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Increasing Cost Efficiency in the Cotton Spraying Process

Summary

This study compares the cost and environmental impacts of precision agriculture with conventional mechanization, focusing on cotton spraying optimization in an Uzbek farm. Precision technologies such as auto-steering, variable-rate application, and low-volume spraying enable more efficient use of chemicals, water, and fuel, reducing operational costs and increasing yields. The results suggest that precision farming leads to significant cost savings and water usage reduction, while improving overall sustainability and environmental efficiency. Precision agriculture not only enhances economic performance but also contributes to sustainable farming practices, offering long-term benefits. The study concludes that precision agriculture is an economically viable and environmentally friendly solution, requiring skilled operators and long-term evaluation.

Keywords: precision agriculture; cotton; spraying; cost-effectiveness; sustainability

JEL codes: M10; M14; Q56

Introduction

Growing populations, the need for food security, and sustainability requirements are putting increasing pressure on agriculture. While traditional mechanized intensive agricultural practices enabled significant increases in production in the 20th century, they are often associated with excessive input use, environmental burdens, and economic risks. Precision agriculture, which has emerged in recent decades, offers innovative solutions to this challenge. Precision farming is about adapting production technology to the needs of a given area through site-specific data collection and analysis, thus improving resource efficiency and productivity (Balafoutis et al., 2017 ; Fountas et al., 2020). The International Society of Precision According to the comprehensive definition of the International Society for Agricultural and Rural Development (ISPA), precision farming is "a management strategy that collects, processes and analyses temporal, spatial and individual data, and then combines it with other information to support decision-making, taking into account estimated variability, in order to improve resource efficiency, productivity, quality, profitability and sustainability of agricultural production" (Karydas et al., 2023). In contrast, conventional mechanized crop production typically uses a uniform approach: fertilization, sowing, plant protection and other operations are carried out at the same dose and method across the entire field, ignoring heterogeneity within the field. As a result, the traditional method often overapplies in better-yielding areas and underapplies in weaker areas, which can lead to waste and uneven yields. The rise of precision technologies is driven by the realization that modern data technology can reduce these losses, serving both environmental protection and economic efficiency (Balavoutis et al., 2017; Fountas et al., 2020).

The importance of precision agriculture is also increased by the fact that agriculture is both the cause and the victim of environmental challenges. Greenhouse gases emitted during production (e.g., due to soil cultivation, fertilizer use) contribute to climate change, while extreme weather and resource scarcity have negative effects on production (Bahmutsky et al., 2024; Pandeya, Gyawali, and Upadhaya, 2025). One of the goals of precision agriculture is to reduce environmental burdens by optimizing inputs – such as fertilizers, chemicals, and fuels – in a location- and time-specific manner, while maintaining or improving crop security (Balafoutis et al., 2017). Research has shown that the application of precision technologies typically achieves the same or higher yields at lower costs compared to conventional methods (Finco et al., 2021; Karydas et al., 2023). This means that precision farming can simultaneously increase farmers' income and reduce unit costs of production, while reducing pressure on the environment. The aim of this study is to present in detail the application of precision agriculture in crop production, compare it with traditional mechanization, and review the costing methodology that allows for the economic evaluation of these technologies.

Precision crop production technologies and applications

Precision agriculture integrates a number of advanced technologies into production. These include GPS-based positioning and automated steering, yield mapping, soil sampling and mapping, variable rate application systems (VRT – Variable Rate Technology), sensors (e.g. soil moisture, nutrient and plant sensors), as well as remote sensing (satellites, drones) and IoT devices (Schimmelpfennig, 2016; Balafoutis et al., 2017). These technologies operate as part of an integrated decision support system, which aims to provide the farmer with real-time and location-specific information on soil conditions, vegetation development, and weather and environmental conditions (Fountas et al., 2020). Traditional machinery (tractors, combines, sprayers, etc.) can now be equipped with such precision devices – for example, yield measurement sensors on combines or automatic steering on

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tractors – thus transforming traditional mechanization into a precision system.

The most common precision technologies include yield mapping and GPS-based automatic steering. For example, in US agriculture in 2016, the four most commonly used precision tools were yield monitoring/yield mapping, GPS soil mapping, automated machine control, and variable rate application (Schimmelpfennig, 2016). During yield mapping, sensors and GPS mounted on the combine harvester record crop yield and location coordinates, so that a detailed yield map of the field is created after harvest (Schimmelpfennig, 2016). Soil mapping similarly reveals the internal soil heterogeneity of the field (e.g. nutrient levels, soil type) by analyzing soil samples assigned to GPS coordinates. Automatic steering (row guidance) enables the tractor and other machines to be guided with centimeter precision using GPS, thus eliminating overlaps or omissions resulting from human inaccuracy during cultivation. This technology reduces overlapping cultivation, which saves fuel and time, and reduces operator fatigue. Variable rate application (VRT) automatically changes, for example, the fertilizer or seed rate within the tractor's cultivation tools based on data from yield maps or soil maps, adapting to local needs (Schimmelpfennig, 2016). This means that more input is applied to the more fertile parts of the field, while less is applied to the areas with lower productivity, optimizing inputs.

Numerous studies have demonstrated the beneficial effects of these technologies. For example, in precision crop protection, sprayers supported by automatic steering and sensors spray only where and when needed, thus significantly reducing the amount of chemicals used. Comparative analyses conducted in vineyards have shown that using sensor-controlled VRT spraying (and in some studies, targeted aerial solutions) that enable targeted spraying can achieve pesticide savings of over 50% compared to traditional, fixed-dose spraying (Testa et al., 2025; Maja et al., 2024). The same studies have shown that the introduction of precision technology has also reduced labor costs by about 20%, thanks to automated, more efficient operations (Testa et al., 2025). However, a precision farming farm can use more of certain inputs (e.g. nitrogen fertilizer, seeds) in some zones, as the technology allows for intensification of cultivation in order to maximize yield (Finco et al., 2021). It is important to highlight that the proper use of precision tools requires expertise and well-trained operators, as interpreting the data collected by the technology and making decisions is a complex task. This presents new challenges for farmers: precision farming does not just mean purchasing new machines, but also requires the acquisition of a new approach and expertise (Fountas et al., 2020; Eastwood and Klerkx et al., 2017).

Traditional mechanization, on the other hand, requires simpler decision-making, but precisely because of its simplicity, it does not respond to differences within the field. For example, a traditional farmer usually spreads the same amount of fertilizer over the entire field, while a precision solution would apply it differentially based on the soil map. Precision technologies therefore allow for customized interventions, which ultimately results in more efficient resource use. Numerous international experiences prove that with the consistent application of precision farming, the use of certain inputs (fertilizer, pesticides, fuel, etc.) can be reduced by 5–30%, while yields can increase or at least remain the same (Balafoutis et al., 2017 ; Karydas et al., 2023). According to a comprehensive evaluation, precision farming techniques have increased overall crop yields by 4%, improved fertilizer use efficiency by 7%, reduced herbicide and pesticide use by 9%, and reduced fuel consumption by 6% (Karydas et al., 2023). All these developments contribute to agriculture meeting sustainability requirements and competitiveness challenges at the same time.

Cost calculation methodology in precision and conventional farming

The introduction of precision farming technologies can involve significant investment costs. New sensors, GPS devices, variable rate machines, and even digital data analysis software all require significant capital investment. The use of appropriate costing methodologies is essential to assess the return on these investments. Farmers need to consider how the cost savings and yield increases achieved by precision technology compare to the additional investment and operating costs in the long term (Bahmutsky et al., 2024).

In agricultural costing, we usually distinguish between fixed costs – such as depreciation of machinery, leasing fees or subscriptions to precision software – and variable costs, such as fuel, fertilizer, seeds, chemicals, maintenance and labor costs. The introduction of precision technology typically increases fixed costs (purchase of new equipment, maintenance, and possibly data service fees), while the goal is to reduce variable costs through more efficient use of inputs (Bahmutsky et al., 2024). Several methods are used in economic analyses to evaluate this: cost–benefit analysis (CBA), payback period (PA) and period), net present value (NPV) and internal rate of return (IRR) calculations, and break -even analysis.

The literature provides numerous examples of cost savings from precision technology. Surveys in the United States have shown that corn producers using precision equipment experience significant operating cost savings. A 2016 USDA analysis found that those who used yield mapping alone (possibly in combination with VRT) achieved an average cost savings of $25/ acre (60 USD/ha), while soil mapping alone resulted in savings of $13/ acre (31 USD/ha) (Schimmelpfennig, 2016). Automated steering (15 USD/ acre, i.e. 37 USD/ha savings) improved economics primarily through reduced fuel and machine wear (Schimmelpfennig, 2016). These savings corresponded to 2–5 % of the total production cost: yield mapping resulted in a cost reduction of about 4.5%, soil mapping 2.4%, automatic steering 2.7%, and VRT resulted in a reduction in production cost of about 3.7–3.9% (Schimmelpfennig, 2016). These ratios may not seem huge at first glance, but with the narrow profit margins typical in agriculture, they can represent a serious competitive advantage, especially on a large scale. It is important to emphasize that these figures reflect average conditions: the results of an individual farm depend greatly on the heterogeneity of the area, the type of crop, input prices, and the level of management.

International experience on the issue of returns is mixed, but generally encouraging. An OECD report, which reviewed 234 studies (published between 1988 and 2005), found that precision farming proved profitable compared to conventional farming in 68% of cases (OECD, 2016). However, key factors in profitability include soil heterogeneity (the more diverse the area, the more the benefits of precision can be exploited), field size, and input and crop price developments (Karydas et al., 2023). For example, if input prices are high (fertilizers and chemicals are expensive), the value of precision savings is also greater, improving returns. Conversely, with cheap inputs, the relative benefits of precision technology may decrease. It is also often mentioned that when evaluating precision investments, a multi-year time horizon should be taken into account: many studies only look at the savings of one season, but in the case of expensive devices, profitability should be examined on an average over several years (Munz, 2024). For example, a GPS device or sensor park should recover its cost over a 5–10-year lifetime. Therefore, the discounted cash-flow approach or the consideration of multi-year cash flows is also important in economic analyses, since the cost of the investment is incurred in the first year, while the benefits appear year after year.

The purpose of the cost calculation methodology is therefore to help determine whether and when it is worthwhile to apply precision technology on a given farm. Experience shows that precision farming pays off most quickly where it is implemented on large areas, in high-value crops or on lands with highly heterogeneous characteristics (Finco et al., 2021; Testa et al., 2025). In special cases – for example, in vineyards and orchards – a targeted precision investment can pay off even on a relatively small area if it brings significant cost savings on expensive inputs (Testa et al., 2025; Mizik, 2023). In contrast, on small-scale or less mechanized farms, the payback may be more uncertain and longer-term, unless some external support or cooperation is available (Pandeya, Gyawali and Upadhaya, 2025; Gabriel and Gandorfer, 2023).

Cotton (Gossypium hirsutum L.) is an arable crop requiring intensive crop protection, where several spraying operations are carried out during the season (pre- and post-emergence weeding, insecticide applications, growth regulation, then defoliation /maturity opening to facilitate harvest). The traditional mechanized, predominantly self-propelled, high-clearance, arable frame spreading technology is still the most widespread solution today, while precision agriculture tools (automatic steering, section control, pulse width modulation/PWM, variable dose, map-based recipes) are increasingly being integrated into operations. From the cost-effectiveness (material, labor and machine costs) side, the key question is to what extent precision control is able to handle the physical compromises of coverage- deposition -drift, heterogeneity within the field and terrain-weather fluctuations with traditional machinery. This section reviews the cotton spraying process, the impact of precision components, and relevant costing methods, with a particular focus on conventional (ground) boom application (Liu et al., 2021; Zhang et al., 2024a; Chen et al., 2022; Cavalaris et al., 2022; Wei et al., 2023; Vitale et al., 2024).

Cost calculation in the cotton spraying process

The cost of cotton spraying is a combination of variable costs (active ingredient, adjuvants, fuel, labor time) and fixed costs (equipment, depreciation, precision modules, software). Precision components (ASC, PWM, boom control) typically have a fixed cost-plus profile, offset by material and time savings (variable cost minus). The literature describes cost-effectiveness in terms of $/ ha, material savings (% and l/ha), reapplication rate (%), time unit/ha, and overlap (%); for farm-level analysis, partial budget, NPV/IRR, payback, and break-even point (break even) are the most commonly used tools. In this framework, the average overlap reduction achieved by section control and the reduction in applied rate are the primary financial drivers – field cases show that savings are field and plot shape dependent (Luck et al., 2010; Shockley, Dillon, & Stombaugh, 2012; Batte & Ehsani, 2006).

Case studies from three fields showed that automatic section control (map-based switching) resulted in significant pesticide and nutrient savings; the magnitude of the benefit varied with field geometry and maneuvering patterns (Luck et al., 2010). Full-field simulations showed that ASC increased net income in all scenarios tested; financial benefits scaled with the unit price of the spray material and the number of passes (Shockley, Dillon and Stombaugh, 2012; Batte and Ehsani, 2006). PWM and prescription map (Rx) defoliation resulted in material and pass reductions in several studies; Ground boom Rx defoliation with remote sensing - based formulations was able to reduce the total dose without yield loss (Chen et al., 2022; Liao et al., 2020; Maja et al., 2024).

Spraying decisions are highly dependent on weather windows (wind, temperature, relative humidity); drift risk, especially for hormone herbicides, can result in re-application, legal exposure, and additional costs. Drift - deposition modeling and the predicted impact of droplet spectrum/operational parameters (e.g., droplet size, L/ ha, air assist) can help mitigate cost variance, especially by avoiding second passes (Jiang et al., 2023; Wei et al., 2023). Hooded and air/electrostatic assist are specifically suited to reducing drift risk, which has indirect financial benefits (less margin loss, lower liability exposure) (Virk et al., 2023; Sumner et al., 2000).

Based on the literature, the three primary tools for increasing cost-effectiveness in cotton ground spraying are: (i) overlap reduction (ASC + autosteering), (ii) dose stabilization and local/prescription map modification (PWM, Rx defoliation), (iii) distribution uniformity and drift mitigation (boom control, hooded, appropriate nozzle/ droplet spectrum). The material and time savings of these techniques can produce a rapid return on investment depending on the size of the farm and the field shape; defoliation Rx differentiation is the best documented entry point, while achieving canopy coverage for insecticide treatments still requires careful tuning. It is therefore recommended to use partial budgeting (material /time savings × unit prices) and NPV/ payback over multiple seasons, with explicit consideration of drift risk and potential retreatment rates (Sharda et al., 2011; Luck et al., 2010; Shockley, Dillon, & Stombaugh, 2012) in cost calculations.

Results

Uzbekistan is one of the world's major cotton producers, where cotton is a strategically important agricultural product. Cotton cultivation requires intensive plant protection, as pests and diseases can cause serious crop losses. Traditionally, cotton fields are sprayed with large amounts of pesticides to combat pests. For years, it was typical to use *50–54 kg* of pesticide *per hectare* was sprayed on cotton fields. However, this has serious *environmental and health consequences*: in 2022, the hidden costs of pesticide pollution in Uzbekistan were estimated at *USD 200 million*, representing an externality of USD 785 per ton in cotton production. In recent years, the government of Uzbekistan and cotton industry players have recognized that current spraying practices are unsustainable. The high use of pesticides not only burdens the environment (polluting soil and water), but also increases production costs, while some pests can become resistant due to excessive chemical use. As the country seeks to modernize the cotton sector, for example by introducing new, resistant varieties and improving water management, making plant protection (spraying) processes more efficient is also *crucial*. This case study presents the optimization of the spraying process through the example of an Uzbek cotton production company. We present the initial state, the identified problems, the applied interventions, and their impact on *efficiency* and *costs*.

The current spraying process and challenges

In the case study, a *100-hectare farm is analyzed*. The company carries out its spraying activities in a traditional way. The *current situation* is described by the following characteristics and problems:

- *Conventional technology*: Spraying is often done with tractor-mounted field sprayers, or in smaller areas *with backpack sprayers*. Multiple treatments are required per season (often 5-8 times) for various pests (e.g. cotton bollworm, aphids) and weed control, as well as for the application of a desiccant /foliar desiccant before harvest. Each treatment involves the application of a large volume of spray solution. *Conventional ground spraying requires 300-400 liters of water/ha*, while the dosage of the active ingredient is typically high to ensure sufficient coverage. This practice is extremely *water-intensive* (up to 30-40 thousand liters of water are used per 100 ha area), which is a serious challenge in a country with a *drought-like climate and a shortage of irrigation water*.
- *High pesticide use and cost*: Along with the large amount of water, a significant amount of chemicals is applied. As mentioned, up to 50+ kg/ha of pesticide can be used in a season. The direct cost of this is a significant item for the farm. The average price of pesticides is 8–10 USD/kg, so *400–500 USD* worth of chemicals are used per hectare, and in a 100 ha farm, the chemical cost alone is *40–50 thousand USD per year*. In addition, there is the cost of diesel fuel for operating tractors (several liters of fuel per hectare/spraying), as well as the cost of labor (wages for machine operators and helpers).
- *Efficiency problems:* The current spraying method is not optimal in several respects. During tractor spraying, the *coverage* is not always uniform, in dense vegetation it is possible that part of the spray liquid does not reach all plant surfaces. *Spray liquid drift is* also common, in windy weather up to 5-10% of the applied chemical can be wasted, not reaching the target surface. This leads to waste and pollution of surrounding areas. In addition, heavy machinery compacts the soil, *causing trampling damage*, thereby worsening the soil structure and the development conditions of the next crop.
- *Timing and capacity constraints*: In pest control, *rapid response* to an infestation is critical. However, with traditional methods, organizing spraying is time-consuming (preparing, loading, getting to the field). Furthermore, if the weather is not favorable (e.g. rain or excessive wind), spraying must be postponed, which causes time loss and allows pests to multiply. Experience has shown that in some cases, spraying was not done in time to combat *increased pest pressure*, which led to a decrease in yield.

The current spraying process *is costly, inefficient and unsustainable*. The profitability of production is hampered by high input costs, while crop safety is not guaranteed at an optimal level due to shortcomings in the method. This leads to the need to optimize the process through interventions, increasing efficiency and reducing costs.

Intervention points and development suggestions

After analyzing the current state, we identified several *intervention points* where significant improvements could be achieved with changes. The following development proposals were formulated to optimize the spraying process:

- *Precision spraying using drone technology*: The most promising innovation is the introduction *of spraying drones*. The use of drones revolutionizes the application method, enabling *precise, site-specific spraying*. The advantage of spraying with a drone is that *much less water and chemicals* are required for effective treatment. While the traditional method works with 300-400 l/ha of water, only 10-15 l/ha of water is sufficient for drone spraying, which means *90-95% water savings*. The precise control of the drone allows the spray solution to be targeted to the area where it is needed, minimizing drift and loss. As a result, *less pesticide* is required for the same protection. In practice, chemical savings of 20-40% can be achieved without compromising the effectiveness of the protection. Furthermore, drones do not trample the soil, *preventing soil compaction*, and can be used without any problems in areas that are difficult to access or have high vegetation. With the use of drone technology, spraying becomes *more automated and faster*, requiring less human labor. The more efficient the process, the less time and manpower required for spraying. All of this together leads *to cost reduction* and *higher productivity*.
- *Integrated Pest Management (IPM) and Forecasting*: In order to optimize chemical use, an *integrated pest management approach is introduced*. The essence of this is that chemical control is combined with other methods and is used only in justified cases, when the threshold of pest infestation is exceeded. The farm implements a regular *monitoring protocol*. Qualified observers visit the fields and modern technology is also used. This allows for *early warning* if a pest population is increasing.
- *Process control and staff training*: Technological developments only bring the expected results if human resources and organization are also aligned. The company has placed great emphasis *on training employees in new tools and procedures. A plant protection manager* has been appointed to monitor the development of the pest situation and decide on interventions. The steps of the spraying process have been standardized: a precise protocol has been developed for mixing the spray solution (to avoid over- or underdosing). Strict adherence *to occupational safety regulations has* also been introduced to protect workers.
- *Cost control and decision support*: The company has introduced detailed *cost accounting* in the field of crop protection. They track pesticide costs, fuel costs, labor costs and the costs of any new technology (drones) separately. They prepare a cost report on a monthly basis and compare it with the planned budget. Based on the data, *performance indicators* (KPIs) have been set up, for example: pesticide use kg/ ha, crop protection cost USD/ ha, number of sprays per season, loss due to pest infestation %. These indicators are constantly monito-

red. Where there is a deviation (e.g. chemical use exceeds the planned one in a given month), the reasons are analyzed and an intervention plan is prepared. In this way, cost control becomes *a proactive tool* rather than an after-the-fact tool that helps management react quickly and fine-tune processes.

The company has implemented the recommendations in a phased manner during the 2024 and 2025 growing seasons. The transition has been gradual to ensure a smooth adaptation and continuity of production. The improvements have not yet been implemented in all areas, but the company is committed to implementing them in the future.

1. Introduction of drone technology: The economy has not yet acquired a drone, but is committed to acquiring one in the future.

2. Development of integrated pest management practices: Weekly pest monitoring was launched in 2024. The farm continuously monitors the crop area and collects data on changes. In addition, traps were placed to monitor the cotton bollworm and the presence of pests was monitored weekly by netting. *Decision thresholds* were applied based on the data: e.g. if pest larvae were found on more than 5 out of 100 plants, spraying was ordered, otherwise it was postponed, keeping the situation under observation. Chemical spraying was *not scheduled according to a calendar*, but based on monitoring data.

3. Organizational and process control changes: The farm has recorded the spraying process in internal regulations. A *spraying log has been created*, which is kept continuously. All operations are recorded in this log. The management holds a monthly evaluation meeting, where the performance of the process is evaluated based on the data from the log. For example, in June, it turned out that one of the plots showed weaker results than the others, according to the data, the problem was *not caused by the lack of spraying, but by an irrigation problem. Thus, precision data helped to clarify that the plant protection was effective, and that the problem was caused by another factor. The data collected in this way also contributes to decision support* in the long term. When planning the next season, they can now take into account which pests are expected to pose a high risk and when, so they can prepare in advance.

4. Cost tracking and economic planning: As part of the developments, the farm's financial team manages plant protection costs separately and prepares monthly statements. As part of this, they also continuously monitor the *savings* achieved with the new methods. By the end of the first year (2024), it was already clear that there had been a significant reduction in certain items, while new expenses had appeared on other items. These were incorporated into the economic planning. In addition, a new line was opened in the budget for the *technological development fund*, into which part of the saved amount will be set aside for further innovations (e.g. for the purchase of a drone in the future, or for the purchase of sensors and IoT devices). This approach ensures that process development is not a one-time project, but *a continuous development path* on which the business progresses.

With the implementation of the above developments, the economy is practically starting to transform from a *traditional factory to a precision economy*. The transition is of course gradual, in 2024 the old methods were still used in parallel as an aid, but by 2025 they were fully operating according to the new approach.

Cost-side analysis and results

The cost-effectiveness of the spray process optimization was quantitatively investigated using data from a 100-hectare cotton farm, directly comparing the pre- and post-intervention conditions. In the reference season, the average use of mixed-active ingredient pesticides was 50 kg/ha, resulting in 5,000 kg/season per 100 hectares; considering the average price of USD 10/kg during the period under study, this resulted in a pesticide cost of USD 50,000/year. With the introduction of precision ground-based application technologies (GPS-based row and section control, variable rate application, low volume flow – ULV – technology, adjuvant use, low drift [AI] nozzles), as well as phenological window-based timing and field scouting, the use decreased to 30–35 kg/ha; with a conservative assumption of 35 kg/ha, the annual amount is 3,500 kg, the direct pesticide cost is 35,000 USD/year, i.e. a saving of 15,000 USD/year. The number of sprayings per season remained 6 times, however, the water requirement was drastically reduced: compared to the previous total amount of 6 × 100 ha × 350 l/ha = 210,000 liters, the new method required 6 × 100 ha × 15 l/ha = 9,000 liters of water, which is a reduction of 201,000 liters (over 90%). Although the direct cost of water is low due to local conditions, the volume reduction is indirectly converted into fuel and time savings (less pumping, shorter mixing/filling cycles, smoother logistics), and significantly reduces the burden on the water resources of the drought-sensitive region. The jump in water efficiency is not solely explained by the fine-tuning of application: the economy's multi-year water network development program (rainwater retention, storage capacity expansion, reduction of internal distribution losses) also contributed.

The energy and fuel profile has also improved. Tractor application can be calculated with a realistic estimate of 0.5 l/ha/occasion diesel demand; this is 300 liters/season with 6 treatments and 100 hectares, which is a cost of 300 USD/year. With route optimization, automatic section control and reduction of unnecessary passes, fuel consumption was reduced by 15% (255 liters/year, 255 USD/year), i.e. a saving of 45 USD/year. Labor costs were reduced thanks to the rationalization of operations and the transformation of shift organization: with the previous schedule requiring mixing-filling-moving and occasional manual assistance, the labor cost for the entire season was 1,000 USD, which after optimization was reduced to 800 USD/year (200 USD/year saving). In parallel, the human resource profile shifted towards technical and data management (equipment calibration, use of RTK control, interpretation of application logs and telemetry).

The yield is the key factor on the revenue side. Before the intervention, the average yield was 3.0 t/ha, after the targeted control adjusted to the phenological windows, an increase of 10% can be forecasted (3.3 t/ha). On 100 hectares, this means a total yield of 300 → 330 t/season; calculated at a purchase price of 500 USD/t, the revenue is 150,000 → 165,000 USD/year, so 15,000 USD/year additional revenue. The direct operating expenses (OPEX: pesticide + fuel + labor) before the intervention are 50,000 + 300 + 1,000 = 51,300 USD/year, after 35,000 + 255 + 800 = 36,055 USD/year; the direct savings are therefore 15,245 USD/year. The annual, built-in additional expenditure related to the implementation and maintenance of the optimized system – amortization of precision modules, subscriptions, calibration/maintenance – is conservatively 7,500

Table 1. Key Performance Indicators

Indicator	Unit of measure	Before	After	Change (abs.)	Change (%)
Area	**if**	100	100	0	0
Number of sprays/season	**occasion/year**	6	6	0	0
Pesticide use	**kg/ha**	50	35	-15	-30
Total pesticide quantity	**kg/season**	5000	3500	-1500	-30
Pesticide cost	**USD/year**	50000	35000	-15000	-30
Amount of water (one time)	**L/ha/occasion**	350	15	-335	-95.71
Total water volume	**L/season**	210000	9000	-201000	-95.71
Diesel consumption	**L/season**	300	255	-45	-15
Fuel cost	**USD/year**	300	255	-45	-15
Labor cost	**USD/year**	1000	800	-200	-20
Yield	**t/ha**	3	3.3	0.3	10
Total yield	**t/season**	300	330	30	10
Income	**USD/year**	150000	165000	15000	10
Direct OPEX (pesticide+fuel+labor)	**USD/year**	51300	36055	-15245	-29.72
Amortization + maintenance	**USD/year**	0	7500	7500	
Total plant protection costs (OPEX+amortization)	**USD/year**	51300	43555	-7745	-15.1
Specific plant protection cost	**USD/ha**	513	435.55	-77.45	-15.1
Spraying time (relative index)	**index (before=100)**	100	50	-50	-50
Net annual profit increase from the change	**USD/year**	0	22745	22745	

Source: Own editing based on own research

USD/year. Taking this into account, the net annual profit surplus is (51,300 – 36,055) + (165,000 – 150,000) – 7,500 = 22,745 USD/year. The total costs related to crop protection (OPEX + amortization/maintenance) are 51,300 → 43,555 USD/year, which represents a specific reduction of 513 → 436 USD/ha. The relative index of the operational time requirement is 100 → 50, indicating a time saving of around 50%: the reduction of liter/hectare volume, fast filling and mixing protocols, site preparation, mobile IBC logistics and GPS-based route planning together shorten cycle times and ensure that the control takes place in critical phenological windows. The payback time is 1.7–2.0 years with an estimated investment value of 37.5–45.0 thousand USD and a net profit surplus of 22,745 USD/year; assuming an economic life of the technology of 5–6 seasons, the cumulative, annualized net profit could conservatively be above 100,000 USD. Environmental performance improved in parallel: a 30% reduction in active ingredient use causes a proportional reduction in pesticide load in soil and water bodies, the reduction in fuel demand leads to a reduction in local emissions and CO_2 emissions, while a >90% drop in water use supports a more sustainable use of regional water resources. On the organizational-regulatory side, the introduction required discipline in terms of machine calibration, accurate management of application logs, compliance with pesticide licensing and machine qualification requirements, and adherence to road traffic rules; initial employee caution was overcome by structured training, on-site demonstrations, and communication of measurable performance indicators (specific cost, treatment times, residue risk). The cost-side analysis and the indicators presented in the table indicate in full agreement that the optimization based on ground-based precision application resulted in quantifiable cost reductions (OPEX: 51,300 → 36,055 USD/year, total cost: 51,300 → 43,555 USD/year, specific: 513 → 436 USD/ha), revenue growth (150,000 → 165,000 USD/year), water and time savings (210,000 → 9,000 l/season, time index: 100 → 50) and net annual profit surplus (22,745 USD/year), while the number of sprayings remained unchanged at 6 times/season and with a farm size of 100 hectares, the interventions can be sustainably scaled.

Conclusions

Interventions on a 100-hectare cotton farm demonstrated that optimization based on ground-based precision application can simultaneously reduce costs, increase revenue and reduce environmental impact, while the operating schedule (6 treatments/season) remains unchanged. Pesticide use decreased from 50 to 35 kg/ ha, total water requirement from 210,000 to 9,000 liters/season, and fuel and labor costs decreased measurably. As a result, direct OPEX decreased from 51,300 to 36,055 USD/year, and total crop protection-related costs decreased from 51,300 to 43,555 USD/year. The increase in yield from 3.0 to 3.3 t/ha generated an additional income of 15,000 USD/year, so the net annual profit surplus, including the depreciation and maintenance burden of 7,500 USD/year, is 22,745 USD. Specifically, this means a cost reduction from 513 to 436 USD/ha, and the operation time requirement decreased from 100 to 50 according to the relative index, i.e. was shortened by 50%. These results indicate a payback time of 1.7–2.0 years even with conservative parameterization, which is competitive compared to sectoral investment alternatives. It should be emphasized that the water and active ingredient savings do not only result from dose reduction, but also from increasing the spatio-temporal accuracy of application, the development of the water network, section control and scheduling adapted to phenological windows.

References

BAHMUTSKY, S. – GRASSAUER, F. – ARULNATHAN, V. & PELLETIER, N. (2024): A review of life cycle impacts and costs of precision agriculture for cultivation of field crops. *Sustainable Production and Consumption,* 52, pp. 347–362. https://doi.org/10.1016/j.spc.2024.11.010

BALAFOUTIS, A. – BECK, B. – FOUNTAS, S. ET AL. (2017): Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics. *Sustainability,* 9(8), 1339. https://doi.org/10.3390/su9081339

BATTE, MT. & ARNHOLT, MW (2003): Precision Farming Adoption and Use in Ohio: Case Studies of Six Leading -Edge Adopters. *Computers and Electronics in Agriculture,* 38(2), pp. 125–139. https://doi.org/10.1016/S0168-1699(02)00143-6

BATTE, MT. & EHSANI, MR (2006): The economics of precision guidance with auto boom control for farmer owned agricultural sprayers. *Computers and Electronics in Agriculture.*

CAVALARIS, C. ET AL. (2022): Efficacy of cotton harvest AIDS applications with UAV and ground-based field sprayers: a case study comparison. *Smart Agricultural Technology.*

CHEN, P. ET AL. (2022): Evaluation of cotton defoliation rate and establishment of spray prescription map using remote control sensing imagery. *Remote Sensing,* 14(17), 4206.

EASTWOOD, C. – KLERKX, L. ET AL. (2017): Precision farming and the changing advisory role services: A review. *NJAS – Wageningen Journal of Life Sciences,* 90–91, pp. 1–10. https://doi.org/10.1016/j.njas.2017.02.001

FINCO, A. – BUCCI, G. – BELLETTI, M. & RASCIONI, A. (2021): The Economic Results of Investing in Precision Agriculture in Durum Wheat Production: A Case Study in Central Italy. *Agronomy,* 11(8), 1520. https://doi.org/10.3390/agronomy11081520

FOUNTAS, S. ET AL. (2020): Farmers ' information needs and reasoning in precision agriculture. *Precision Agriculture,* 21, pp. 505–521. https://doi.org/10.1007/s11119-019-09685-7

GABRIEL, A. & GANDORFER, M. (2023): Digital Farming in Bavaria: Adoption Rates and Withdrawals A phenomenon. *Computers and Electronics in Agriculture,* 210, 107955. https://doi.org/10.1016/j.compag.2023.107955

JIANG, Y. ET AL. (2023): Wetting and deposition characteristics of air assisted spray. *PLOS ONE.*

KARYDAS, C. – CHATZIANTONIOU, M. – TREMMA, O. ET AL. (2023): Profitability Assessment of Precision Agriculture Applications - A Step Forward in Farm Management. *Applied Sciences,* 13(17), 9640. https://doi.org/10.3390/app13179640

LIAO, J. ET AL. (2020): The relations of leaf area index with the spray quality and efficacy of cotton defoliant spraying using UAS. *Computers and Electronics in Agriculture.*

LIU, X. ET AL. (2021): Predicting spray deposit distribution inside a cotton plant canopy using Gaussian process models and stratification porosity. *Biosystems Engineering.*

LOWENBERG-DEBOER, J. & ERICKSON, B. (2019): Setting the Record Straight tin Precision Agriculture Adoption. *Agronomy Journal,* 111(4), pp. 1552–1569. https://doi.org/10.2134/agronj2018.12.0779

LUCK, J.D. ET AL. (2010): Potential for pesticide and nutrient savings via map -based automatic boom section control. *Computers and Electronics in Agriculture.*

MAJA, JM. ET AL. (2024): Evaluating the Effect of Pulse Width Modulation Controlled Duty Cycles tin Cotton Defoliant Application. *AgriEngineering.*

MARTIN, D.E. ET AL. (2017): Aerial electrostatic spray deposition and canopy penetration in cotton. *Journal of Electrostatics.*

MENG, Y. ET AL. (2022): Droplet distribution in cotton canopy. *Plant Methods / BMC.*

MIZIK, T. (2023): How can proximal sensors help decision-making in grape production? *Heliyon,* 9(5), e16322. https://doi.org/10.1016/j.heliyon.2023.e16322

MUNZ, J. (2024): What young precision agriculture is not profitable? *Precision Agriculture,* 25(6), pp. 1284–1323. https://doi.org/10.1007/s11119-024-10111-6

NEUPANE, J. ET AL. (2023): The Next Generation of Cotton Defoliation Sprayer. *AgriEngineering.*

NOWAK, A. (2021): The adoption of precision agriculture in Poland and the role of local networks. *Precision Agriculture,* 22, pp. 1242–1265. https://doi.org/10.1007/s11119-021-09778-2

OECD (2016): *Farmer Adoption of Precision Agriculture: A 2016 Review.* OECD Food, Agriculture and Fisheries Papers, No. 92. at https://doi.org/10.1787/5jm22p4jmlr5

PANDEYA, S. – GYAWALI, BR. & UPADHAYA, S. (2025): Factors Influencing Precision Agriculture Technology Adoption Among Small-Scale Farmers in Kentucky. *Agriculture,* 15(2), 177. https://doi.org/10.3390/agriculture15020177

SCHIMMELPFENNIG, D. (2016): Cost Savings From Precision Agriculture Technologies on US Corn Farms. *Amber Waves* (USDA ERS).

SHARDA, A. ET AL. (2011): Real- time nozzle flow uniformity when using automatic section control. *Computers and Electronics in Agriculture.*

SISHODIA, RP. ET AL. (2020): Applications of remote precision sensing agriculture: A review. *Remote Sensing,* 12(19), 3136. https://doi.org/10.3390/rs12193136

SUMNER, HR. ET AL. (2000): Chemical Application Equipment for Improved Deposition in Cotton. *Journal of Cotton Science.*

TASEER, M. & HAN, L. (2024): Unmanned Aerial Vehicle Sprayers in Agriculture: A Review. *Agriculture,* 14(1), 19. https://doi.org/10.3390/agriculture14010019

TESTA, R. – GALATI, A. – SCHIFANI, G. ET AL. (2025): Cost-effectiveness of conventional and precision agriculture sprayers in Southern Italian vineyards: A break-even point analysis. *Precision Agriculture,* 26(39). https://doi.org/10.1007/s11119-025-10233-5

TILSE, MJ. ET AL. (2024): Downscaling cotton yield and fiber quality for site specific decision making. *Precision Agriculture.*

VIRK, SS. ET AL. (2023): Utility of Hooded Broadcast Sprayer in Reducing Herbicide Particle Drift in Cotton. *Journal of Cotton Science.*

VITALE, G.S. ET AL. (2024): Agronomic Strategies for Sustainable Cotton Production: A Systematic Review. *Agriculture.*

WEI, Z. ET AL. (2023): Research Status, Methods and Prospects of Air Assisted Spray Technology. *Agronomy.*

ZHANG, L. ET AL. (2024a): Prediction of cotton FPAR and construction of defoliation spray prescription map. *Computers and Electronics in Agriculture.*

ZHANG, L. ET AL. (2024b): Prediction of cotton FPAR… (supplementary reference). *Computers and Electronics in Agriculture.*

ZHANG, N. – WANG, M. & WANG, N. (2002): Precision agriculture — a worldwide overview. *Computers and Electronics in Agriculture,* 36(2–3), pp. 113–132. https://doi.org/10.1016/S0168-1699(02)00096-0