Farm-level economic viability site-specific weed management (SSWM)

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A paper from the Proceedings of the

17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture

13-15 July 2026

Porto Alegre, Brazil

Abstract.

SSWM can substantially reduce herbicide use in maize, but its economic viability remains uncertain. UAV-based weed maps were used with a multi-year bioeconomic model to evaluate two different application strategies at 25 × 25 cm resolution. Herbicide savings ranged from about 35% under the Dual-Dose strategy to about 70% under the Presence-Based strategy. However, future weed penalties from untreated escapes made the Presence-Based strategy economically unviable. The Dual-Dose strategy was the only profitable option and reached break-even at approximately 58–110 ha, depending on the cost scenario.

Keywords.

Spot-Spraying; Digital Agriculture, herbicides, bio-economic modelling.

Introduction

Herbicides are a significant component of variable costs in arable crop production in Europe, and reducing chemical inputs without compromising yield is a key objective of modern agriculture. Site-specific weed management (SSWM) has emerged as a promising approach, enabled by recent advances in artificial intelligence (AI), unmanned aerial vehicles (UAVs) for mapping, and precision spraying technologies (Gerhards *et al.*, 2022). Unlike earlier systems based on interpolation and manual scouting, modern approaches allow the detection of individual weeds at very high spatial resolution. Despite these technological advances, the economic viability of

SSWM under practical conditions remains uncertain. Several key limitations complicate its evaluation. First, current AI systems typically distinguish only broad weed classes (monocots vs. dicots), limiting species-specific decision-making. Second, a mismatch exists between biological models and technical capabilities. Classical density-driven yield-loss models are most appropriate at approximately 1 m² resolution, whereas modern sprayers can operate at resolutions as fine as 25 × 25 cm. Third, sensor accuracy remains imperfect, with a substantial proportion of weeds remaining undetected. Finally, many previous studies have focused only on short-term outcomes and neglected multi-year weed population dynamics and resulting long-term economic consequences.

This study addresses these limitations by combining high-resolution UAV-based weed maps with a multi-year bio-economic simulation framework. It evaluates different decision strategies across multiple spatial resolutions and cost scenarios while explicitly accounting for imperfect detection and long-term weed population dynamics. The objective is to identify the conditions under which SSWM becomes economically viable in maize production in a region with small- to medium-scale farms.

Materials and Methods

Data and study design

The analysis is based on high-resolution UAV-derived weed distribution maps from 19 conventional maize fields in Lower Bavaria in 2025. Weed positions were detected and classified into monocots and dicots using AI-based image processing. Fields were subdivided into grid cells representing three application resolutions: 1 × 1 m, 50 × 50 cm, 25 × 25 cm. These grids served as the spatial basis for simulating herbicide application and economic outcomes. In this paper, the results of the 25 x 25 cm resolution are reported.

Decision strategies

Two site-specific spraying strategies were evaluated:

Presence-Based (PB): herbicide applied if at least one weed is detected.

Dual-Dose (DD): reduced dose applied in cells with zero weeds captured by the sensor, full dose in cells with at least one weed captured

Yield loss and economic modelling

Yield loss was estimated using a multispecies rectangular hyperbola model (Deines *et al*., 2004) based on competition indices (Coble, 1986) and total competitive load (TCL, Neeser *et al*., 2004), which integrates weed density and competitiveness. Due to limited classification accuracy, class-level competitive indices were used for monocots and dicots. The net return was calculated using a partial budget approach, subtracting herbicide and technology costs, together with a future weed penalty from crop revenue. The future weed penalty represents the long-term economic consequences of weed escapes and was derived from a 10-year simulation of weed population dynamics based on the reparametrized RIM model (Pannell et al., 2004).

Sensor uncertainty and weed escapes

To account for imperfect detection, a recall rate of 0.41 was assumed based on own empirical evaluation, implying that 59% of weeds were missed. These false negatives were spatially distributed using a biologically allocated approach, distinguishing between patch-associated escapes (70% of false negatives) and isolated background escapes (30% of false negatives). This enabled realistic modelling of future weed infestations and their economic consequences.

Future penalties from weed escapes

Weed population dynamics were simulated over a 10-year span using parameters for seed production, emergence, and survival. A sensitivity analysis (±20%) was conducted to reflect uncertainty in weed population dynamics parameters.

Costs Scenario

To assess the economic viability of the site-specific strategies, two technology cost scenarios were evaluated. These scenarios account for varying equipment investments, including new section-control sprayers and retrofitted systems, with external weed-mapping costs (Table 1).

Table 1. **Cost scenario assumed in the evaluation.**

Scenario	Technical setup assumption	Mapping setup	Annual cost 25 × 25 cm € year^{-1}
1	Acquisition of a section-control kit in addition to a new 21 m sprayer	External weed map provider	2280
2	Acquisition of a retrofit section-control kit for the existing 21 m sprayer	External weed map provider	6000

Results and discussion

Herbicide savings at 25 x25 cm spatial resolution

At 25 × 25 cm resolution, both PB and DD strategies resulted in substantial herbicide savings (Fig. 1). The PB strategy achieved the highest herbicide reduction ~70%, while the DD strategy achieved moderate savings ~35%. The greater reduction in the PB strategy results from treating only explicitly detected weeds, leaving the rest of the field completely unsprayed. Conversely, the DD strategy yields lower savings because it continuously applies a baseline herbicide dose across the entire field to manage undetected weeds. These results demonstrate the strong potential of high-resolution SSWM to reduce chemical inputs. However, they also reflect fundamentally different risk profiles between strategies.

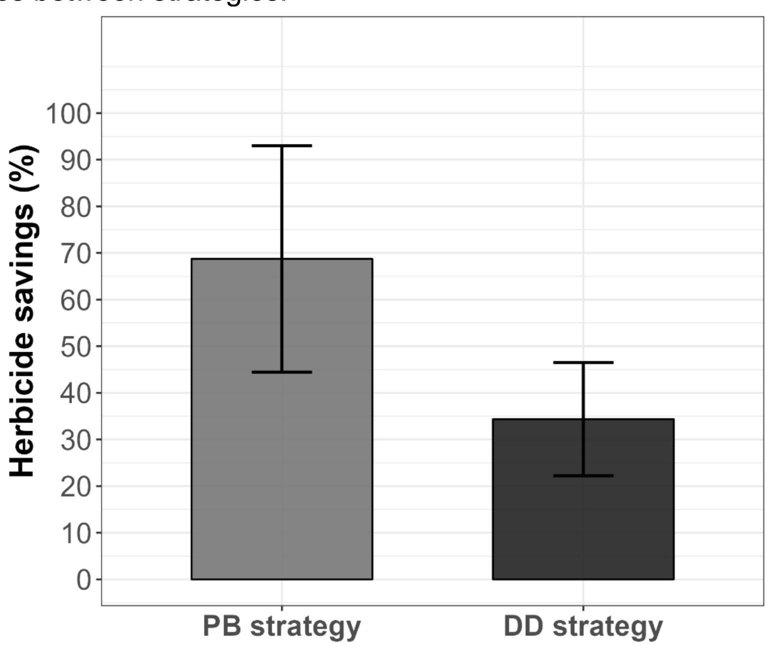

Figure 1**: Average simulated herbicide savings for Presence-Based (PB) and Dual-Dose (DD) strategies at 25 x 25 cm spatial resolution for 19 conventional maize fields.**

Future penalties from weed escapes

Table 2 summarises the sensitivity analysis of future weed penalties under alternative weed population dynamics assumptions. Future weed penalty represents the expected long-term economic cost of weeds that escape control, including future yield loss and additional control requirements associated with seedbank replenishment. To reflect uncertainty in key weed population dynamics parameters, these were varied by ±20%, generating optimistic and pessimistic scenarios. At a resolution of 25 × 25 cm, the PB strategy resulted in future weed penalties ranging from €78.26 ha^{-1} to €214.10 ha^{-1}, depending on the assumed weed population dynamics. In contrast, the DD strategy showed no additional future weed penalty because its herbicide efficacy was assumed to be equivalent to that of broadcast application, although applying a reduced dose could cause weeds to develop herbicide resistance more quickly. These results indicate that herbicide savings should be interpreted together with the long-term biological and economic consequences of weed escapes.

Table 2: **Future weed penalty from sensitivity analysis under alternative weed population dynamics assumptions.**

Resolution	Decision Strategy	Optimistic weed dynamics (-20%) € ha^{-1}	Baseline penalty € ha^{-1}	Pessimistic weed dynamics (+20%) € ha^{-1}
25 x 25cm	Presence-Based	78.26	159.24	214.1
25 x 25cm	Dual-Dose Strategy	0	0	0

Economic performance and break-even analysis

Despite large herbicide savings, SSWM was not economically viable under most scenarios due to future penalties from weeds that escape being killed. The only positive net return (excluding technology and information cost) was achieved by the DD strategy. The break-even analysis (Fig. 2) shows that the DD strategy becomes economically viable only below a specific application costs threshold. The break-even is reached at 58 ha (cost scenario 1) and 110 ha (cost scenario 2), respectively. Larger maize cultivation areas reduce per-hectare technology costs and further improve feasibility. Thus, economic viability depends on the interaction between technology costs, crop cultivation area scale, and long-term weed dynamics. For the PB strategy, the net returns were -€214 ha^{-1}, indicating that the technology will not become profitable even at zero cost.

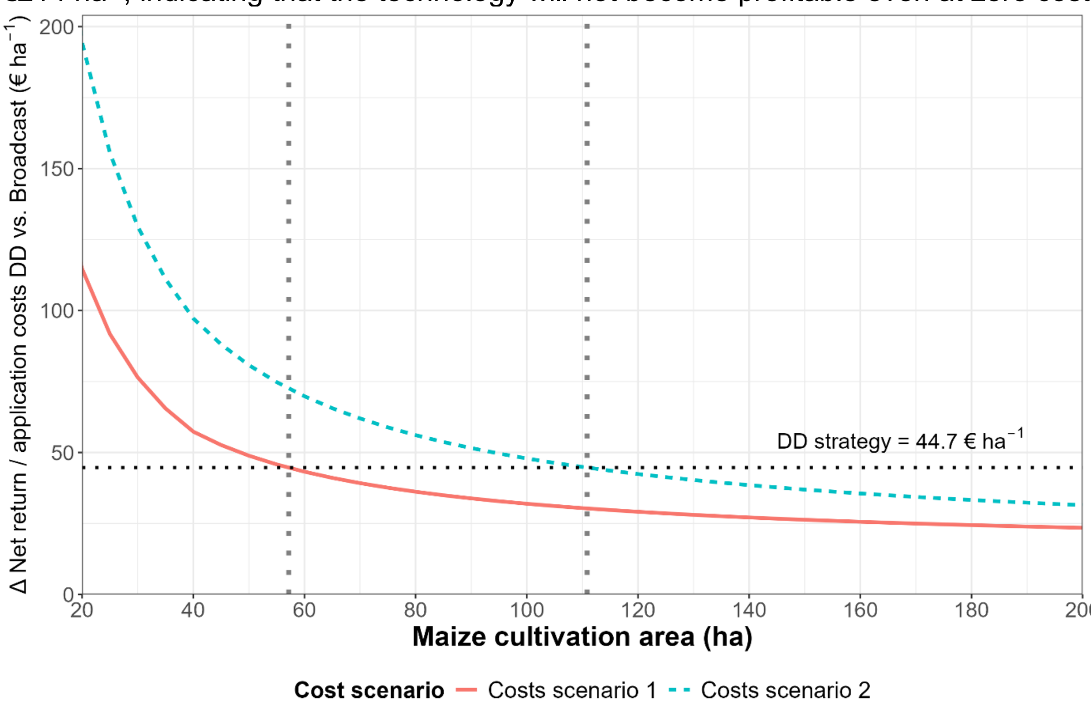

Figure 2: **Break-even analysis for DD strategy with 3 different cost scenarios.**

Conclusions

The results highlight a central trade-off in SSWM, specifically short-term herbicide savings versus long-term economic risk from weed escapes. While high-resolution application increases precision, it also increases the probability that undetected weeds remain untreated. This leads to higher future weed pressure and associated costs. Hence, the PB strategy, despite maximising herbicide savings, performed poorly in economic terms due to the high future penalty of untreated weeds. In contrast, the DD strategy reduced this risk by maintaining a baseline level of control across the field. These findings demonstrate that the key limitation of current SSWM systems is not technology cost alone, but the interaction between high spatial precision, imperfect sensor information and multi-year weed dynamics. Successful implementation of SSWM will require improvements in sensor accuracy, species-level classification and spatially explicit bio-economic modelling. Without these advances, the economic benefits of high-resolution SSWM remain limited.

Acknowledgments

We would like to thank the Bavarian State Ministry of Food, Agriculture, Forestry and Tourism for funding this research project (grant reference: G2/N/22/11).

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