Guiding Spot Sprayer Decisions: Toward Species-Selective Weed Control

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Abstract

Site-specific weed management is a key approach in precision crop protection, enabling spatially targeted herbicide application based on within-field variability in weed distribution. However, most operational spot-spraying systems rely on uniform nozzle activation rules, implicitly treating all detected weeds equally despite differences in competitive ability and ecological function. This limits the potential of precision systems to exploit species-level differentiation in practice.

This study introduces a rule-based decision framework supported by a spatially explicit simulator, enabling ecological differentiation in automated weed control by allowing management decisions to vary between species based on their agronomic and ecological roles. The simulator was calibrated using operational data from a field-deployed sprayer to ensure realistic spray geometry and actuation behavior, under conditions representative of field operation.

Weeds were detected from RGB images using a pretrained hierarchical deep learning model (YOLOv11), generating bounding boxes and class labels for crops and weeds.

Three strategy types were evaluated: non-selective spot spraying (NS), generic rule-based spot spraying (GR) and crop-specific species-selective spot spraying (SP). Outputs were aggregated at image level and included treated plants, preserved plants, missed targets, vetoed plants, and spray volume.

SP increased simulated weed preservation from 0% under NS and 1.7% under GR to 3.8% of weed detections. Preservation was concentrated in intended preservation groups, which accounted for 87.7% of preserved detections under SP, indicating that non-treatment was taxonomically structured rather than random. However, increased preservation was associated with reduced realized hit rate, which declined from 97.3% under NS and 95.6% under GR to 91.8% under SP. Veto rate increased from 0% under NS and 1.7% under GR to 5.4% under SP, showing that protection of selected plants created local conflicts with treatment of neighboring targets. Mean spray volume declined from 10.0 g image^{-1} under NS to 9.01 g image^{-1} under SP, corresponding to a 10.05% reduction.

These results show that species-selective decision rules can modify not only how much spray is applied, but also which weed taxa are preserved and which targets are lost through actuator-level conflicts. The simulator provides a practical framework for evaluating these trade-offs before field implementation by separating plant detection, decision logic and nozzle-level outcomes.

Keywords: site-specific weed management; precision crop protection; spot spraying; species-selective weed control; weed detection; decision rules

Introduction

Crop production requires the control of harmful weeds to mitigate yield loss, but the complete removal of non-crop vegetation can further simplify agricultural landscapes that are already biodiversity-poor. Weed management is therefore essential, as weeds can cause yield loss, harvest-quality problems and may persist as reservoirs for pests and pathogens (Oerke, 2006). At the same time, arable weeds are part of the spontaneous plant diversity of agricultural fields and can support ecological functions by providing floral resources, seeds and habitat for pollinators, natural enemies, granivorous birds and other farmland organisms (Kleiman et al., 2020; Marshall et al., 2003; Nicholls & Altieri, 2013; Tamburini et al., 2020), while more diverse weed communities may also reduce dominance by highly competitive or herbicide-resistant species (Adeux et al., 2019; Storkey & Neve, 2018).

This challenge is particularly relevant in intensively managed regions where agricultural land dominates the landscape and semi-natural habitats are fragmented. In these systems, arable fields may need to contribute more actively to biodiversity conservation while remaining productive (Balfour & Ratnieks, 2022; Kremen & Merenlender, 2018). Weed management should therefore not necessarily aim at complete eradication, but at selective regulation: suppressing weeds that pose high agronomic risk while tolerating selected low-risk plants where this does not compromise crop protection (Esposito et al., 2023). However, implementing this idea in practice requires tools that can distinguish not only where weeds are present, but also which weeds should be targeted, tolerated or protected.

Precision crop protection provides a technical pathway towards this goal. Site-specific weed management uses weed mapping, patch spraying or real-time detection to apply control measures according to within-field variation rather than treating the field uniformly (Fernández-Quintanilla et al., 2018). Advances in ground-based sensing, computer vision and deep learning have improved weed detection, crop–weed discrimination and species-level recognition under field conditions (Rai et al., 2023; Zhao & Wang, 2025). More recently, image-based spot spraying has combined cameras, machine-learning models and electronically controlled nozzles to target individual plants or small plant patches (Allmendinger et al., 2022; Wang et al., 2019). These systems can reduce herbicide use compared with uniform application, particularly where weed distribution is spatially heterogeneous (Azghadi et al., 2025; Spaeth et al., 2024).

Despite these advances, many spot-spraying systems still use relatively simple decision logic. In practice, a detected weed is often translated directly into nozzle activation (Gerhards et al., 2023; Peteinatos et al., 2014). This means that the sensing layer may provide increasingly detailed information on plant identity, size and position, while the decision layer still treats most weeds as equivalent targets. This is a limitation if the objective is not only to reduce spray volume, but also to regulate weed communities more selectively. A precision system that can identify individual plants should, in principle, be able to use that information to make different decisions for different weed taxa, growth stages and spatial contexts.

Before such decision rules are implemented in the field, their consequences need to be evaluated. The outcome of a spraying strategy does not depend only on the intended plant-level decision. It also depends on nozzle footprint, plant overlap, crop proximity and spatial conflicts between plants assigned different actions. For example, preserving one low-risk weed may also prevent spraying of a nearby target weed if the spray footprint would overlap both plants.

The aim of this study was to evaluate whether crop-specific, species-selective decision rules could alter the biological and operational outcomes of spot spraying compared with non-selective and generic rule-based strategies. A spatially explicit simulator was used to apply alternative decision strategies to RGB image detections collected in oat (*Avena sativa* L.), sugar beet (*Beta vulgaris* L.) and winter wheat (*Triticum aestivum* L.) in Denmark. The simulator translated plant-level decisions into nozzle activation while accounting for spray footprint and spatial conflicts between target and protected plants. Three strategy types were compared: non-selective spot spraying (NS), a generic rule-based spot spraying (GR), and crop-specific species-selective spot spraying (SP). The analysis quantified simulated preservation of selected weed taxa, targeting of weed plants, spray volume and decision conflicts. By separating plant detection, decision logic and actuation outcomes, the study provides a practical framework for evaluating how biological priorities can be incorporated into next-generation precision weed management systems.

Materials and methods

Image dataset and crop systems

This study used RGB field images collected during the 2025 growing season in Denmark to evaluate alternative spot-spraying decision strategies under comparable weed detection conditions. The dataset included images from three crop systems: oat (*Avena sativa* L.), sugar beet (*Beta vulgaris* L.) and winter wheat (*Triticum aestivum* L.). Image acquisition was timed to coincide with the practical spring spraying window, based on crop growth stage and visible weed presence.

Images were acquired from approximately 1 m above the ground, covering about 1 m^2 per image, with a ground sampling distance of approximately 0.35 mm $pixel^{-1}$, enabling the detection of small weed seedlings. The camera was mounted on an autonomous agricultural robot travelling at 5 km h^{-1}, and images were captured at approximately 1–2 m intervals. The final dataset comprised 119 m2 of images from oat, 121 m2 from sugar beet and 124 m2 from winter wheat.

Each image was treated as the experimental unit for the simulation-based comparison. For each crop, the same set of images was evaluated under each decision strategy, allowing paired comparisons among strategies while holding the underlying weed community constant. The detections included both crop plants and weeds. Crop detections were retained in the simulation because they affected spray decisions and crop-protection logic.

Weed and crop detection

Plant detections were generated from the RGB images using an in-house pre-trained hierarchical deep learning model (YOLOv11 object detection model) designed to detect and classify crop plants and weed taxa. For each detected plant, the model returned a bounding box, a predicted class label and size-related attributes derived from the bounding-box geometry. Class labels were expressed as EPPO codes and included crop plants, weed species, genus-level weed groups or broader taxonomic classes (monocot, dicot). The classification model followed a hierarchical structure. Detections were first assigned to broad plant categories and, when sufficient visual information was available, were resolved progressively to lower taxonomic levels, including family, genus and species. As a result, the dataset contained detections at different levels of taxonomic resolution rather than only species-level records. Species-level rules were therefore applied when species-level EPPO codes were available, while broader fallback rules were used for detections classified at higher taxonomic levels. For example, unresolved dicot and monocot weed detections were represented by the class-level labels PPPDD and PPPMM, respectively.

This structure reflected realistic classification constraints during field operation and was retained in the simulation. The decision framework was therefore taxon-informed rather than strictly species-specific: species-specific decisions were possible where the detector provided species-level labels, but higher-level taxonomic decisions were used when the model returned broader classes. Bounding-box area was used as a proxy for plant size.

Simulation framework

A spatially explicit simulation framework (Ponti et al., manuscript submitted for publication) was used to evaluate how alternative decision strategies would translate plant detections into spot-spraying actions. For each image, the simulator used the detected plant positions, bounding-box dimensions and taxonomic labels as input. Each detected plant was then evaluated against a predefined set of decision rules, applied sequentially from highest to lowest priority. The first rule matching the plant determined the assigned management action.

To ensure that simulated outputs reflected realistic sprayer behavior rather than an idealized plant-level treatment assumption, the simulator was parameterized using the physical and operational characteristics of an in-house field spot sprayer. These included the spatial footprint of individual nozzles, nozzle spacing, activation geometry and the corresponding spray volume associated with nozzle actuation.

The simulator allowed three possible plant-level actions: TARGET, PRESERVE and IGNORE (Fig. 1). TARGET assigned the plant for spraying. PRESERVE excluded the plant from treatment and could prevent nearby nozzle activation when the spray footprint would overlap the protected plant. IGNORE excluded the plant from direct treatment but did not provide the same level of spatial protection as PRESERVE. This distinction allowed the strategies to separate active protection from simple non-treatment.

Plant-level decisions were subsequently translated into nozzle activation commands using the spatial position of each bounding box and the calibrated nozzle footprint. The simulator accounted for footprint overlap, adjacency between plants and spatial conflicts between plants assigned different actions. Consequently, a plant could be targeted by the decision rules but not sprayed if nozzle activation was vetoed to protect a nearby preserved plant. Outputs were then aggregated at image level and by taxon to quantify weed targeting, preservation, missed targets (caused by nozzle-position constraints or actuation limits), vetoes and spray volume.

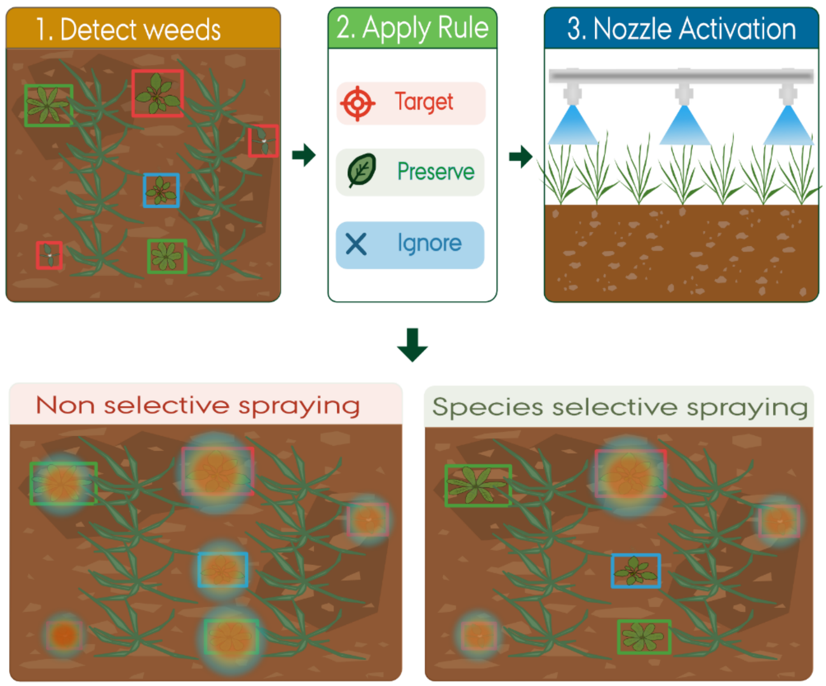

Fig 1 Conceptual workflow of the rule-based spot-spraying simulator. Weed detections from RGB images were assigned to one of three decision classes, TARGET, PRESERVE or IGNORE, according to the selected strategy.

Spot-spraying strategies

All strategies were applied to the same image detections within each crop, allowing differences among strategies to be attributed to the decision logic rather than to differences in the underlying weed community. Three strategies were compared: non-selective spot spraying (NS), a generic rule-based strategy (GR), and a species-led strategy (SP). The full set of decision rules is not listed because the aim of the study was to compare overall decision strategies rather than document every individual rule. Instead, the strategies are described through their functional logic and resulting spraying outcomes.

NS was used as the non-selective spot-spraying reference. Under this strategy, detected weed plants were assigned to treatment without taxon-specific differentiation. This strategy represented a conventional detection-to-spray logic in which the presence of a detected weed was sufficient to trigger nozzle activation, subject to the physical constraints of the simulated sprayer. It should therefore be interpreted as non-selective spot spraying, not as blanket spraying.

GR represented a generic rule-based strategy. It used plant size, spatial context and local density to differentiate between plants, but did not implement crop-specific taxonomic prioritization of weed species. This strategy was included as an intermediate baseline between non-selective spot spraying and the more explicitly taxon-informed SP strategy.

SP represented a crop-specific, taxon-informed decision strategy. Separate SP rule sets were used for oat, sugar beets and winter wheat to account for differences in crop sensitivity to weeds, crop-safety requirements and expected weed-management priorities. The agronomic assumption underlying these rules was that weed species differ in both competitive risk and potential ecological value, and that plant size and spatial aggregation modify this risk.

Highly competitive or high-priority taxa were generally targeted irrespective of local context, because their retention was assumed to increase the risk of crop interference. By contrast, selected low-risk or potentially beneficial taxa were eligible for preservation when they occurred as small, isolated individuals or at low local density, because such plants were assumed to impose limited immediate competitive pressure. When the same taxa occurred as larger individuals or in dense local patches, they were more likely to be targeted. For example, a low-risk broadleaf weed occurring as a small, isolated plant could be preserved, whereas a larger individual or a group of conspecific plants exceeding a density threshold would be assigned to treatment. Broader taxonomic detections, such as unresolved dicots or monocots, were managed through conservative fallback rules based on size and density rather than species identity. An example of different outputs is reported in Fig. 2.

Crop detections were retained in the strategy evaluation because they influenced the spatial decision logic of the simulator. In particular, crop-related rules were used to avoid nozzle activation over crop plants or to prevent spray footprints from overlapping crop detections. However, crop detections were excluded from weed-targeting, weed-preservation and biological selectivity metrics. This distinction separates crop-protection logic, which concerns avoidance of potential crop injury, from weed preservation, which represents the biodiversity-oriented component of the decision framework.

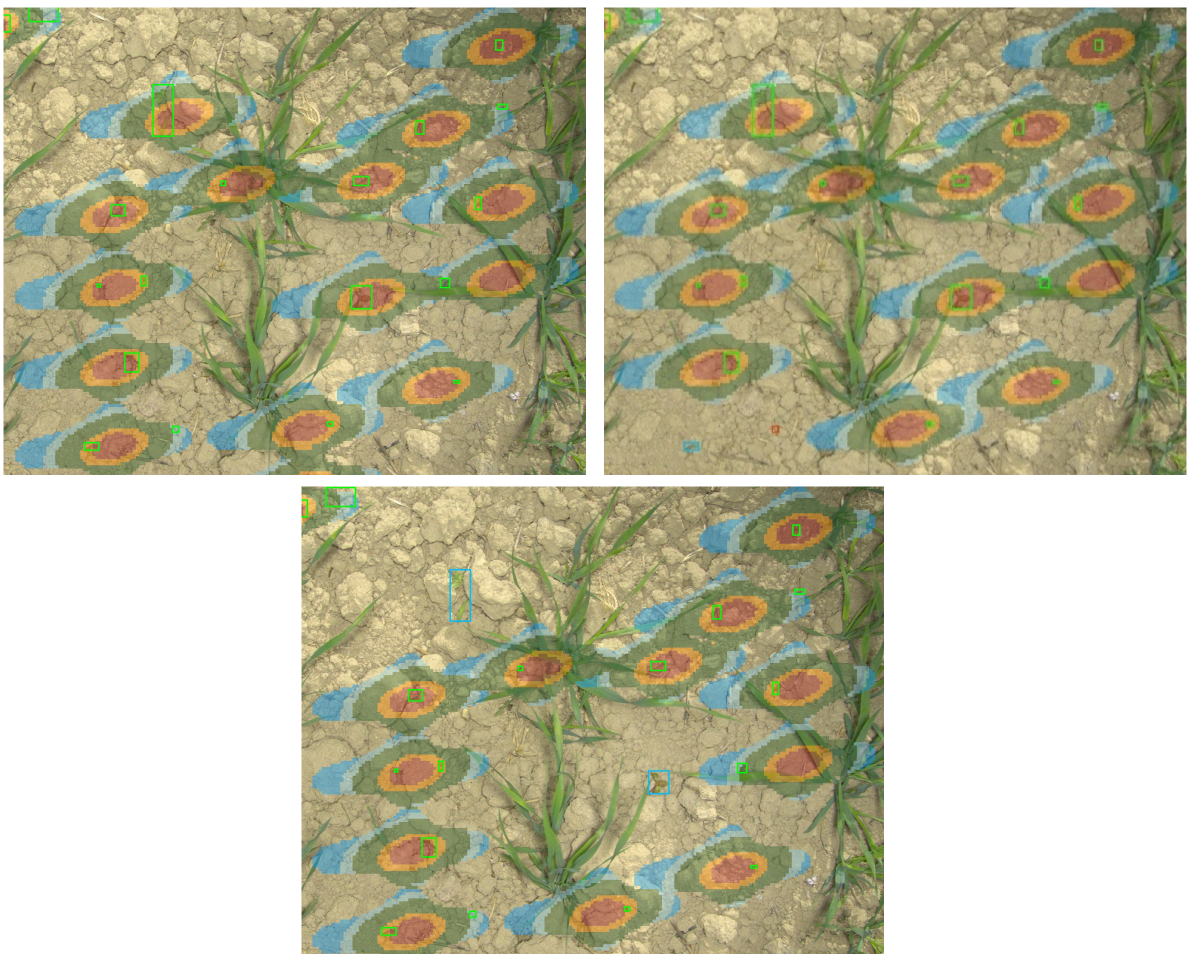

Fig. 1 Example of simulated model outputs for the same image in oat, under the three spot-spraying strategies: non-selective spot spraying (NS, top left), generic rule-based strategy (GR, top right) and species-led strategy (SP, bottom). Green rectangles indicate targeted weed detections, blue rectangles indicate preserved weed detections, and red rectangles indicate vetoed detections. The comparison illustrates how the same plant detections generated different target, preservation and veto outcomes depending on the decision logic.

Algorithm 1: Simplified plant – level decision logic of the three spot-spraying strategies

For each detected plant:

NS

If the detection was classified as weed vegetation:

assign TARGET.

Else:

apply the default strategy action.

GR

If the detection corresponded to a crop plant:

assign IGNORE for crop-protection logic.

Else if the detection belonged to a predefined competitive weed group:

assign TARGET.

Else if the detection was an unresolved dicot or monocot and met all preservation criteria:

assign PRESERVE.

Preservation criteria: biodiversity threshold reached, small plant size, and spatial isolation.

Else:

assign TARGET.

SP

If the detection corresponded to a crop plant:

assign PRESERVE for crop-protection logic.

Else if the detection belonged to a selected low-risk or potentially beneficial weed group:

assign PRESERVE, subject to rule-specific protection settings.

Else if the detection belonged to a predefined competitive weed group:

assign TARGET.

Else if the detection belonged to an intermediate-risk group:

assign TARGET when plant size or local density indicated higher competitive risk.

assign PRESERVE when the plant was small, locally sparse, and the biodiversity threshold had been reached.

Else if the detection was an unresolved dicot or monocot:

assign TARGET when density or plant size exceeded the relevant threshold.

assign PRESERVE only when the plant was small and the biodiversity threshold had been

Output metrics

Simulator outputs were summarized at both image and taxon level. Image-level summaries were used to compare overall strategy performance, whereas taxon-level summaries were used to evaluate biological selectivity, including which weed taxa were targeted, preserved, missed or vetoed under each strategy.

Weed control performance was quantified using the number of weed plants assigned to treatment, the number of targeted weeds reached by the simulated spray footprint and the number of targeted weeds that were missed. Hit rate was calculated as the proportion of targeted weeds that were hit, while missed target rate was calculated as the proportion of targeted weeds not reached by the simulated spray footprint. This distinction separated the decision to treat a plant from the simulated hardware outcome.

Weed preservation was quantified as the number and proportion of weed plants assigned to PRESERVE and not treated. Preservation metrics were calculated only for weed detections; crop detections were excluded from these metrics. Preserved weeds were further summarized by EPPO code and by risk group to evaluate whether preservation was concentrated in selected low-risk or potentially beneficial taxa rather than distributed randomly across the weed community.

Decision conflicts were quantified using veto-related outputs. A veto occurred when nozzle activation associated with a target plant was prevented because the simulated spray footprint would overlap a plant assigned to protection. Veto rate was used to describe the frequency of these conflicts relative to the number of targeted plants. These metrics were included because they represent the main operational cost of preserving selected plants in spatially complex weed communities.

Spray use was quantified from the simulated nozzle activations and expressed as total liquid use per image and estimated application volume in L ha^{-1}. Spray-use metrics were used to compare the operational consequences of each decision strategy and to evaluate whether increased biological selectivity was associated with changes in liquid use.

Data summarization and comparative analysis

Simulator outputs were analyzed as a deterministic paired comparison among decision strategies. For each crop, the same set of images was evaluated under each strategy; therefore, differences among strategies reflected changes in the decision logic rather than differences in the underlying weed community. Image-level summaries were used for comparisons among strategies, whereas taxon-level summaries were used to interpret biological selectivity.

For each image and strategy, weed control, preservation, veto and spray-use metrics were calculated from the simulator outputs. These image-level outputs were summarized by crop and strategy using totals, means and relative differences. Because the simulator was deterministic conditional on the input detections, rule sets and sprayer geometry, no hypothesis-testing framework was used to infer treatment effects. Instead, the analysis focused on quantifying paired differences in simulated outcomes among strategies. Paired differences were calculated by comparing SP with NS and GR within the same image, and 95% confidence intervals were used to describe the consistency of these differences across the image dataset.

Proportional outcomes were calculated directly from count data. Hit rate was calculated as the number of targeted weeds that were hit divided by the total number of targeted weeds. Preservation rate was calculated as the number of preserved weed plants divided by the total number of weed detections. Veto rate was calculated as the number of vetoed plants divided by the number of targeted plants. Crop detections were excluded from all weed-focused response variables.

Taxon-level summaries were used to evaluate biological selectivity. Preserved, targeted, missed and vetoed plants were summarized by EPPO code and by predefined risk group. These summaries were used to assess whether preservation was concentrated in selected low-risk or potentially beneficial taxa, and whether high-priority competitive taxa remained primarily targeted.

Spray-use metrics were derived from simulated nozzle activations and summarized as total liquid use per image and estimated application volume per hectare. When converting liquid mass to volume, spray solution density was assumed to be approximately 1 g mL^{-1}. Relative differences in spray volume were calculated using NS as the non-selective spot-spraying reference.

Results

Overall strategy performance

The three decision strategies differed in weed preservation, hit rate, veto frequency and spray use. As expected, NS did not preserve any weed detections, whereas GR preserved 1.7% and SP preserved 3.8% of weed detections. This increase in preservation was associated with reduced hit rate: SP achieved a hit rate of 91.8%, compared with 95.6% for GR and 97.3% for NS. Veto rate showed the opposite pattern, increasing from 0% under NS to 1.7% under GR and 5.4% under SP. Mean spray volume declined from 10.0 g image^{-1} under NS to 9.5 g image^{-1} under GR and 9.01 g image^{-1} under SP, corresponding to a 10.05% reduction for SP relative to NS.

Paired image-level contrasts confirmed this pattern (Table 1). Compared with NS, SP increased preservation by 3.9 percentage points (95% CI: 3.5 to 4.3), reduced hit rate by 4.5 percentage points (95% CI: −5.00 to −4.09), increased veto rate by 4.6 percentage points (95% CI: 4.1 to 5.04), and reduced spray volume by 1.01 g image^{-1} (95% CI: −1.10 to −0.91). Compared with GR, SP increased preservation by 2.09 percentage points, but reduced hit rate by 3.16 percentage points and increased veto rate by 3.09 percentage points (Tab. 1, Fig. 3).

Contrast	Metric	Mean difference	95% CI	Unit	Relative difference (%)
SP - NS	Preservation rate	3.9	3.5 to 4.3	percentage points	
SP - NS	Hit rate	-4.5	-5 to -4.1	percentage points	-4.7
SP - NS	Veto rate	4.6	4.1 to 5.0	percentage points	
SP - NS	Spray volume	-1.0	-1.1 to -0.9	g image^{-1}	-10
SP - GR	Preservation rate	2.1	1.7 to 2.5	percentage points	116.3
SP - GR	Hit rate	-3.2	-3.5 to -2.8	percentage points	-3.3
SP - GR	Veto rate	3.1	2.7 to 3.5	percentage points	204.7
SP - GR	Spray volume	-0.5	-0.5 to -0.4	g image^{-1}	-4.8

Tab. 1 Paired image-level contrasts between the species-selective strategy (SP) and the two reference strategies, non-selective spot spraying (NS) and generic rule-based spot spraying (GR).

Biological selectivity and competitive weed control

Preservation under SP was concentrated mainly in the predefined intended preservation groups. Of the 1,358 weed detections preserved under SP, 1,191 belonged to the intended preservation groups, corresponding to 87.7% of all preserved weeds. The remaining 167 preserved detections, equivalent to 12.3%, belonged to non-intended preservation groups. This indicates that the strategy did not simply increase non-spraying at random, but preferentially preserved taxa classified as low-risk or potentially beneficial.

Preservation was also taxonomically concentrated. The two most frequently preserved taxa were *Fumaria*

officinalis (FUMOF) and *Sinapis arvensis* (SINAR), which accounted for 53.3% and 16.0% of all preserved detections under SP, respectively. Together, these two taxa represented 69.3% of all preserved detections. Other preserved taxa included *Taraxacum officinale* (TAROF; 8.7%), *Veronica persica* (VERPE; 7.3%), unresolved dicot detections (PPPDD; 3.5%), *Poa annua* (POAAN; 3.4%), *Fallopia convolvulus* (POLCO; 3.1%) and *Viola arvensis* (VIOAR; 2.7%).
The increase in preservation was accompanied by an increase in vetoed plants, indicating a spatial trade-off between protecting selected weeds and treating neighbouring targets. This pattern is important because vetoed plants represent detections that would otherwise have been sprayed but were not treated because of the protection logic around preserved plants. Thus, the Species-led strategy increased biological selectivity, but also created local decision conflicts between preservation and control.
Competitive weeds remained mostly targeted under SP, but realized control was lower than under the two reference strategies. Across all crops, SP targeted 98.2% of competitive weed detections, compared with 100% under both GR and NS. However, the competitive-weed hit rate declined to 93.7% under SP, compared with 97.1% under GR and 98.4% under NS. The veto rate for competitive weeds increased from 0% under NS and 1.3% under GR to 4.3% under SP.
These results show that SP retained the agronomic intent of targeting high-priority competitive taxa, but the preservation logic reduced realized control performance. The main cost of selectivity was therefore not a complete failure to target competitive weeds, but an increase in vetoes and a lower final hit rate.

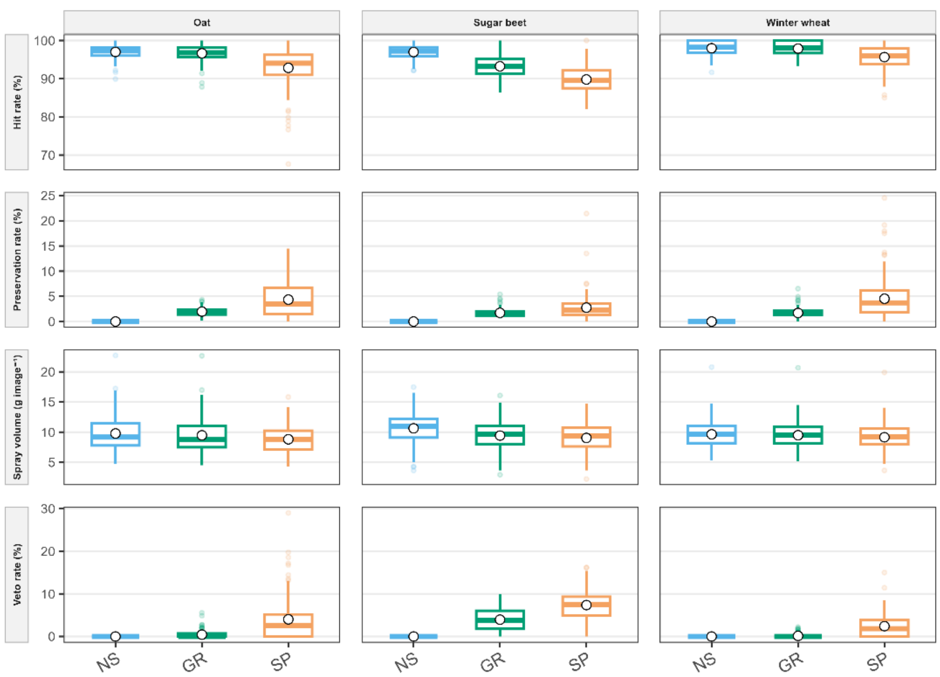

Fig. 2 Simulated weed-control, preservation and spray-use outcomes by crop and strategy. The figure illustrates how strategy choice affected realized hit rate, weed preservation, veto rate and spray-volume outcomes under the same image-based detection input.

Spray-use and preservation-control trade-offs

The increase in simulated preservation under SP was accompanied by a moderate reduction in spray use. Mean spray volume was lower under SP than under both NS and GR, with paired image-level contrasts indicating reductions of 1.01 g image^{-1} relative to NS and 0.46 g image^{-1} relative to GR. This corresponded to a 10.05% reduction in spray volume for SP relative to the non-selective reference.
However, reduced spray use was not the only consequence of species-selective decision logic (Fig. 4). Relative to NS, SP reduced realized hit rate by 4.5 percentage points and increased veto rate by 4.6 percentage points. Relative to GR, the corresponding differences were −3.16 and +3.09 percentage points.

These changes indicate that SP redistributed simulated outcomes among hit, preserved and vetoed weed detections, rather than simply reducing application intensity.

The main trade-off was therefore between biological selectivity and realized target coverage. SP increased the decision-level preservation of selected weed taxa and reduced spray volume, but this was achieved partly through increased protection-related vetoes, which prevented some target plants from being sprayed. This suggests that biodiversity-aware spot spraying is constrained not only by the choice of weed taxa to preserve, but also by local plant proximity and nozzle-footprint geometry.

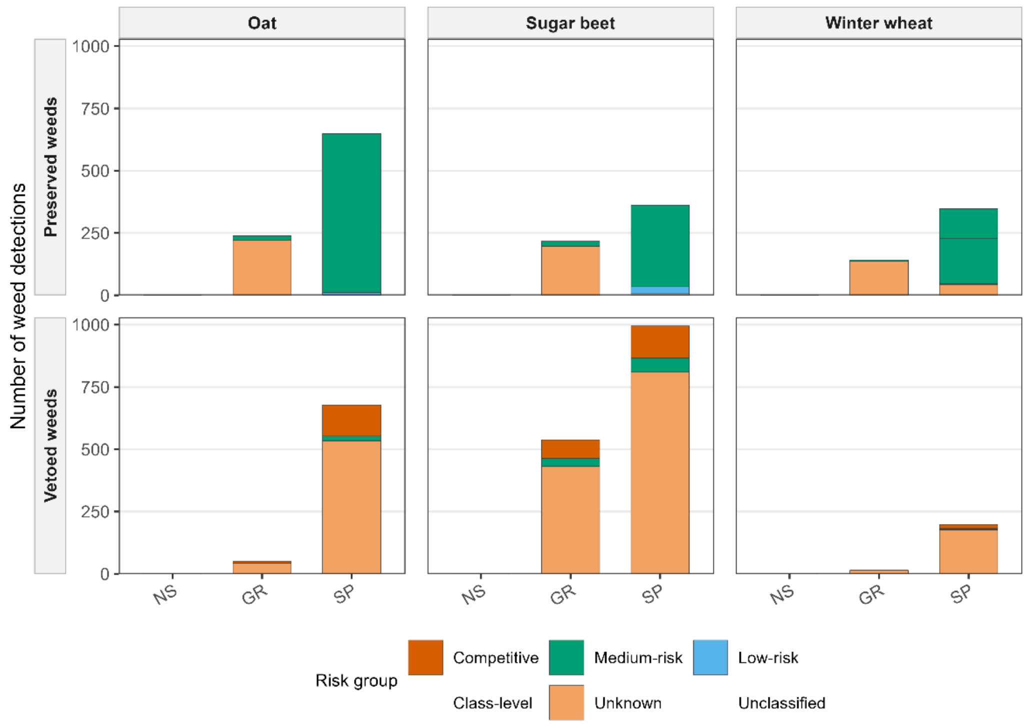

Fig. 3 Distribution of preserved and vetoed weed detections by crop, strategy and risk group. Stacked bars show the number of weed detections classified as preserved or vetoed under the non-selective spot-spraying reference (NS), the generic rule-based strategy (GR) and the species-led strategy (SP). Colours indicate the assigned weed risk group or taxonomic-resolution category.

Discussion

This study evaluated how crop-specific, species-selective decision rules would modify the outcomes of image-based spot spraying beyond a simple reduction in spray volume. The results show that decision logic strongly affected the distribution of simulated outcomes among targeted, preserved, vetoed and hit weed detections. Compared with non-selective spot spraying, the species-selective strategy increased simulated preservation of selected weed taxa and moderately reduced spray use, but this came at the cost of lower realized hit rate and more veto conflicts. These findings support the central premise of the study: in precision weed management, the decision layer is not a neutral step between detection and actuation, but a major determinant of agronomic and ecological outcomes.

This is consistent with recent conceptual work arguing that robotic weed management can reduce the trade-off between crop production and biodiversity only if robots process ecologically relevant information, including weed species identity, weed abundance and competitiveness (Zingsheim & Döring, 2024). The present study supports this argument by showing that species- or taxon-level information can be incorporated into crop-specific spraying rules. However, it also adds an important operational step. Ecological decisions cannot be evaluated only at the level of intended action. Once translated into nozzle activation, a decision to preserve one plant may also affect the treatment of neighbouring target plants. In this study, this occurred through protection-related vetoes, where the spray footprint needed to treat a target weed would also have overlapped a preserved plant.

The increase in preservation under the species-selective strategy was modest in absolute terms, but biologically structured. Most preserved detections belonged to the intended preservation groups, and preservation was concentrated in a limited set of taxa, especially *Fumaria officinalis* and *Sinapis arvensis*. This indicates that the strategy did not simply reduce spraying at random. Instead, it altered which weed plants were left untreated according to predefined taxonomic and risk-based rules.

However, the results also show that selectivity introduces operational costs. The species-selective strategy retained the agronomic intent of targeting competitive weeds, with most high-priority competitive detections still assigned to treatment. The reduction in realized competitive-weed hit rate was therefore not mainly caused by failure to identify competitive weeds as targets, but by the interaction between preservation rules and nozzle-footprint geometry. Protected plants created veto zones that prevented some neighboring target plants from being sprayed. Similar constraints have been reported in recent robotic weeding work, where biodiversity-aware intervention could not be evaluated from classification output alone: in Ahmadi et al. (2024), both intervention planning and vision-system limitations contributed measurable losses under field conditions, despite plant-level prioritisation. This supports the interpretation that ecological selectivity must be assessed jointly with perception, planning and actuation constraints, rather than as a purely biological rule set.

The reduction in spray use under the species-selective strategy should therefore be interpreted with caution. Although spray volume declined relative to the non-selective reference, the main outcome of the strategy was not simply reduced application intensity. Rather, the strategy redistributed outcomes among hit, preserved and vetoed detections. A strategy that saves spray but also increases missed or vetoed competitive weeds may not be agronomically acceptable unless the retained plants are low risk and the loss of realized target coverage remains within tolerable limits. Conversely, a strategy with slightly lower spray saving may be preferable if it preserves selected low-risk taxa while maintaining better control of competitive weeds. Future decision rules should therefore be evaluated as multi-objective systems rather than ranked only by herbicide reduction.

These findings also highlight the importance of hardware-aware rule design. A purely biological decision rule may classify a plant as suitable for preservation, but the sprayer can only implement that decision through discrete nozzle activation and a finite spray footprint. When target and protected plants occur close together, the simulator must resolve conflicts between control and protection. The resulting vetoes are not artefacts of the analysis, but an expected consequence of translating plant-level ecological decisions into actuator-level commands.

The simulation approach provides a useful intermediate step between conceptual decision-rule design and full field implementation. It allows alternative strategies to be compared on identical image inputs while accounting for realistic actuator constraints. Simulation cannot replace field validation, but it can identify promising rule structures, quantify likely trade-offs and reveal operational conflicts before field deployment.

Overall, the results suggest that species-selective spot spraying is technically feasible as a decision-rule concept, but its value depends on how selectivity is balanced against realized target coverage. The key contribution of this study is therefore not the absolute level of weed preservation achieved, but the demonstration that biological priorities can be encoded in a spot-spraying decision layer and evaluated under realistic nozzle-footprint constraints. Future work should validate these strategies under field conditions, test sensitivity to detection errors and rule thresholds, and link simulated preservation outcomes with post-treatment weed survival, crop response and biodiversity indicators.

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