdon-les-Bains, Switzerland) (Figure 2). The system consists of a tractor-mounted unit with internal lighting to ensure consistent image capture regardless of ambient light conditions. It is equipped with RGB cameras that feed data to an on-board computer, which identifies plants using AI-driven recognition. The "all-but-the-crop" setting of the ARA sprayer, without a safety-zone setting, was compared with a conventional broadcast treatment. Herbicides were applied on January 6, 2025, which corresponded to 15 days after the onion transplanting date. Both the ARA and the broadcast treatments utilized a tank mix of Pendimethalin (Prowl® H20), 0.94 L/ha and Oxyfluorfen (Goal® 2XL) 0.94 L/ha. The target application rate was set at 249.7 L/ha for both systems. The amount of spray mixture used by the ARA system was recorded to calculate the percentage reduction in herbicide use compared to the broadcast application.

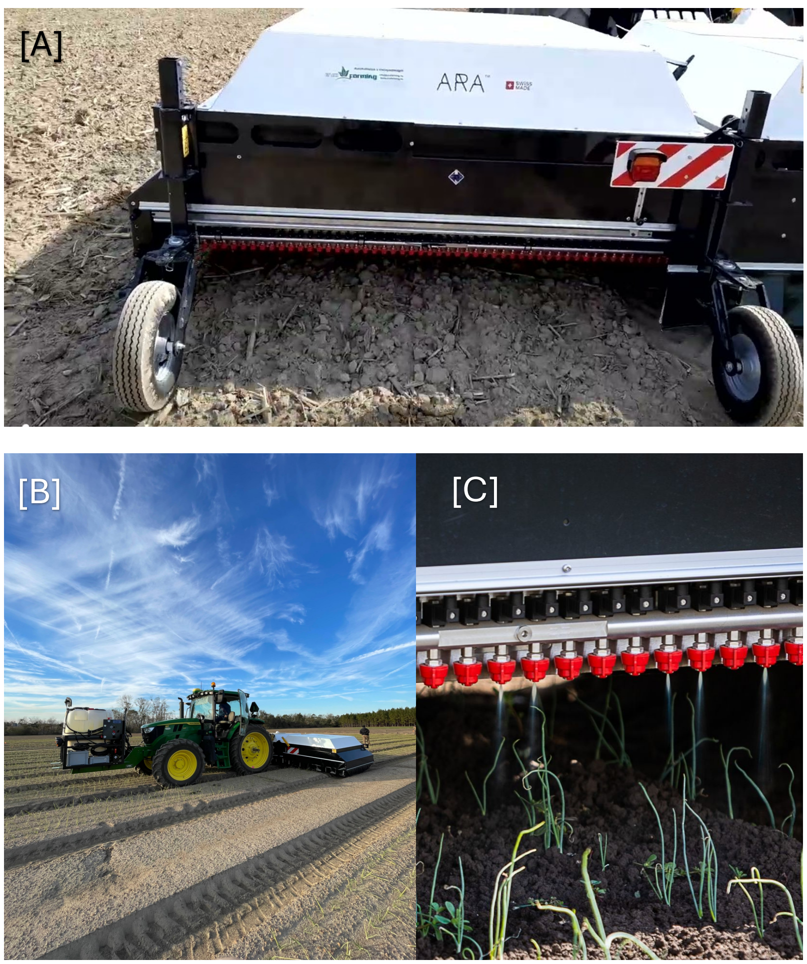

Figure 2: Left-side view of the Ecorobotix ARA system showing the spraying unit [A]; Overview of the Ecorobotix ARA system operating in the onion field [B]; C: Detail of the high-frequency nozzles used for targeted application [C]

After application, chemical usage, phytotoxicity, weed counts, bulb size, and yield were measured at 14, 30, and 44 days after application (DAA). Weed density was measured by counting within a 0.93 m² area, with three random samples collected per 30.48 m plot. To assess phytoxicity, visual ratings of crop injury were recorded on a scale of 0 to 100%, where 0 represented no injury and 100 represented complete crop death. Yield and quality were assessed after onions were harvested using the "undercutting" method. Marketable yield was determined by collecting the gross weight of onions within a 4.57 m section of each plot. Bulb size was evaluated by measuring the diameter of 30 randomly selected bulbs from the harvested samples. Data were analyzed using analysis of variance (ANOVA), and means were compared using Tukey's test at the 5% significance level.

3. Results

One of the most significant findings was the efficiency of the AI-driven targeting system. The Ecorobotix ARA achieved a 59% reduction in total chemical volume compared to the conventional broadcast application. The machine used only 41% of the total spray mixture while covering the same area.

At 14 DAA, the ARA treatment exhibited significantly lower phytotoxicity compared to the broadcast application. This is attributed to the AI's ability to avoid spraying directly on the onion foliage. In contrast, the broadcast treatment subjected the entire plant to the herbicide mix, resulting in typical "stunting" and leaf tip burn associated with oxyfluorfen. Regarding weed control, the ARA system-maintained weed counts that were statistically equivalent to the broadcast treatment at 14, 30, and 44 DAA. As expected, the untreated control plots showed significantly higher weed pressure across all evaluation dates.

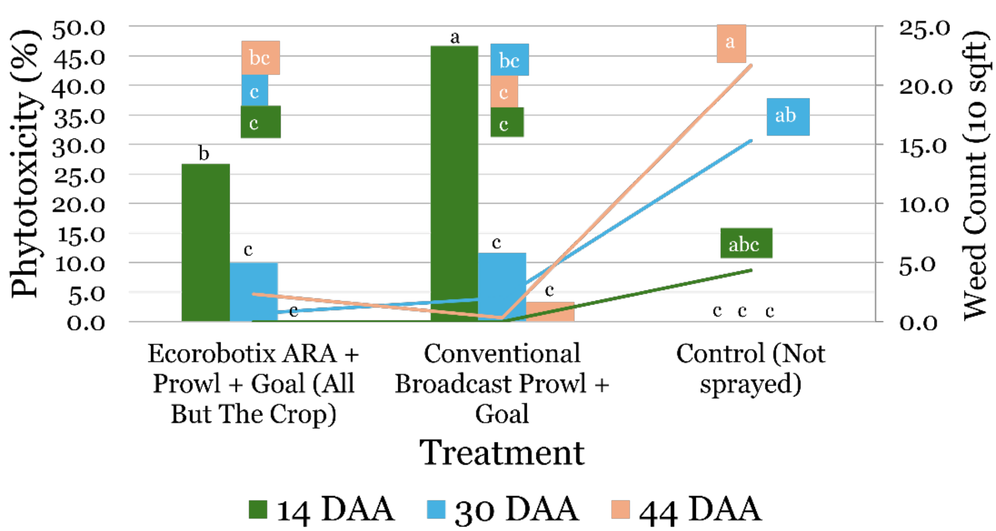

Figure 3. Weed density and crop phytotoxicity in transplanted onions at 14, 30, and 44 days after application (DAA). Bars indicate weed density, lines indicate phytotoxicity, and different letters denote significant differences among treatments within each evaluation date at $p \leq 0.05$.

There were no significant statistical differences in bulb size between the high-precision sprayer and broadcast treatments, though both outperformed the untreated control. Regarding marketable yield, the ARA treatment showed a positive trend, with data suggesting an approximate advantage of 2,914 kg/ha over the broadcast system.

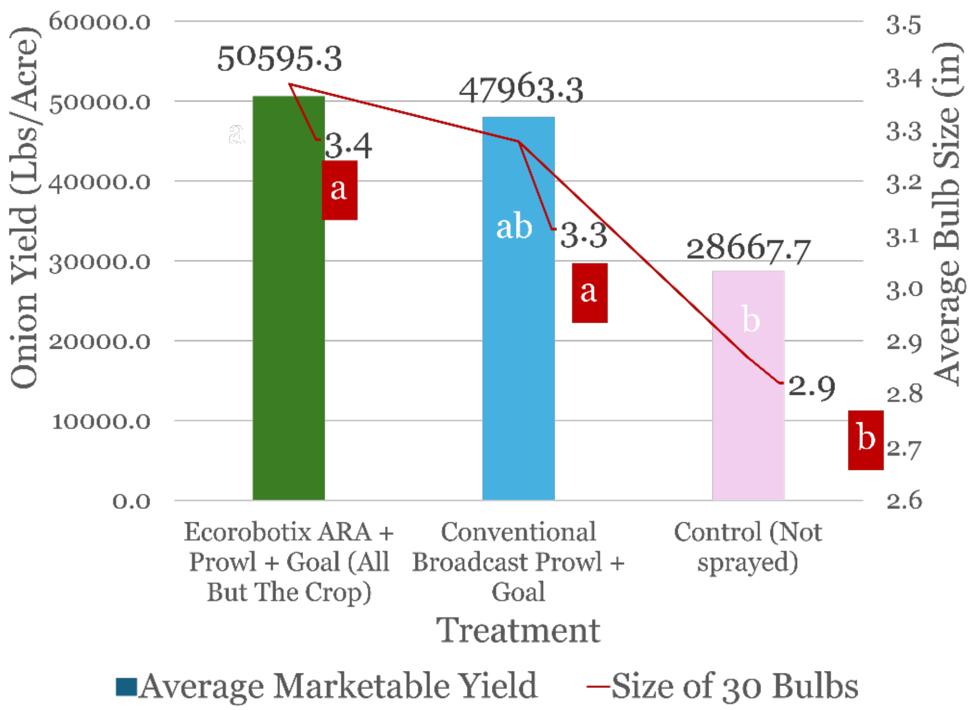

Figure 4. Marketable onion yield and average bulb size. Bars represent average marketable yield in lb/acre using the left y-axis, and the red line represents average bulb size in inches using the right y-axis. Different letters indicate significant differences among treatments within each response variable according to the mean separation test at $p \leq 0.05$.

4. Discussion

The results show that AI-driven, high-precision spraying can enhance herbicide targeting in transplanted onions by minimizing crop exposure and still effectively controlling weeds. Recent progress in deep-learning-based plant recognition and object detection supports these systems' ability to differentiate crops from weeds or other non-crop areas (Murad et al. 2023; Patel et al. 2023). This study shows that the lower phytotoxicity seen with high-precision sprayer at 14 days after application indicates that reducing direct herbicide contact with onion plants helps lessen early crop stress. Similar reductions in crop damage have been observed with ultra-precise spraying systems that utilize artificial intelligence to safeguard the crop while aiming herbicides at specific targets (Anne et al. 2024). This advantage is especially important for onion, as crop tolerance can be affected by factors such as herbicide formulation, application timing, crop growth stage, and tank-mixture composition (Kaur et al. 2023). Therefore, the lower early phytotoxicity seen with the high-precision sprayer treatment probably results from enhanced spatial selectivity instead of decreased herbicidal effectiveness.

The weed control effectiveness of the high-precision sprayer "all-but-the-crop" treatment, comparable to that of conventional broadcast application at 30 and 44 DAA, is a significant agronomic insight. Unlike traditional spot-spraying that targets only detected weeds, the "all-but-the-crop" approach also treats the non-crop area, including bare soil between onion plants. This is important because herbicides like pendimethalin and oxyfluorfen help provide residual or early-season weed suppression, and their effectiveness partly relies on proper treatment of the soil surface where weeds can emerge (Herrmann et al. 2017). As a result, the high-precision sprayer system probably preserved the herbicide-treated soil necessary for weed suppression while reducing direct contact with onion plants. Similar weed-control effectiveness has been observed for ultra-precise spraying in onions and for other site-specific weed-management systems, showing comparable results between targeted and broadcast methods (Gerhards et al. 2022). More broadly, site-specific crop management integrates sensing, spatial data, and precise application technologies to address field variability and enhance input placement (Ali, Hassan, and Kaul 2024).

The high-precision sprayer system's 59% decrease in herbicide mixture usage shows a significant decrease in chemical inputs compared to the broadcast treatment. This aligns with experimental evidence demonstrating that real-time, deep-learning-based precision sprayers can sharply cut spray volumes by targeting specific field areas or identified objects (Farooque et al. 2023; Zanin et al. 2022). Reviews of site-specific weed management similarly report substantial herbicide savings without necessarily compromising weed-control efficacy (Gerhards et al., 2022). However, caution is advised in interpreting the 59% reduction economically. While decreased herbicide use lowers variable input costs, overall profitability of precision spraying also hinges on factors like equipment cost, depreciation, maintenance, field capacity, labor needs, service fees, farm size, and the number of crops and applications for which the equipment is utilized (Vijayakumar et al. 2025). These results indicate possible operational savings; however, they do not specify a definitive equipment payback period. Conducting a partial-budget analysis in the context of Vidalia onion production is necessary to assess the system's economic feasibility.

From an environmental standpoint, reducing the treated area and overall herbicide usage lowers the amount of active ingredients entering the production system. Precision weed-control technologies can therefore help minimize exposure to non-target species and promote more efficient use of crop-protection products (Gerhards et al. 2022; Vijayakumar et al. 2025). However, the environmental benefit should not be viewed only as a direct decrease in groundwater contamination. The mobility of herbicides relies on the physicochemical traits of each active ingredient and soil properties like texture, organic carbon content, water retention capacity, and sorption behavior (Sharipov et al. 2021). Coarse-textured soils with low organic carbon may be more vulnerable to pesticide transport under certain rainfall or irrigation conditions, but the magnitude of this risk varies across herbicides (Ibrahim and Al-Turki 2020). A more defensible interpretation is that the ARA treatment lowered the total chemical load applied to the field. This could potentially reduce non-target deposition, runoff, and other environmental exposure routes, all while still effectively controlling weeds.

Overall, AI-guided "all-but-the-crop" spraying achieved weed control similar to broadcast application, while also decreasing herbicide use and minimizing early onion phytotoxicity. These results align with the overall progress in automated weed-recognition and precision-application technologies (Murad et al. 2023; Qu and Su 2024). However, achieving successful adoption relies not just on recognition accuracy but also on factors like operational robustness, speed of application, equipment cost, field conditions, and how well it integrates with existing crop-management practices (Gerhards et al. 2022; Vijayakumar et al. 2025). Future research should assess the system over multiple growing seasons, weed densities, soil-moisture conditions, onion growth stages, and herbicide application methods. Integrating agronomic assessments with economic analysis and environmental monitoring would offer more robust evidence for its commercial adoption in Vidalia onion cultivation.

5. Conclusions

The field trial showed that the high-precision, AI-powered sprayer is a practical and highly efficient substitute for traditional broadcast spraying in onion farming. It achieved comparable weed control results, caused less initial crop phytotoxicity, and showed a tendency towards higher marketable yields. Future studies should aim to assess the system's performance in direct-seeded onion systems and carry out multi-year economic impact evaluations.

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