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A comparative study of three weed management technologies on a typical farm in Western Pomerania, Germany: integrating economic analysis and soil compaction risk modeling

Jannik Aaron Dresemann[1,2] · Leon Ranscht[2] · Michael Kuhwald[3,4] · Marco Lorenz[4]

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Abstract

Purpose EU policies aim to reduce pesticide use, yet the on-farm competitiveness of site-specific weed management (SSWM) technologies remains unclear. This study evaluates the economic performance of three SSWM technologies in Western Pomerania, Germany, at both crop and whole-farm levels, integrating soil compaction risk and workability assessments resulting from practice changes.

Methods A typical farm model representing regional production systems served as a reference. Data on plant protection, machinery, costs and capacities were collected for a hoe plus band-spraying system, spot spraying based on unmanned aerial vehicle (UAV) field mapping and real-time spot spraying. Ex-ante scenario calculations and break-even assessments evaluated economic viability. The Spatially Explicit Soil Compaction Risk Assessment (SaSCiA) model assessed technology applicability based on wheel load carrying capacity and topsoil field capacity over nine years.

Results SSWM technologies outperformed broadcast spraying in certain crops. However, at the farm level, costs of spot spraying based on UAV field mapping nearly offset herbicide savings, while real-time spot spraying increased costs by 24%, making it uncompetitive. Hoe plus band spraying raises costs by 10% and significantly exceeds wheel load limits in edge-season operations, posing agronomic challenges for winter oilseed rape.

Conclusion A farm-level approach is essential for evaluating SSWM adoption. The combination of typical farm modeling, detailed plant protection data and soil compaction risk assessment proved effective for scenario analysis. Future research should refine weed pressure assessments, herbicide-saving potential and agronomic feasibility factors.

Impact

This study addresses a critical research gap by introducing a methodology for the ex-ante assessment of site-specific weed management technologies at both the farm and crop levels. Beyond economic evaluation, it incorporates an operational perspective by considering regional weather patterns and soil conditions, offering a more comprehensive analysis of technology feasibility and impact.

Extended author information available on the last page of the article

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Keywords Site-specific weed management · Typical farm approach · Ex-ante scenario analysis · Farm-level economic assessment · Soil compaction

Introduction

Although pesticide use is heavily debated, plant protection plays a pivotal role in European agriculture, contributing to crop productivity and food security. Synthetic pesticides have been one major factor in increasing productivity patterns (Cooper & Dobson, 2007; Popp et al., 2013). At the same time, the principle of integrated pest management (IPM) is mandated by national and European policies, including Directive 2009/128/EC. However, the European Court of Auditors has criticized the slow progress in IPM adoption as well as use and risk reduction, with pesticide sales volume stagnating in recent years (ECA, 2020; Eurostat, 2024a; Deguine et al., 2021). Additionally, research findings indicate a link among pesticide use, agricultural intensification and biodiversity loss, highlighting adverse consequences for non-target organisms (Sánchez-Bayo & Wyckhuys, 2019; Maskell et al., 2019; Beketov et al., 2013; Wan et al., 2025). In response to such concerns, the European Farm to Fork strategy and national initiatives such as Germany's Future Program for Plant Protection aim to reduce pesticide use and risk by 50% by 2030 (Böcker & Finger, 2016; EC, 2020, 2022; BMEL, 2024).

Further, precision farming technologies are emerging as potential solutions for reducing pesticide inputs through site-specific management. Trials conducted across various sites and crops have demonstrated the potential for herbicide savings of between 10% and 90% by implementing site-specific weed management (SSWM) technologies (Gerhards & Christensen, 2003; Allmendinger et al., 2022; Rajmis et al., 2022; Spaeth et al., 2024). However, these savings are highly dependent on the crop and regional conditions. Furthermore, when considering new technologies, farmers must evaluate not only the anticipated financial benefits from reduced herbicide use at the crop level but also the relative costs compared with their current mechanization and operational practices. This comprehensive cost–benefit analysis is pivotal in guiding farmers' decisions and, ultimately, determining the extent to which new technologies are adopted. Hence, crucial questions are which treatments can be replaced by SSWM technologies and whether their implementation can be economically viable at the farm level (Gerhards et al., 2022).

Pierpaoli et al. (2013) found that one of the most important drivers of precision farming technology adoption is farm size. This finding is in line with other studies assuming that the profit-maximizing decisions of a representative farmer determine the adoption of site-specific technologies. Because these technologies can increase land productivity and require access to capital, larger farms will be more willing and able to adopt. This already is reflected by the fact that adoption is limited mainly to large-scale farms in developed countries (Bowman & Zilberman, 2013; Finger et al., 2019).

This study presents an ex-ante assessment of three SSWM technologies – hoe plus bandspray, spot spraying based on UAV field mapping and real-time spot spraying – on a typical farm in Western Pomerania, Germany, a region characterized by large-scale arable farms. The analysis aims to evaluate the economic competitiveness of these technologies both at the crop level and across the entire farm, taking into account the structural and operational conditions specific to the case study region. A reference plant protection program was developed using secondary data and input from local experts to furnish the analysis with detailed information on the active ingredients used. The integration of typical farm data with the regional plant protection program forms the foundation for the economic evaluation. The analyzed technologies were selected because they likely are capable of meeting the operational demands of large-scale arable farms and are close to or readily accessible in the commercial market. In contrast, autonomous weed management equipment was not included due to its limited working capacity and adaptation in management practices that likely would be required (Zhang et al., 2022; Gerhards et al., 2022).

In order to facilitate a robust assessment of the different technologies, the economic analysis was complemented with a regional trafficability analysis. Soil compaction represents a significant environmental concern, affecting a variety of soil types across the globe (Nawaz et al., 2013; FAO, 2015; Keller & Or, 2022). It occurs when the load capacity of soil is exceeded due to exposure to field traffic in specific conditions (Horn et al., 1995). Soil compaction has a detrimental impact on soil functionality and agricultural productivity, and it increases the risk of nutrient leaching (Weisskopf et al., 2010; Nawaz et al., 2013). Region-specific factors, such as agroclimatic conditions and farm structure, were integrated into the SaSCiA model (Kuhwald et al., 2018, 2020). This model evaluates the feasibility of the technologies by comparing the soil's wheel load carrying capacity (WLCC) to the equipment weight on a daily basis from 2015 to 2023. Trafficability is a critical factor, as it directly impacts the timely execution of field operations and, consequently, the feasibility for new practices to be introduced in a region (Duttmann et al., 2021). However, assessing the effectiveness of an operation such as mechanical weed control requires considering additional agronomic and environmental factors beyond trafficability (Hussain et al., 2018; Zimdahl, 2018; Weimar-Bosse et al., 2018). Therefore, workability as an additional limiting factor for hoeing was analyzed based on topsoil moisture content.

The study provides scenario-based calculations at both the crop and whole-farm levels to assess the competitiveness of the technologies compared with the current practice of broadcast application, while ensuring practical applicability via the analysis of daily WLCC. The main contribution of this research is the combination of an ex-ante economic analysis of SSWM technology adoption with soil compaction risk. The implemented approach is standardized to enable inter-regional comparisons.

Materials and methods

This study employed the *agri benchmark* 'typical farm' approach to ensure a regionally specific and methodologically robust analysis of innovative plant protection technologies. In this approach, the typical farm is a theoretical construct representing the dominant farm type and production system in a given region. The approach was chosen because it integrates regional production practices and farm size into the assessment, allowing for a contextually accurate representation of agricultural systems, mechanization and cost structure. Additionally, this approach provides a standardized methodology that enables meaningful scenario analyses and cross-regional comparisons.

The involvement of regional agronomists and a local agricultural advisor was integral to extending the typical farm dataset, particularly for plant protection practices, ensuring that regional conditions such as weed pressure and resistance dynamics were reflected accurately. Researchers who specialize in plant protection and experts for the agricultural technology sector also contributed to deriving feasible assumptions for technology costs and potential herbicide savings, factors that are critical for the economic evaluation of site-specific weed management technologies.

The typical farm approach

The typical farm approach is used to represent the dominant farm type and production system within a specific region. Rather than depicting an actual farm, it serves as a theoretical construct developed in close collaboration with farmers and agricultural advisors. This model incorporates key parameters such as farm size, crop rotation, acreage distribution and yield levels, which are validated against regional statistics. By abstracting from the unique characteristics of individual farms, the typical farm enables a generalized yet detailed analysis of both farm-level economics and the prevailing production systems (Feuz & Skold, 1992; Nehring, 2011). The parameters pertinent to this study, as they are part of the dataset of a typical farm, are illustrated in Fig. 1.

The definition of an *agri benchmark* typical farm follows a standardized five-step procedure applied consistently across farm types and regions (Chibanda et al., 2020; Zimmer & Deblitz, 2005). First, relevant production regions are identified based on agricultural statistics and expert knowledge, with a focus on areas that contribute significantly to national agricultural output. Second, typical production systems are characterized in collaboration with local experts, using indicators such as crop composition, yield levels, mechanization and input use.

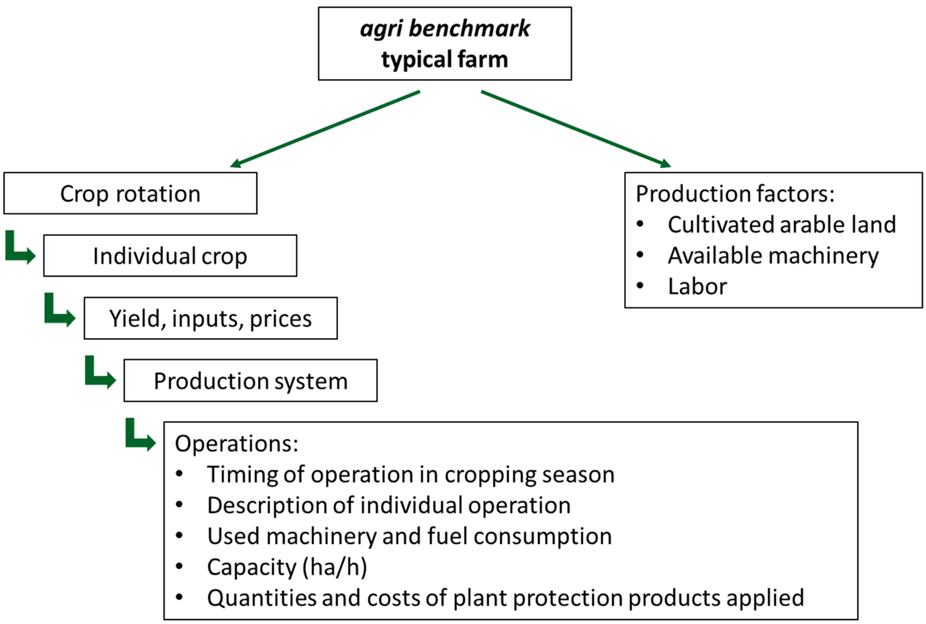

Fig. 1 *agri benchmark* typical farm approach data granularity (own illustration based on Chibanda et al. (2020) and Dehler (2023)

Third, data are collected through focus group discussions involving local research partners, advisors, and four to six producers, or through individual interviews. To ensure representativeness, the data are adjusted to reflect prevailing regional conditions rather than farm-specific characteristics. Fourth, the collected data are processed and validated using agri benchmark's TIPICAL model, which generates detailed economic, physical and, where available, environmental indicators. This process is iteratively refined until consensus is reached on the accuracy and consistency of the dataset.

Finally, the data are updated regularly: annually for prices and yields, and every three to five years for structural parameters such as farm size, machinery inventory and labor organization. The standard operating procedure also provided the foundation for the data collected from the typical farm in Western Pomerania, as described subsequently. This includes current weed management practices and a structural review conducted as part of this study. Furthermore, the typical farm dataset was extended to include the active ingredients used in plant protection, allowing for a more detailed and technology-relevant analysis, as explained in the following sections.

A typical farm case study in Western Pomerania

The northeastern German state of Western Pomerania encompasses approximately 1.35 million hectares of agricultural land, representing about 8.4% of Germany's total agricultural area (Statistisches Amt Mecklenburg-Vorpommern, 2024; Statistisches Bundesamt, 2024). About 40% of the land in Western Pomerania is farmed by farms larger than 1,000 ha in size, reflecting the predominance of large arable farms (Statistisches Amt Mecklenburg-Vorpommern, 2024). Given the extensive acreage under cultivation in Mecklenburg–Western Pomerania, the region plays a pivotal role in national crop production. Therefore, the case study region is of significance not only from an economic point of view but also for policymakers in regard to the national and European plant protection reduction efforts.

The typical farm is located in the temperate climate zone. The mean annual temperature in the Neubrandenburg region in Western Pomerania for the period between 1991 and 2020 was 9.2 °C. Annual precipitation was recorded at 578 mm. Typically, the main rainfall occurs in the summer months of June and July. However, there is a potential risk of early summer droughts (DWD, 2024).

The typical farm covers 1,100 ha arable land and emerged from an agricultural cooperative in the former German Democratic Republic (Wolz, 2013; Statistisches Amt Mecklenburg-Vorpommern, 2024). Historically, the region is characterized by very narrow crop rotations focusing on winter oilseed rape (WOSR), winter wheat and barley production (Statistisches Amt Mecklenburg-Vorpommern, 2024). Over more recent years, the crop rotation was diversified by including spring crops, initially corn silage. This was due to special payments under the Common Agricultural Policy (CAP) and additional subsidy programs at the state level requiring at least five crops per farm and 10% legumes in the crop rotation. As part of the CAP, the "Diverse Crops in Arable Farming" program (Eco-Scheme 2) provides a subsidy of 60 € per ha^{-1} for all agricultural land on participating farms. However, due to oversubscription in 2023, the actual subsidy paid was reduced to 58.50 € ha^{-1}. This Eco-Scheme support is further complemented by state-level funding under the second pillar of the CAP, which offers an additional 60 € ha^{-1} for diversified crop rotations. In 2023, these programs provided total subsidies of 118.50 € for every hectare in arable production if requirements were fulfilled (BMEL, 2023; Ministerium für Klimaschutz, Landwirtschaft, ländliche Räume und Umwelt, 2023). The current crop rotations of the typical farm are WOSR – winter wheat – winter wheat (120 ha); WOSR – winter wheat – corn silage – winter wheat (77 ha); WOSR – winter wheat – peas – winter barley (50 ha); WOSR – winter wheat – fava beans – winter wheat (60 ha). The share dedicated to each crop is about 51% for winter wheat, 28% for WOSR, 7% for corn silage and around 5% each for winter barley, peas and fava beans.

Except for the application of organic fertilizers and corn silage harvest, the farm is self-mechanized, with tractors ranging from 110 kW to 260 kW. The tillage system is primarily conservation-focused, with the exception of plowing for stubble wheat and winter barley. For the purposes of this study, it was assumed that all row crops were planted with equal row spacing, which was necessary to avoid introducing an additional planter solely for WOSR and fava beans. According to Andert et al. (2021), more than 20% of farmers in northern Germany intend to cultivate WOSR in wide row spacings. Accordingly, WOSR was regarded as a row crop in this study and planted in singulation with 0.5 m row spacing, as also endorsed by Peters (2023).

The granularity of the typical farm data generated based on the standard operating procedure provides information about the single treatments on an individual crop level as well as the differentiation for herbicides, fungicides and insecticides based on the direct cost for individual applications (Fig. 1). Because of the high volatility in agricultural markets in previous years, 2023 is selected as the reference year, providing a more stable and representative basis for analysis than the preceding period (Ziesemer, 2024). In the typical farm data set, weed management in WOSR is the most intensive, with costs amounting to 199 € ha^{-1}, compared with the crop share-weighted farm average of 132 € ha^{-1}, which is in accordance with the findings of Dachbrodt-Saaydeh et al. (2018). In contrast, weed management in legume cultivation is more extensive, typically comprising a single in-crop herbicide application and cover crop termination prior to planting. In corn silage production, cover crops are terminated using a non-selective herbicide before planting, followed by two in-crop herbicide applications during the growing season. Within the given crop rotation and reference year of the typical farm data, winter barley exhibits the lowest weed management costs, at 59 € ha^{-1}.

Regional plant protection data

For this study it was essential to evaluate the technologies at the level of active ingredients, as the reduction potential depends on the type of action (foliar-active vs. soil-active). The reduction of pesticide use can be achieved only if two conditions are met: first, that foliar-active substances are available for the treated crop and, second, that they are suitable for the weed spectrum to be treated.

In order to create a reference scenario for the technology assessment, a typical plant protection program was developed. In the standard typical farm data, plant protection is differentiated only among herbicides, fungicides and insecticides at the operation-specific direct- and operating-cost level. For this study, the typical farm dataset is further refined by incorporating appropriate quantities of active ingredients into the plant protection program, enabling a more detailed representation of input use. Regional advisory recommendations for treatments in the specific crops were used as a point of departure (LFA, 2023; Heilmann, 2023a). This information was critically reviewed by a regional agronomic advisor. This approach has proven to be effective in similar research contexts and therefore was adopted in this study (Rajmis et al., 2022; Walther et al., 2022; Dehler, 2023).

Table 1 presents data regarding the timing of individual applications, the product and its active ingredient, the quantity applied and the cost per hectare. The product costs per hectare in Table 1 are based on the mean market prices provided by the regional research institution Landesforschungsanstalt für Landwirtschaft und Fischerei MV (Ziesemer, 2024; Heilmann, 2023a). These initial price figures have been validated based on the prices listed on public price databases and online platforms representing the offerings of agricultural commodity traders.

The historically high proportions of cereal crops and WOSR, coupled with their continued prevalence, place growers at considerable risk with regard to the potential for particularly hard-to-manage weed infestations (Andert et al., 2016; Andert & Ziesemer, 2022). On the typical farm, WOSR incurs the highest herbicide expenditure, averaging 158 € ha^{-1} (Table 1). A significant challenge in weed management is the control of black grass and loose silky bent grass (Andert et al., 2024). In the modeled production system, the use of expensive graminicides is a crucial element in control of these weeds. The application of propyzamide (Kerb FLO®) is contingent on annual weed pressure and is not used every year. In years without application, herbicide costs are reduced by 46 € ha^{-1}. For fava beans, a cover crop is cultivated prior to their planting in spring. The termination of the cover crop is initiated at the beginning of March with the application of glyphosate. In spring, the soil-active ingredient aclonifen is applied pre-emergence. In the weed management program for corn silage, the initial treatment with glyphosate, again, provides the termination of the cover crop prior to planting. Cover crop termination is followed by the application of one soil-active and one foliar-active ingredient in two passes.

Table 1 Reference weed control program including cover crop termination for the typical farm (*agri benchmark* data; LFA, 2023; Ziesemer, 2024)

Crop type	Time of application	Product name	Active ingredient	Product amount (1 ha^{-1})	Cost (€ ha^{-1})
WOSR	Aug. mid	Stomp Aqua®	Pendimethalin	1	21
WOSR	Aug. late	Agil-S®	Propaquizafop	1	26
WOSR	Nov. mid	Belkar®+Synero®	Halauxifen-methyl, Picloram, Aminopyralid	0.25	26
WOSR	Nov. late	Belkar®	Halauxifen-methyl, Picloram	0.25	39
WOSR	Feb. mid	Kerb FLO®	Propyzamide	1.25	46
Fava beans	Feb. early	RoundUp Power Flex®	Glyphosate	2.25	22
Fava beans	May early	Bandur®	Aclonifen	4.5	99
Corn silage	Mar. early	RoundUp Power Flex®	Glyphosate	2.25	22
Corn silage	May early	MaisTer power®	Foramsulfuron, Thiencarbazone, Iodosulfuron, Cyprosulfamide	1.25	45
Corn silage	May early	Aspect®	Terbuthylazine, Flufenacet	1.25	20

Characterization of technologies

A variety of studies was examined to identify potentially relevant innovations in weed management and gain insight into their technical performance (Andert et al., 2021; Walther et al., 2022; Witzke & Herchenbach, 2022). Products that were at least close to market and considered feasible to meet the capacity demands of the typical farm were selected. These included a sequential combination of mechanical hoeing and band spraying, spot spraying based on UAV field mapping and real-time spot spraying based on a conventional sprayer. In order to assess the viability of a potential alternative, it is necessary to consider a number of relevant parameters. These include the capacity of the machinery against the available field working days, the level of investment required and the costs associated with repair and maintenance, depreciation and potential service provider fees (Krug, 2013; Mußhoff & Hirschauer, 2020).

A reliable economic analysis of new technologies is crucially dependent on relevant purchase prices and the technical performance of the technology, including intended and unintended side effects. First, publicly available information was reviewed. Second, available literature was reviewed regarding the savings and potential side effects of the different technologies. Third, this information was cross-referenced during guideline-based expert interviews (Roberts, 2020).

In the context of technology adoption, it is essential to consider a range of influencing factors, including risk, learning and uncertainty (Marra et al., 2003; Paustian & Theuvsen, 2017). However, this study did not explicitly account for the associated costs of these factors. Instead, the analysis focused on the long-term economic competitiveness of the technologies, rather than on short-term adoption barriers or transitional costs. The following paragraphs provide an overview of the implementation of different technologies in a typical farm setting, along with the cost and herbicide reduction assumptions for the case study region.

Broadcast application

Based on Ziesemer (2024) and the current practice of the analyzed *agri benchmark* typical farm, the conventional broadcast application of plant protection products was chosen as the reference scenario. In this method, plant protection products are applied uniformly across the entire treated area without any site-specific differentiation.

Hoe and band spraying

For the hoe plus band-spraying scenario, hoeing and band spraying are considered to be split into two operations: A hoe is used for mechanical weed control between the rows at 0.5 m row spacing. The standard broadcast sprayer of the typical farm is equipped with a band-spraying accessory. The sprayer capacity remains the same as in broadcast application. The camera-guided hoe used for the scenario calculations is suitable to work 12 rows per pass. Feasibility of mechanical weeding coupled with band spraying for various regions and row crops such as corn, soybeans and WOSR has been shown in different studies (Perez-Ruiz et al., 2013; Vasileiadis et al., 2016; Kunz et al., 2018). The additional labor demand resulting from the limited operational capacity of hoeing implements can be accommodated by full-time farm staff, as labor availability typically exceeds demand during the relevant periods of the cropping season.

Spot spraying based on UAV field mapping

The process of spot spraying based on UAV field mapping analyzed in this study was considered to be a two-step weed control method. The first step consisted of the use of a UAV to map the field and assess the extent of weed infestation. In the second step, the resulting prescription map was transferred from the reference scenario to the pulled sprayer, which was equipped with nozzle control technology to enable prescription-based spot spraying.

The potential of UAV imagery for mapping weeds in row crops has been discussed in various academic publications (López-Granados et al., 2016a, b; Fernández-Quintanilla et al., 2018; Maes & Steppe, 2019). It was assumed that the UAV-based weed mapping was provided as a contractor service. This assumption is based on expert feedback indicating that agricultural operations typically lack the necessary capabilities. Moreover, specialized service providers can utilize their systems across multiple farms, making this approach likely more cost-effective and competitive compared with individual on-farm acquisition. As the literature is limited, service provider costs were assumed to be 15 € ha^{-1}per flight, as provided by a service provider. This assumption is consistent with a similar study, which also applied a rate of 15 € ha^{-1} (Walther et al., 2022).

Real-time spot spraying

In recent decades, a variety of technologies has been developed for the detection of weeds and crops (Felton & McCloy 1992; Spaeth et al., 2024). This study considered the use of camera-based spot-spraying systems mounted on conventional sprayers that enable real-time imagery processing and can be operated at similar capacities. The requisite capacity and technological specifications for scenario calculations were derived from publicly accessible resources and subsequently validated during interviews with experts. This process was particularly crucial in establishing the price for the spot-spraying attachment, which was sourced from U.S. list prices and aligned with expert knowledge for the European market.

Equipment capacity and cost

The reference sprayer has a tank volume of 5,000 and working width of 36 m, which serves as reference in all scenarios, and reaches an effective capacity of 14 ha h^{-1} with estimated fuel consumption of 1.1 l ha^{-1}. The sprayer can be used for plant protection across all crops. Therefore, only the additional costs specifically associated with enabling SSWM, such as sensors, nozzle kits and real-time processing units, were allocated to row crops. This approach reflects the principle that the base investment in the sprayer serves general plant protection purposes, while the incremental costs for SSWM technology are justified only for crops in which such precision measures are applicable and beneficial.

The hoe has a working width of 6 m and a row spacing of 0.5 m. It is estimated to have a capacity of 2.7 ha h^{-1} and a fuel consumption of 3.6 l ha^{-1} (KTBL, 2025). The cost of the hoe was allocated only to row crops. The machinery and operating cost for the different scenario technologies are summarized in Table 2; diesel price including German agricul-

Table 2 Overview of machinery cost assumptions for the three different scenarios that were taken as reference for the economic analyses (*agri benchmark* data; expert knowledge; KTBL, 2025)

	Purchase price (€)	Depreciation period	Salvage value (€)	Annual depreciation (€)	Annual repairs (€)
Equipment					
Sprayer 36 m; 5,000 l	175,000	10,000 m^3	35,000	23,333	3,175
Hoe 12 rows	71,000	3,000 ha	14,200	9,467	2,610
Attachment					
Band-spraying kit	2,000		400	267	0
Spot-spraying technology	250,000		50,000	33,333	500

tural diesel refund was assumed at 1.2 € l^{-1} (*agri benchmark* data). Equipment investment assumed linear depreciation, 20% salvage value and an interest rate of 2.7% (Deutsche Bundesbank, 2024).Depreciation was calculated based on hectares worked on the typical farm. For spraying, an average application rate of 200 l $ha^{-1}$was assumed.

Herbicide reduction assumptions

The herbicide reduction potential plays a crucial role in determining the competitiveness of the evaluated technologies, making scientifically sound assumptions essential. Given that weed pressure and the prevalence of resistance are highly region-specific, general assumptions are insufficient and must be tailored to local conditions. In the absence of regional field trial data, this study integrated findings from existing literature with insights from experts and regional agronomists to ensure robust and context-specific estimates. These estimates were linked to the reference weed control program of the typical farm, as presented in Table 1.

The herbicide input reduction in band spraying depends on factors such as crop type, row spacing and band width (Ozaslan et al., 2024). Depending on the crop, studies showed a herbicide input reduction of 50% to 70% while maintaining high levels of efficacy (Vasileiadis et al., 2016; Kunz et al., 2018).

For this analysis, hoeing was applied to the row crops - i.e., WOSR, corn silage and fava beans. Field trials suggest that two or three hoe passes, combined with band spraying, provide weed control efficacy comparable to conventional applications in corn silage (Wienberg, 2022; LALLF M-V 2024). For this study, two hoe passes were assumed in corn silage. For fava beans, one hoeing pass was assumed (Rücknagel, 2017). Therefore, both assumptions are dependent on annual meteorological conditions and regional weed pressure. Hoeing passes and economic effects are further differentiated in a sensitivity analysis.

In WOSR, Nilsson et al. (2014) observed similar weed control efficacy when comparing one inter-row hoe pass combined with band spraying versus conventional herbicide application. Herbicide savings in the case study region were estimated at 50%. This estimate accounts for the use of broadcast applications rather than band spraying in the headlands. The estimation is based on expert knowledge and the findings of Arendholz et al. (2022) and Peters (2023). Peters (2023) also found that implementing hoeing in late fall proved challenging in field trials in Western Pomerania due to local weather conditions. In this scenario, one hoe pass and band-spraying application were assumed after broadcast applications, with a cost comparison conducted to assess the impact of an additional hoe pass if required.

Potential savings from spot spraying based on UAV field mapping and real-time spot spraying on row crops are highly dependent on factors such as infestation level, crop growth stage and spatial distribution, leading to substantial variability across farms, fields and regions (Dammer & Wartenberg, 2007; Spaeth et al., 2024). For example, Timmermann et al. (2003), Gerhards and Oebel, (2006), and Gutjahr et al. (2012) reported herbicide savings from 11% to 78% in corn. Leithold et al. (2018) conducted multiyear on-farm research trials and reported average herbicide savings of 8% to 68%, depending on management thresholds. Other studies suggest that savings may reach up to 90%(Wiles, 2009; Allmendinger et al., 2022), and trials in Germany have indicated potential savings of 10% to 55% in sugar beets, corn and sunflowers (Spaeth et al., 2024). Given the influence of regional climatic conditions and annual effects, generalizations are challenging. Consequently, literature findings were used as a reference and further refined with expert input and field trial data to determine the potential savings in the case study region.

As applied in other studies, the first herbicide pass was assumed to rely on broadcast spraying even in the spot-spraying scenarios to reduce weed pressure (Walther et al., 2022; Spaeth et al., 2024). It was assumed that the herbicide use reduction potential of the two spot-spraying technologies would be equivalent. The application of the soil-active ingredient propyzamide to control annual grasses in WOSR did not qualify for site-specific application. For glyphosate applications before spring crops, field trials indicate a wide range of potential savings due to the presence of unfrozen cover crops. Based on expert opinion, an average 50% savings in pre-seeding glyphosate applications was assumed for grain legumes and corn silage in the case study. The assumed reduction rates for individual operations of the analyzed technologies within the weed control program (as outlined in Table 2) are summarized in Table 3.

Economic figures for comparison

Weed management costs were based on the specified crop cycle, the plant protection strategy and whole-farm level effects. The economic comparison of the different technologies was based on the weed management cost, as there is no evidence in the literature regarding additional effects apart from those related to labor, machinery and inputs. The efficacy of

Table 3 Assumptions on herbicide reduction potential in the relevant crops on the typical farm based on type of technology and timing in the season (*agri benchmark* data; expert knowledge)

Crop	Date	Product	Reduction Spot Spraying (%)	Reduction Band Spraying (%)	Possible Hoe Application
WOSR	Nov. mid	Belkar®	30	50	Oct. beg-end
WOSR	Nov. late	Belkar®	30	50	Mar. beg
WOSR	Feb. mid	Kerb FLO®		50	Mar. beg
Fava bean	Feb. early	RoundUp Power Flex®	50		---
Fava bean	May early	Bandur®		50	May beg
Corn silage	Mar. early	RoundUp Power Flex®	50		---
Corn silage	Mar. early	MaisTer power®	64	50	May beg

all analyzed technologies has been demonstrated in various studies. Therefore, technology-induced yield losses were not taken into account (Vasileiadis et al., 2016; Kunz et al., 2018; Spaeth et al., 2024). Equation 1 outlines the weed control cost calculation scheme for individual operations.

Equation 1 Weed control cost calculation.

$$WC = DC_{weed\,control} + OC_{weed\,control}$$

$$OC = MC_{weed\,mgt} + CC + \ FC + LC$$

Weed control cost (WC) was calculated as the sum of direct cost ($DC_{weed\ control}$) and operating cost ($OC_{weed\ control}$) per hectare. In this study, only herbicide expenses that are allocated to specific operations were considered as direct cost. Operating costs (OC) comprised fixed (depreciation and finance) and variable machinery costs ($MC_{weed\ mgt}$), contractor cost (CC), fuel cost (FC) and labor cost (LC).

Equation 2 Machinery cost allocation, weed management.

$$MC_{annual} = D + \ I + R$$

$$MC_{weed\,mgt} = MC_{annual} * \frac{T_{weed\,mgt}}{T_{annual}}$$

Variable and fixed machinery cost shares were calculated by using the TYPICAL model. The cost allocation is shown in Eq. 2 (Chibanda et al., 2020). Machinery costs were calculated based on linear depreciation on repurchase prices (D), finance cost (I) and annual repair cost (R). The fixed machinery cost related to weed management ($MC_{weed\ mgt}$) was determined by dividing the time spent on this activity ($T_{weed\ mgt}$) by the total operational hours of the machinery annually (T_{annual}). Consequently, additional costs were attributed only to the row crops for which the technology is applicable.

For this study, production system data for individual crops include only herbicide expenses as direct cost. Contractor fees, which were allocated to specific operations, were taken into account accordingly (Chibanda et al., 2020). The calculation excluded overhead labor and machinery costs, such as work preparation or traveling between farm and fields, which are aggregated at the whole-farm level.

In general, it is recommended that key parameters are normalized over a period of several years to circumvent the generation of results that are significantly influenced by an annual effect. However, a comparison of current price levels with the three-year average prior to 2022 (2019–2021) revealed that these averages align more closely with 2023 market prices for inputs than a three-year average that includes more volatility. This alignment reflects an overall increase in direct cost levels (Eurostat, 2024b). Consequently, 2023 data were selected as the reference to ensure a more accurate and representative analysis.

Soil compaction risk and workability

Soil compaction risk, expressed as WLCC (Gut et al., 2015), and workability, was modeled using the SaSCiA model, which integrates soil data, weather conditions, present crop type and machinery-specific parameters (Kuhwald et al., 2018, 2020). The SaSCiA model was used to estimate trafficability at the depth of 0.35 m over a nine-year period on a daily basis, utilizing available timeseries data from the local weather station in Trollenhagen (DWD, 2025). The soil characteristics used for the representative typical farm's region was a Luvisol with loamy sand, sandy loam soil texture (BGR, 2025; Appendix 1). Of the four crop rotations practiced on the farm, the WOSR – winter wheat – winter wheat rotation was selected as the reference. This rotation was chosen because these three crops represent the largest share of arable land on the typical farm, and herbicides in WOSR are typically applied during the edge-season.

By factoring in machinery specifications, weight and tire inflation pressure, the model provides a realistic assessment of the WLCC under varying environmental conditions (Kuhwald et al., 2018; Duttmann et al., 2021). In general, the typical farm model does not incorporate brand-specific machinery details (Table 2). However, the characteristics of the tractor and implement combinations for spraying and hoeing listed in Table 4 were used as proxies for the soil compaction risk assessment. The load distributions and corresponding wheel loads were determined on the basis of weighings, *agri benchmark* data and manufacturer information on weights and sizes of machines and implements. The tire sizes were taken from *agri benchmark* information on the typical farm and manufacturer specifications. The corresponding tire inflation pressures were determined for the corresponding tire size and wheel load from tire tables provided by the manufacturers.

In working position, the hoe is supported by four wheels, two at the sliding frame for inter-row guidance (tire size: 255/55) and two on the hoe itself (tire size: 6.5/90 − 15), thereby ensuring appropriate weight distribution. In order to approximate the weight distribution and wheel loads during hoeing, it was assumed that the support wheels carry 1,250 kg. In addition, the tractor is equipped with a 1,000 kg front weight for balancing the weight distribution across the two axles and ensuring optimal traction. The additional possible downforce due to working the soil was not taken into account as it is unknown and

Table 4 Machine characterization including wheel load (*agri benchmark* data; expert knowledge)

	Front axle	Rear axle	Implement
Sprayer:			
John Deere 7530 tractor with AMAZONE UX5200 sprayer			
Wheel load (kg)	1,298	4,039	3,500
Tire size	600/65 R28	650/75 R38	520/85 R46
Pi* (kPa)	80	100–120	140–160
Hoe:			
John Deere 6830 tractor with Schmotzer Venterra 12 row hoe, 0.5 m row spacing			
Wheel load/implement weight (kg)	2,042	2,146	2,000
Tire size	320/85 R32	320/90 R46	
Pi* (kPa)	200	200	

*tire inflation pressure

cannot be calculated without further specific field tests. For the sprayer, a constant weight (fully loaded) was assumed for soil compaction risk analysis.

When assessing hoeing, in addition to soil WLCC, soil moisture plays a crucial role in determining the effectiveness of the operation (Weimar-Bosse et al., 2018; Hussain et al., 2018). To account for the workability aspect, the SaSCiA model and the integrated MONICA-model(Nendel et al., 2011) were used to simulate field capacity at a depth of 0.05 m for each day in the nine-year period. By comparing the simulated field capacity with the established workability thresholds defined by Petelkau et al. (1983) and Sommer (1997), an additional evaluation criterion was introduced to assess the feasibility of hoeing under varying soil and weather conditions during the year.

Results

Economic competitiveness of technologies

Winter oilseed rape (WOSR)

Figure 2 illustrates the economic impact of the different technologies on weed management cost in WOSR compared with broadcast application.

In the hoe and band-spray scenario, operational cost increased due to the low productivity of the 12-row hoe (2.7 ha h^{-1}), resulting in labor cost rising by 104% (7 € ha^{-1}). These additional costs are not offset by 32 € ha^{-1} in herbicide savings, resulting in an overall weed management cost of 213 € ha^{-1}. A second hoeing pass in fall or early spring, combined with band spraying of Kerb FLO® instead of broadcast application, would increase weed management cost by 9%, due to higher machine costs resulting from more intensive use.

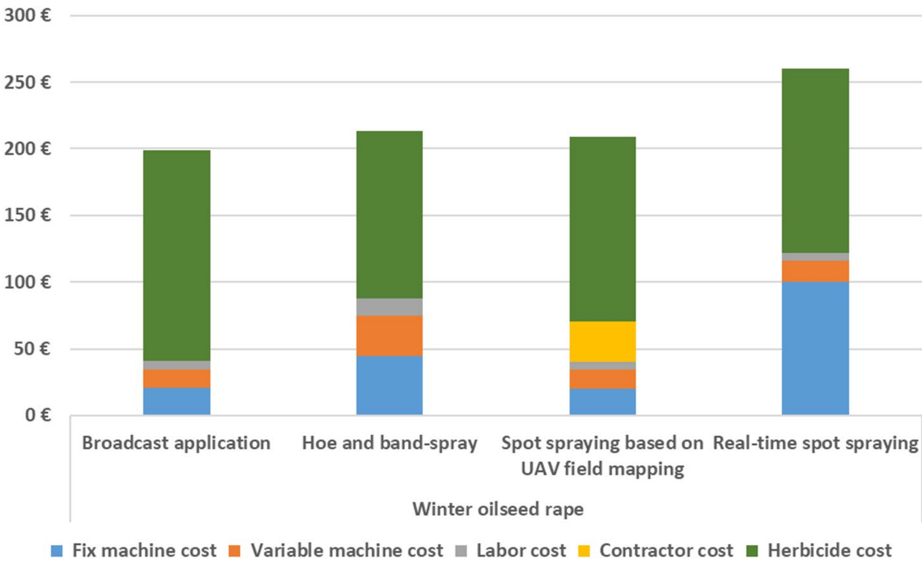

Fig. 2 Cost for weed management in WOSR (€ ha^{-1}) for the different technologies in comparison to broadcast application

In years when Kerb FLO® is not required but a second hoeing pass is performed, weed management costs rise from 145 € ha^{-1} (broadcast application) to 201 € ha^{-1}, representing a 39% increase.

For spot spraying based on UAV field mapping, contractor cost (including drone and mapping services) contributes 30 € ha^{-1}, while herbicide savings amount to 19 € ha^{-1}, leading to weed management costs that are 5% higher than broadcast application. In real-time spot spraying, herbicide savings remain the same, but a high fixed machinery cost (i.e., 100 € ha^{-1} compared with 21 € ha^{-1} for broadcast) significantly reduces its competitiveness, increasing weed management cost by 31%. Since propyzamide is a soil-active ingredient that targets weeds at the pre-emergence or early post-emergence stages, it is not suitable for site-specific application.

Fava beans

The high weed management cost for fava beans of 137 € ha^{-1} for broadcast application is primarily driven by the in-crop application of aclonifen (Table 2). In the hoe plus band-spray scenario, substituting 50% of the in-crop herbicide application with mechanical weed control compensates for the additional machine costs for hoeing, reducing weed management cost by 3 € ha^{-1} (2%) compared with broadcast herbicide spraying.

The potential savings in spot spraying based on UAV field mapping (3% cost increase) and real-time spot spraying (22% cost increase) are limited, as annual grasses require a broadcast application of both soil- and foliar-active ingredients. For this crop, spot spraying based on UAV field mapping and real-time spot spraying are suitable only for site-specific termination of unfrozen cover crops.

Corn silage

Figure 3 shows the weed management cost for corn silage. The necessity to hoe twice in corn raises machine cost and labor cost by more than 500% compared with broadcast application. The 33 € ha^{-1} herbicide cost reduction does not compensate for these additional costs. The second hoeing pass raises overall weed management cost by 41%, rendering the practice economically uncompetitive. For spot spraying based on UAV field mapping, the 46% herbicide cost reduction exceeds contracting services, resulting in a cost advantage of 2 € ha^{-1} compared with the reference technology, thus making this weed control technology the most competitive in corn.

Similar to other crops analyzed so far, the increase in machine cost is the main economic disadvantage of real-time spot spraying. The herbicide saving is equal to spot spraying based on UAV field mapping but the increase in machinery cost results in a weed management cost of 153 € ha^{-1}, an increase of 48% compared with broadcast application.

Farm-level effects

The average weed management cost at the whole-farm level were calculated based on a weighted average, reflecting crop allocation percentages, including both row and non-row crops (Fig. 4). Spot spraying based on UAV field mapping (136 € ha^{-1}) is close to break-even with broadcast application (132 € ha^{-1}).

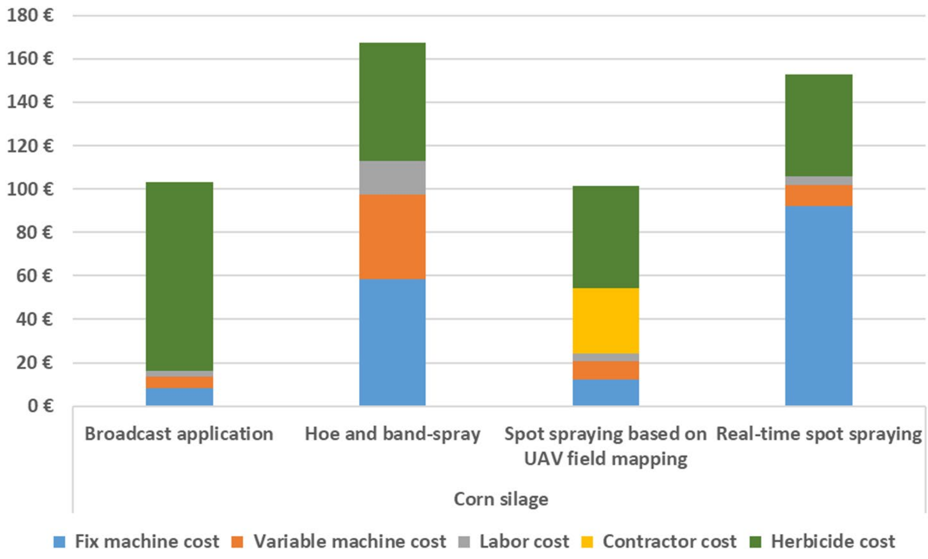

Fig. 3 Cost for weed management in corn silage (€ ha^{-1}) for the different technologies in comparison with broadcast application

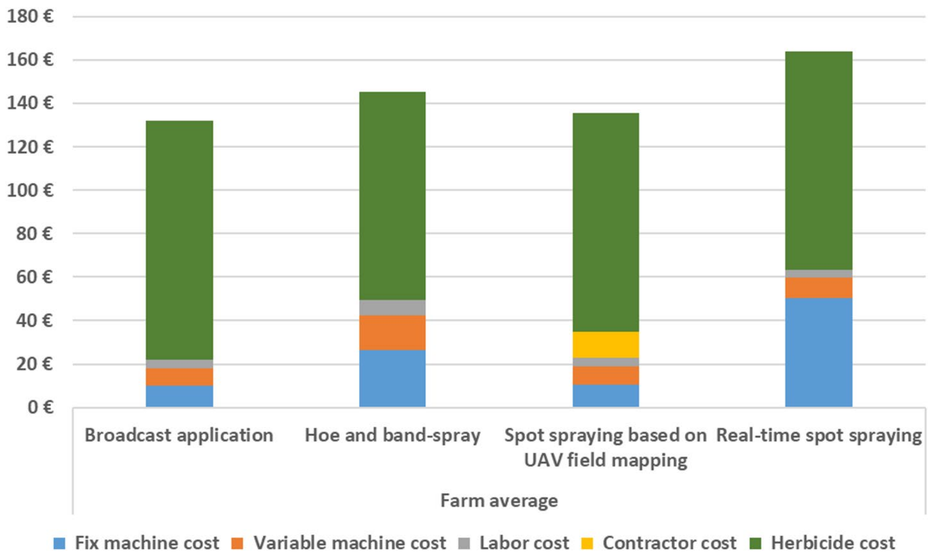

Fig. 4 Cost for weed management for farm average based on weighted crop share (€ ha^{-1}) for the different technologies in comparison to broadcast application

The highest average increase in weed management cost (24%) was observed in the real-time spot spraying scenario (164 € ha^{-1}), which was primarily driven by fixed machinery cost. In contrast, hoe plus band spraying resulted in the second highest cost (145 € ha^{-1}). Hoe and band spraying cost rose to 147 € ha^{-1} if two hoeing passes and band spraying of propyzamide were performed. In a scenario with two hoeing passes and no propyzamide application in WOSR, costs increased by 19% compared with broadcast application without propyzamide, which had a cost of 118 € ha^{-1}.

The results show that while spot spraying based on UAV field mapping and hoe plus band spraying are economically competitive at the individual crop level, their cost-effectiveness diminishes when evaluated across the whole farm. This is primarily due to limited scalability and operational constraints arising from the given crop rotation and the proportion of row crops suitable for treatment with these technologies. In contrast, real-time spot spraying does not achieve economic viability at either the crop level or the farm level under current conditions.

Break-even calculations

To assess the economic viability of each technology, the additional herbicide savings or process cost reductions required for them to be as cost-effective as conventional broadcast application were calculated. Table 5 presents a comparison between the actual herbicide cost savings achieved on a typical farm and the threshold savings needed to reach the break-even point. Additionally, the table includes the required reductions in overall process costs, incorporating herbicide cost, machinery and labor expenses.

For spot spraying based on UAV field mapping to break even, either contractor cost would need to be reduced by 22% or average herbicide savings need to be increased by additional 3%. Hoe plus band spraying achieved a 23% reduction in herbicide cost in row crops, which compensated for the increased annual machinery cost. However, when the associated 10% increase in labor cost resulting from lower operation capacity was accounted for, the herbicide cost reduction in row crops would need to be 39% to be competitive.

In contrast, real-time spot spraying would require a 52% reduction in herbicide cost in row crops (or 30% in total herbicide cost) compared to assumed savings of 15% in row crops. Alternatively, the total annual machinery cost increase would have to be limited to 10,278 € (37%), compared with the current 35,796 € (128%) rise to be competitive against conventional weed management. In an additional scenario, a real-time spot spraying technology purchase price reduction of 50% was assumed; i.e., a 125,000 EUR investment cost. In this case, the cost increase across the whole farm for real-time spot spraying was reduced to an average of 9% (12 € ha^{-1}). However, it remains uncertain whether such a significant cost reduction can be achieved solely through machinery cost adjustments. A balanced distribution of cost reduction requirements between total annual machinery cost and additional herbicide savings in row crops indicates a need for an additional 12% reduction in herbicide cost and a 20% decrease in annual machinery cost.

Table 5 Required cost reductions via herbicide or process cost reduction for break-even compared with broadcast application

Equipment	Total herbicide cost saving (%)	Required herbicide cost saving (%)	Required process cost reduction (%)
Hoe plus band-spray	13	22	9
Spot spraying based on UAV field mapping	8	11	3
Real-time spot spraying	8	30	20

Soil compaction risk and workability

This section presents the results from modeling field working days as well as workability for spraying and hoeing using the SaSCiA model, with particular reference to the timing of operations (Table 1). Figures 5 and 6 illustrate the mean WLCC over the past nine years in comparison to the wheel load exerted by the rear axle (see Table 4). The analysis indicates that the maximum WLCC for spraying is exceeded during February, March and most of April, a period when multiple plant protection applications are typically required, such as herbicide application in WOSR and cover crop termination. Acceptable trafficability is maintained for the remainder of the year. However, the confidence interval indicates an elevated risk of soil compaction within tramlines from November through the end of April, highlighting a critical window of vulnerability for field operations. This is particularly relevant for herbicide applications in WOSR during November.

The analysis of WLCC for hoeing shows that the rear axle load exceeds the maximum WLCC for a shorter duration compared with spraying operations (Fig. 6). This is primarily due to two factors: the hoe's lower overall weight and the reduced rear axle load, resulting from better weight distribution. Specifically, this exceedance occurs from mid-February until early April. The minimal standard error indicates that WLCC is consistently exceeded during early spring, potentially a critical period for hoeing in WOSR. This is particularly relevant, as hoeing involves a significantly larger proportion of trafficked ground compared with spraying, in which soil compaction typically is limited to tramlines. In contrast, from November to early February, the wide spread within the confidence interval suggests that in some individual years the load may also be exceeded, which could pose challenges to hoeing in WOSR in late October. Conversely, hoeing operations during the mid-season (May to October) in fava beans and corn silage pose no significant soil compaction risks on the modeled typical farm.

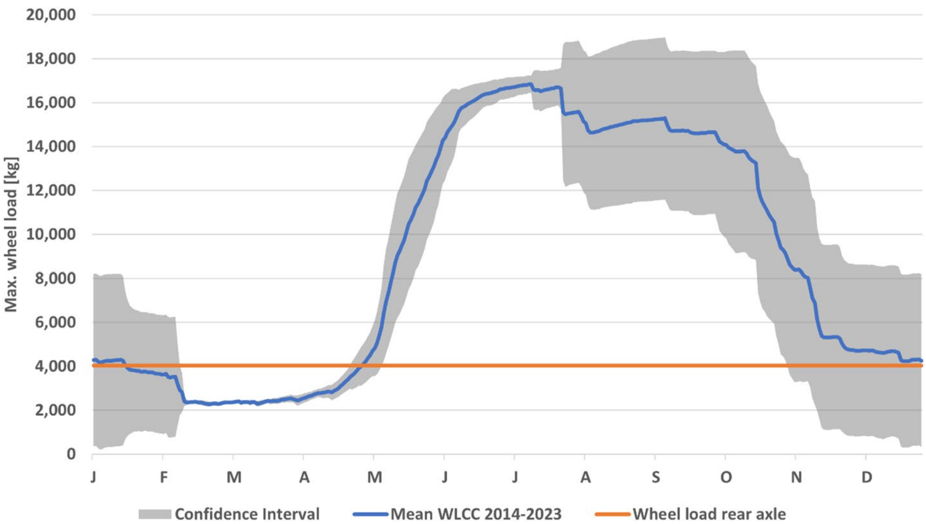

Fig. 5 Mean wheel load carrying capacity (WLCC) for spraying over the past nine years (blue line), including confidence intervals (gray), in comparison to the wheel load at the rear axle for a Pi of 110 kPa (see Table 4) in 0.35 m soil depth

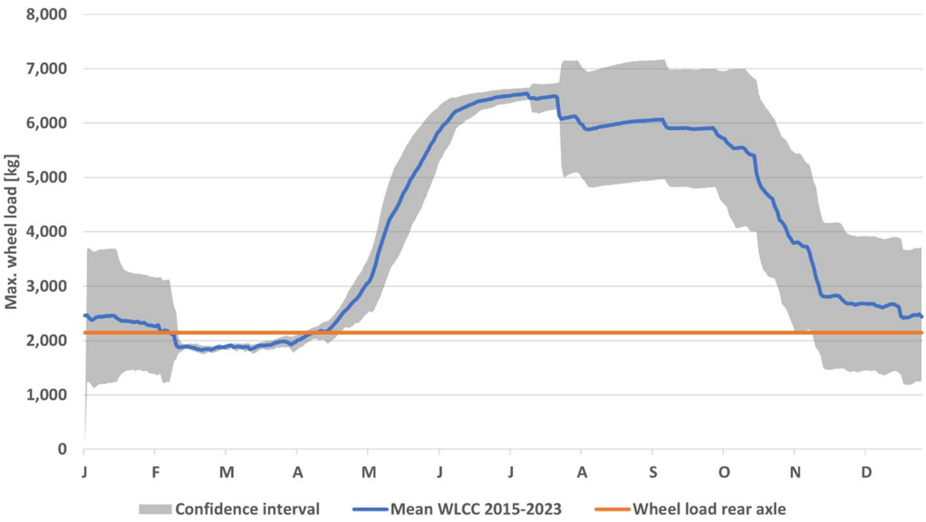

Fig. 6 Mean wheel load carrying capacity (WLCC) for hoeing over the past nine years (blue line), including confidence intervals (gray), in comparison to the wheel load at the rear axle for a Pi of 200 kPa (see Table 4) in 0.35 m soil depth

It is important to note that the values reported refer to the rear axle wheel load in working position, without accounting for the additional downforce due to working the topsoil, likely resulting in a slight underestimation of the actual load on the rear axle during field operation. The wheel load of the rear axle increases in the headland when the hoe is lifted for turning maneuvers (Appendix 3).

On average, the results for workability indicate that the upper threshold of 85% to 90% field capacity for the analyzed soil type is exceeded between mid-October and mid-April. As illustrated in Appendix 4, the modeling results indicate that hoeing generally is not viable until late spring, even when compaction risk is low, due to high moisture levels in the topsoil. This significantly limits the effectiveness of mechanical weed control in WOSR. However, during the key periods for summer crop hoeing, soil conditions appear favorable. Despite annual variations, soil moisture remains a significant constraint in spring and fall, particularly during the critical periods for WOSR hoeing.

Discussion

This study evaluated the feasibility, operational cost and direct cost of hoe plus band spraying, spot spraying based on UAV field mapping and real-time spot spraying by analyzing changes in machinery cost and herbicide savings based on a typical farm in Western Pomerania. These results were compared to broadcast herbicide spraying, which was considered the status quo weed control strategy. As yield increases were not considered, the focus was on process cost, factoring in farm size, crop rotation and the production system. Investment cost and regional data on applied plant protection products were examined. The results show that, under current assumptions, none of the analyzed technologies has a significant competitive advantage in weed management cost over broadcast application. At the farm level, the contractor cost for spot spraying based on UAV field mapping exceeded herbicide savings. Additional costs for hoe and band spraying and real-time spot spraying are not compensated by the estimated herbicide savings in the given production system and crop rotation.

Differentiation of model approaches

The assessment of the potential savings of plant protection products and potential agronomic effects associated with the use of a novel technology for SSWM could be achieved in different ways. Traditional field trials long have been a cornerstone of evaluating plant protection technologies, but on-farm research has emerged as a valuable alternative, enabling localized insights under real-world conditions (Bullock et al., 2019; Alesso et al., 2021; Gerhards et al., 2022). Hence, several approaches have been employed to analyze a range of technologies in diverse contexts ranging from individual crop analysis to crop rotation-based assessments (Gerhards & Christensen, 2003; Ritter et al., 2008; Gutjahr et al., 2012; Kunz et al., 2015; Rajmis et al., 2022; Spaeth et al., 2024). However, a critical limitation of field trials and on-farm research is their cost, time demand and ex-post perspective. This study addressed these limitations by employing the typical farm approach, which integrates regionalized data, enabling more generalized and transferable ex-ante findings across similar agroclimatic contexts, production systems and farm structures (Rajmis et al., 2022; Walther et al., 2022; Dehler, 2023).

Despite its strengths, the typical farm approach requires detailed data on plant protection practices for the presented analysis, including the applicability of herbicides for site-specific use and therefore, to a certain degree, is dependent on field trials in comparable agroclimatic conditions and relevant crops. This study overcame these challenges by consulting regional experts and validating plant protection assumptions. However, future applications of this methodology could benefit from incorporating comprehensive databases on regional plant protection programs to enhance accuracy and comparability.

The integration of the SaSCiA model for assessing soil compaction risk added valuable context to the economic evaluation presented in this study by linking technological feasibility to agroecological principles. The model enabled comparison of working days across different technologies, considering both the timing of operations during the season and capacity needed. Much like the typical farm model, soil compaction risks can be analyzed accurately only on a regional scale to yield feasible results. The WLCC serves as a reliable reference for assessing trafficability (Gut et al., 2015). Notably, the analysis was influenced by the 2018 drought, which resulted in anomalously high soil-bearing capacities in early 2019 (Zscheischler & Fischer, 2020). Given that droughts are increasingly frequent and impactful in German crop production(Schmitt et al., 2022), their inclusion reflects realistic boundary conditions for modeling future scenarios.

The modeling outcomes indicate that, even under current practices within the case study farm's production system, irreversible soil compaction in tramlines is a tangible risk—particularly during early-season herbicide applications in WOSR. This reinforces the need to consider agroclimatic constraints alongside economic factors when evaluating the adoption of alternative weed management technologies.

Although the compaction risk associated with hoeing may have been underestimated due to not factoring in additional downforce during hoeing, the findings remain consistent with prior work by Peters (2023), who identified pronounced constraints in field accessibility and workability for mechanical weed control in WOSR. These results highlight that trafficability, while crucial, is only one of several limiting factors in the practical implementation of mechanical weed control. The results suggest that workability thresholds are exceeded between mid-October and mid-April, restricting hoeing operations until late spring, even when trafficability technically could be achieved. This further complicates the application of hoeing in WOSR, particularly during critical weed control periods. Agronomic variables such as optimal soil moisture levels, weed growth stages and overall system compatibility also play critical roles in determining the effectiveness of hoeing across different crops and time windows (Weimar-Bosse et al., 2018; Hussain et al., 2018; Zimdahl, 2018).

Thus, an analysis based solely on trafficability provides an incomplete picture of hoeing feasibility. Future research is needed to address two key aspects: (a) in-field wheel loads, including the effects of downforce and (b) the effectiveness of mechanical weed control during critical periods, considering additional factors such as crop growth stage and weed pressure. According to Weimar-Bosse et al. (2018), these parameters significantly influence the applicability of hoeing and should be examined through regional, multi-year trials to develop robust, context-specific recommendations.

Competitive factors and implications

The economic competitiveness of SSWM technologies is heavily influenced by farm size, crop rotation and the area qualifying for treatment. In this case study, the limited allocation of row crops constrained the economic potential of the analyzed technologies. Another key factor is the proportion of direct cost within weed management and the corresponding cost-saving potential. This is particularly evident in WOSR, in which high direct cost observed in 2023, which aligns with regional statistics (Ziesemer, 2024), amplified cost saving potential. This also underscores the necessity for conducting such analyses in conjunction with regional data concerning crop protection product prices. This is due to the fact that real prices are not only regional but also, to a certain extent, dependent on the negotiating skills of the individual farmer. However, as the share of direct cost in weed management decreases, the competitiveness of these technologies also declines.

In scenarios in which no additional herbicide is applied to manage resistant grasses in WOSR (i.e., no Kerb FLO®), single hoeing costs are 9% higher at the crop level compared with broadcast application. However, when two hoeing passes are required, the cost-effectiveness of hoe plus band spray diminishes significantly. This is due to a shift in the balance between direct and operating costs, resulting in a total cost increase of 39%. For real-time spot spraying, the same scenario (no additional herbicide use for managing resistant grasses) results in a 43% increase in weed management cost due to the lower share of direct cost in the overall weed management cost. At both the crop and farm levels, the high share of direct costs in overall weed management – and its impact on competitiveness – highlights the need for a regional plant protection program tailored to local conditions. Literature indicates that, in some years, spot spraying can achieve herbicide savings of up to 90%, which could substantially alter the economic outcome and potentially outperform broadcast application (Spaeth et al., 2024; Timmermann et al., 2003; Gutjahr et al., 2012; Wiles, 2009; Allmendinger et al., 2022). This variability underscores the critical influence of regional weed pressure on the economic performance of these technologies.

Furthermore, a change in crop rotation and a shift toward high-herbicide-cost crops like sugar beet could enhance returns, making SSWM technologies more viable (Heilmann, 2023b; Ziesemer, 2024). Future research therefore should explore how changes in crop rotation affect weed management costs and farm-level gross margins. It also would be valuable to analyze rotations with a higher share of row crops, in which the added operational costs of SSWM technologies may be justified by higher crop values. Additionally, examining alternative crop rotations in other regions could reveal further use cases for these technologies; for instance, targeted thistle treatment based on UAV generated weed maps.

Policy developments also play a critical role in shaping the economic landscape for these technologies. Potential changes in herbicide prices – for example, driven by policy initiatives such as the Farm to Fork strategy – could significantly affect the economic landscape for these technologies (EC, 2020). Policy instruments such as levies or license systems frequently are debated and could make SSWM technologies more competitive by raising the direct cost for conventional herbicide application (Lamichhane et al., 2016; Möhring et al., 2020; Nielsen et al., 2023). Break-even analyses in this study revealed that spot spraying based on UAV field mapping is close to cost-effectiveness, with potential gains achievable through reduced contractor fees or UAV ownership by the farmer. For real-time spot spraying, however, even a 50% reduction in machinery costs was insufficient to achieve competitiveness, highlighting the need for further technological advancements and market maturation. While UAV-based herbicide application is currently prohibited in broadacre crops within the European Union, it represents a potentially more cost-effective alternative to tractor-mounted spot-spraying systems in regions where such use is permitted. Future research therefore should explore the interplay of evolving policy frameworks, technological innovation and regional regulatory differences to fully assess the economic prospects and adoption pathways of such technologies across diverse agricultural contexts.

For hoeing, aspects such as labor cost, nutrient mineralization and share of trafficked area represent critical factors alongside direct costs. Although it was assumed that the farm's available labor capacity could accommodate the additional hoeing operations, the opportunity costs are not negligible. Mechanical weed control, to a certain degree, could utilize less productive periods in the cropping season due to the high share of winter crops in the crop rotation. Peters (2023) analyzed the nitrogen mineralization potential of hoeing in WOSR over a four-year period and found that, on average, yields remained consistent while oil content increased with a 35% reduction in nitrogen application. Accounting for the direct cost savings from reduced fertilizer use would yield a discount of 119 € ha^{-1} from the process cost of 213 € ha^{-1} for single hoeing or 233 € ha^{-1} for two hoeing passes, based on a nitrogen price of 1.7 € kg^{-1}. However, these findings were not included in the overall farm-level comparison, hence economic estimates were conservative. Additionally, the narrow working width of the hoe will result in an increase in the area of trafficked land during hoeing, which could potentially lead to adverse effects on soil productivity if the WLCC is exceeded during operations in WOSR during the early or late season. These aspects, along with the effectiveness of hoeing in early spring and fall, should be further explored in future studies. Moreover, the underlying principles could be extended to grain crops by analyzing harrow-based systems instead of hoeing.

While this approach allows for a focused economic comparison of weed control technologies, it does not account for potential positive or negative yield effects that may arise from changes in field operations. For instance, increased soil compaction due to additional machinery passes could lead to yield penalties, as discussed by Stoessel et al. (2018). Conversely, reductions in herbicide use may improve crop performance in certain cases. Future research therefore should aim to incorporate yield variability and agronomic responses to better capture the full impact of site-specific weed management technologies at both crop and farm level.

Conclusions

The aim of this study was to conduct an ex-ante assessment of the feasibility and economics of three weed management technologies – spot spraying based on UAV field mapping, real-time spot spraying and hoe plus band spraying – on a typical arable farm in Western Pomerania, northeastern Germany. By focusing on whole-farm implications rather than crop-specific effects, this research advances the understanding of site-specific weed management technologies in the context of integrated farm systems. The scenario calculations incorporated investment and service provider costs, with assumptions on herbicide savings validated through expert consultations and tailored to region-specific weed pressure and resistance dynamics.

This study makes a significant contribution by demonstrating the critical role of region-specific data in evaluating plant protection technologies, particularly for site-specific weed management. The findings emphasize that economic competitiveness depends not only on crop-level savings but also on farm-level variables such as farm structure, crop rotation, herbicide requirements and weed pressure. The study also demonstrates that the analysis of practice change cannot be confined to economic factors. Additionally, the study underscores the value of the typical farm approach as a robust framework for assessing the competitiveness of emerging technologies relative to current practices, enabling meaningful cross-regional comparisons and context-specific evaluations.

Future research should aim to refine these results by gathering more granular, field-level data on herbicide savings and weed management requirements across different regions. Expanding the scope by adapting the crop rotation to include additional crops such as sugar beet, which are able to absorb more considerable herbicide costs due to their high market value, could enhance the applicability of these technologies in the analyzed typical farm. Furthermore, analyzing regions with a higher proportion of row crops may uncover additional economic advantages. Cross-regional studies applying the typical farm approach could provide further insights into how varying agroclimatic conditions, farm characteristics and crop rotations influence the feasibility and economic viability of site-specific weed management technologies.

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Data availability The datasets generated and analyzed during this study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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Authors and Affiliations

Jannik Aaron Dresemann[1,2] · Leon Ranscht[2] · Michael Kuhwald[3,4] · Marco Lorenz[4]

✉ Jannik Aaron Dresemann
jannik.dresemann@thuenen.de

1 Thünen Institute of Farm Economics, Bundesallee 63, 38116 Braunschweig, Germany

2 agri benchmark Cash Crop, Bundesallee 63, 38116 Braunschweig, Germany

3 Department of Geography, Landscape Ecology and Geoinformation Science, Kiel University, Ludewig-Meyn-Str. 14, 24118 Kiel, Germany

4 Thünen Institute of Agricultural Technology, Bundesallee 47, 38116 Braunschweig, Germany