Economic Performance of Robotic Applications in Field Crop Farming: Examples from Four European Case Studies

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Abstract.

This paper presents a cost benefit analysis of robotic applications in field crop farming based on case studies within an EU project called ROBS4CROPS with pilot cases situated in France, Greece, Spain and the Netherlands. The objective of this paper is to enable farmers and interested stakeholders to evaluate the economic performance of robotic systems as compared to conventional practices of using tractors in the respective case study areas.

The economic model adopted a partial budgeting approach with the assumption that management practices and cost structures of other operations are not influenced by the introduction of robotic application for the target operation in the project experiment. The costs and benefits associated with robotic systems were evaluated against existing practices using conventional tractors in the respective case study areas.

The analysis indicates considerable potential for labour saving, and overall cost saving in some of the use cases. However, economic attractiveness of the robotic system used in the Netherlands is limited by narrow working width of the robotic platform used compared to conventional system using tractor mounted wide implements. The study provides an adaptable framework and baseline data to evaluate economic performance of robotic applications considered. The study sheds light into key research, technology design and policy considerations to further develop robotic systems and promote beneficial adoption.

Keywords.
Autonomous system, mechanical weeding, Robs4crops, spraying.

The authors are solely responsible for the content of this paper, which is not a refereed publication. Citation of this work should state that it is from the Proceedings of the 17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture. Tamirat, T.W., Pedersen, S.M. & Ørum, J.E. (2026). Economic Performance of Robotic Applications in Field Crop Farming: Examples from Four European Case Studies. In Proceedings of the 17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture (unpaginated, online). Monticello, IL: International Society of Precision Agriculture and Brazilian Congress on Precision and Digital Agriculture.

1. Introduction

European agriculture is currently undergoing a profound transformation driven by labour shortages, increasing operational costs, climate change, and environmental concerns. Two major challenges are the scarcity and rising cost of agricultural labour and the detrimental effects of soil compaction caused by heavy machinery (Van Evert et al., 2023; Ørum et al., 2023; Lamandé et al., 2018; Piccoli et al., 2022; Tamirat et al., 2022). These problems are compounded by an ageing farming population, declining interest among younger generations in physically demanding farm work and growing societal pressure to reduce the environmental footprint of agricultural production.

Traditional farming systems depend heavily on seasonal labour and large conventional machinery. The COVID-19 pandemic exposed the vulnerability of agricultural systems to disruptions in labour availability, particularly during critical operational periods. Survey evidence from European farmers also shows that labour dependence and soil compaction are among the most important challenges associated with conventional machinery systems (Pedersen et al., 2023). Furthermore, repetitive field operations such as spraying expose workers to harmful chemicals, while extensive machinery traffic contributes to long-term soil degradation.

Autonomous agricultural robots are increasingly viewed as a promising solution to these interconnected challenges (Anastasiou et al., 2025). Smaller and lighter robotic systems may reduce soil compaction while improving operational precision and reducing dependence on manual labour. In addition, autonomous technologies may improve efficiency in the application of pesticides and other agricultural inputs, potentially lowering both costs and environmental impacts. Across the four Robs4Crops pilot studies evaluated in this paper, robotic systems demonstrated labour savings ranging from 20% to 48%, highlighting their potential contribution to addressing labour scarcity while supporting more sustainable agricultural production systems.

Although autonomous systems are gradually entering commercial agriculture, their economic feasibility remains uncertain. Previous studies have demonstrated technical and economic potential, but the financial viability of robotic farming systems depends on multiple factors, including labour costs, farm size, machine utilization, operational efficiency, and technological maturity (Lampridi et al., 2019; Lowenberg-DeBoer et al., 2021; Vahdanjoo et al., 2023). Credible demonstration of socio-economic and environmental costs and benefits under local conditions is vital to unpacking the potential of farming technologies (Pedersen, S. M., Tamirat, T. W., & Erekalo, K. T., 2025); Pedersen, S. M. et al.,2026).

The Robs4Crops project was developed within the European Union's Horizon 2020 research framework to explore the practical implementation of autonomous systems in European farming contexts. The project evaluated robotic systems in four large-scale pilot areas: vineyard weeding in France, spraying operations in Greece and Spain, and sugar beet weeding in the Netherlands. The central objective of the study was to compare the economic and operational performance of robotic systems with conventional tractor-based systems while also examining broader environmental and societal implications.

2. Methodology

2.1 Data Collection

The cost-benefit analysis combined information from several sources, including scientific literature, project reports, expert consultations, machinery suppliers, agronomists, and farmer groups participating in the Robs4Crops pilots. Data collection was coordinated through local pilot managers who provided operational details such as machinery specifications, labour requirements, working speed, fuel consumption, investment costs, and crop management practices.

The University of Copenhagen research team coordinated the economic modelling process. Although direct farmer interviews were limited, continuous interaction with pilot managers and local stakeholders ensured that the assumptions and operational parameters reflected practical farming conditions.

The iterative consultation process played an important role in validating assumptions and revising economic estimates. The analysis therefore reflects both quantitative operational data and qualitative insights from practitioners and technology developers.

2.2 Assumptions

Several assumptions were introduced to standardize comparisons between robotic and conventional systems. First, the study assumed that introducing robotic systems would not alter other farm management practices beyond the target operation being evaluated. Second, crop yield and product quality were assumed to remain unchanged regardless of whether operations were performed by robots or conventional tractors.

Another important assumption concerned machinery utilization. The study assumed that machinery capacity exceeding the requirements of the reference farm could be utilized through additional operations, contracting services, or rental arrangements. This assumption strongly influenced machinery cost calculations and reflects the importance of maximizing annual machinery use.

2.3 Input Data and Operational Parameters

The economic model incorporated a broad range of operational, agronomic, technical, and market-related parameters to evaluate the costs and benefits associated with autonomous and conventional farming systems. Input data included farm characteristics, machinery specifications, operational schedules, labour requirements, transport logistics, investment costs, fuel consumption, pesticide use, and the degree of robot autonomy. Both capital costs and operating costs were considered in the analysis.

The study defined several important operational concepts to standardize comparisons across the pilot regions. One of these was the operation window, which refers to the agronomically acceptable period during which weeding or spraying must be completed to avoid negative effects on crop growth or pest control. In the baseline scenarios, a seven-day operational window was assumed for most applications.

Another important parameter was workable hours per day, which varies according to weather conditions, crop physiology, machinery capacity, and labour availability. In Greece, for example, spraying was often restricted to early morning or late afternoon because high temperatures and wind conditions reduced spraying effectiveness during midday. Autonomous systems were therefore considered advantageous because they could potentially extend operational hours into evenings or nighttime periods.

The analysis also incorporated the concept of extra machinery capacity, defined as the difference between annual available machinery hours and the hours required to complete operations on the reference farm. Extra capacity was assumed to be fully utilized through contracting services, machinery sharing, or use in other farm operations. This assumption significantly affected machinery cost calculations and reflected the importance of maximizing annual machinery utilization.

Substantial differences existed among the pilot regions regarding farm size, field characteristics, machinery configuration, and operational intensity. The France pilot involved vineyard weeding on 45-hectare farms, while Greece and Spain focused on spraying operations in vineyards and orchards. The Dutch pilot evaluated mechanical weeding in sugar beet production. Workable hours per day ranged from 6 hours in the French conventional vineyard weeding case to 12 hours in the Spanish retrofit spraying system and Dutch Robotti system, depending on weather, labour availability, and operational conditions. Similarly, the number of annual operations varied from 3 operations per season in the French vineyard weeding case to 21 operations per season in the Spanish orchard spraying case.

Investment costs included vehicles, implements, sensors, and enabling technologies required for autonomous operation. Conventional tractors generally involved lower investment costs than robotic systems. The robotic packages additionally required sensors, perception units, precision navigation systems, and annual software subscriptions. Training costs for personnel operating robotic systems were also included. Economic life assumptions differed between technologies, with conventional tractors assumed to last 15 years and robotic systems 10 years because of the greater technological sensitivity and relative immaturity of robotic equipment.

Market-related parameters such as labour price, fuel price, water cost, and machinery rental fees differed substantially across countries. Labour costs were highest in the Netherlands and France, while Greece and Spain exhibited lower labour prices. For spraying operations in Greece and Spain, the robotic systems were assumed to reduce pesticide and water use by improving application precision. Pesticide expenditures represented a major share of operational costs, particularly in Greece and Spain. Total pesticide and fertilizer spraying costs under conventional practice were estimated at €2150/ha/year in Corinth, Greece, and €1663/ha/year in Girona, Spain.

Labour use includes direct machine operation, equipment inspection, fuel filling, transport, mounting and dismounting of implements, and supervision of autonomous systems. Although robotic systems reduced direct driving requirements, human supervision and occasional intervention remained necessary. Degrees of autonomy differed among the pilot areas, with assumed autonomous operation levels of 85% in France and the Netherlands, 80% in Spain, and 65% in Greece. Overall, the input data reflected the complexity of real-world agricultural operations and allowed the study to evaluate robotic systems under diverse operational and economic conditions.

Table 1 summarizes the reference farm characteristics, operational parameters, and machinery features used in the analysis across the four pilot regions. The table highlights substantial variation in farm size, working width, working speed, fuel consumption, and workable hours among the robotic and conventional systems. Table 2 presents the investment costs associated with vehicles, implements, sensors, and robotic enabling technologies. The data illustrate the considerably higher upfront investment requirements associated with autonomous systems relative to conventional tractors. Table 3 summarizes the market-related parameters used in the economic model, including labour prices, fuel prices, water prices, and machinery rental rates across the four case-study countries. Table 4 presents pesticide and fertilizer costs under conventional management practices for the French, Greek, and Spanish spraying and weeding cases. The data show that pesticide expenditures constitute a major share of operational costs, particularly in the spraying systems.

Table 1. Reference Farm, Agronomic, and Vehicle/Implement Features by Pilot Region

Feature	France Trac_C mechanical weeding	France CEOL robot mechanical weeding	Greece Trac_C spraying	Greece retrofit spraying	Spain Trac_C spraying	Spain retrofit spraying	Netherlands Trac_C weeding	Netherlands Robotti weeding
Farm size (ha)	45	45	10	10	40	40	30	30
Field size (ha)	5	5	4	4	8	8	6	6
Field-to-field distance (km)	10	10	3	3	5	5	2	2
Field-to-barn distance (km)	10	10	2	2	5	5	2	2
Fuel use, operation	9	4	5.5	5	3	3	8	6

(L/ha)								
Fuel use, transport (L/hour)	10	10	10	10	10	10	8	8
Transport speed (km/h)	25	40	25	40	40	40	40	40
Working speed (km/h)	5.75	4.5	5	4	7	5	5	5
Working width (m)	2	2	2.7	2.7	4	4	6	3
Workable hours per day (h)	8	10	7	9	8	12	8	12
Operations per season	6	6	11	11	21	21	5	5

Note: Trac_C refers to conventional tractor systems. Values are reported exactly as presented in the original study.

Table 2. Investment Data for Vehicle and Implements (€/unit)

Investment item	**France Trac_C mechanical weeding**	**France CEOL robot**	**Greece Trac_C**	**Greece retrofit**	**Spain Trac_C**	**Spain retrofit**	**Netherlands Trac_C**	**Netherlands Robotti**
Vehicle	90000	110000	50000	85000	70000	90000	118000	175000
Sprayer			10000	10000	31000	46000		
Vine weeding implements[1]	13050	13050						
Tine weeder							16665	7280
Hoeing machine							77877	54015
Sensors		10000		11000		11000		10000
Total investment per package	103050	133050	60000	106000	101000	147000	212542	246295

Note: Sensor costs include speed sensors, work-quality sensors, and perception units where applicable. [1]For the French pilot case, weeding implements include Kress fingers, Intervine knives, Serrated discs, and Harrow disc.

Table 3. Market and Operational Parameters by Use-Case Country

Parameter	Unit	France	Greece	Spain	Netherlands
Labour price	€/h	32	20	18	35
Fuel price	€/L	1.4	1.5	1.3	1.35
Van rent for transport, excluding fuel	€/h	3.6	10	10	15
Water price	€/100 L	0.1	0.15	0.19	-
Amount of water for spraying under conventional practice	L/ha	100	800	1000	-
Rent-out fee per hour of conventional machinery	€/h	15	8	15	27
Rent-out fee per hour of robotic system	€/h	25	10	25	35

Table 4. Pesticide Cost under Conventional Practice by Use Case

Product type	Unit	Corinth, Greece: table grape spraying	Girona, Spain: apple orchard spraying
Fungicides	€/ha/year	800	582
Insecticides	€/ha/year	600	582
Fertilizer spraying	€/ha/year	200	83
Growth regulators	€/ha/year	250	333
Other pesticides	€/ha/year	300	83
Total pesticide and fertilizer cost	**€/ha/year**	**2150**	**1663**

2.4 Cost Estimation

The economic analysis divided costs into machinery costs and non-machinery input costs. Machinery costs included investment, depreciation, repair and maintenance, and insurance. Annual repair and maintenance costs were estimated as 2% of vehicle purchase price and 3% of implement purchase price.

Non-machinery costs included labour, fuel, pesticides, water, transportation, and operational software subscriptions required for autonomous functions such as navigation and planning. The analysis also evaluated alternative scenarios involving changes in labour costs, fuel prices, farm size, field size, and transport distances to examine the sensitivity of economic outcomes.

3. Results

The results indicate that economic feasibility varies considerably depending on operational context, crop type, pesticide savings, farm structure, and machinery utilization rates. Among the evaluated cases, the Spanish spraying system showed the strongest economic viability, whereas the Dutch sugar beet weeding case remained less competitive because of lower operational efficiency.

3.1 French Vineyard Weeding Case

The French pilot evaluated the CEOL robot for vineyard mechanical weeding and compared it with conventional tractor-based mechanical weeding systems. The reference farm size was 45 hectares.

Table 5. Machinery Utilization, Labour Use, Fuel Use and Annualized Cost: French Vineyard Weeding Case

Indicator	Unit	Conventional mechanical weeding	Robotic mechanical weeding
Effective field capacity	ha/h	0.805	0.63
Farm area per day	ha/day	6.44	6.3
Scaling farm size	ha	45.08	44.1
Operation hours	h/ha/year	7.5	9.5
Extra machinery capacity	h/year/farm	664.6	371.4
Labour time	h/ha/year	8.5	4.4
Fuel consumption	L/ha/year	75.6	43.5
Annualized private cost of weeding/spraying	€/ha/year	482	525
Annualized extra societal cost ('C02'+'Pesticide')	€/ha/year	21	12

Note: Scaling farm size refers to the farm area that can be served by one vehicle unit during the operation window. Beyond this level, investment in an additional machinery unit is required.

As shown in Table 5, the robotic system demonstrated substantial reductions in labour and fuel use compared with conventional mechanical weeding. Labour requirements decreased by 48%, while fuel consumption was reduced by 42%, consistent with the figures reported in the original study. Although the robot operated at a lower effective field capacity than the conventional tractor, its ability to work for longer hours partially compensated for slower operational speed.

Despite operational advantages, the robotic system involved significantly higher machinery costs. Investment and maintenance costs for the CEOL robot were approximately three times higher than those associated with the conventional tractor system. Nevertheless, reduced labour and fuel requirements generated non-machinery input cost savings of approximately €169/ha/year.

The results suggest that robotic vineyard weeding becomes economically attractive primarily under conditions of high labour costs and improved machinery utilization. In regions where labour shortages are severe, autonomous systems may therefore provide strategic advantages despite high initial investment costs.

3.2 Greek Vineyard Spraying Case

The Greek pilot examined retrofit autonomous tractors for crop protection spraying in vineyards.

Table 6. Machinery Utilization, Labour Use, Fuel Use and Annualized Cost: Greek Spraying Case

Indicator	Unit	Conventional tractor	Retrofit system
Effective field capacity	ha/h	0.95	0.76
Farm area per day	ha/day	6.62	6.80
Scaling farm size	Ha	46	48
Operation hours	h/ha/year	11.64	14.55
Extra machinery capacity	h/year/farm	883.6	854.5
Labour time	h/ha/year	12.69	8.68
Fuel consumption	L/ha/year	69	76
Annualized private cost of weeding/spraying	€/ha/year	2042	1890
Annualized extra societal cost ('C02'+'Pesticide')	€/ha/year	234	204

Table 6 summarizes the operational performance indicators for the Greek spraying case. The retrofit system operated at a lower effective field capacity than the conventional tractor but compensated through longer daily operational hours.

Labour requirements were reduced by 32%, while fuel consumption increased from 69 L/ha/year under the conventional system to 76 L/ha/year under the retrofit system. The economic performance of the robotic system depended heavily on machinery utilization and the possibility of renting out excess machinery capacity.

The study emphasized that labour savings may not constitute the primary motivation for Greek farmers because many farms rely on family labour rather than hired workers. Instead, the potential for reducing pesticide exposure and improving spraying precision may represent stronger incentives for adoption. The Greek case also highlighted the importance of climatic conditions. Autonomous systems capable of operating during cooler evening or nighttime hours may provide substantial operational advantages in regions characterized by high daytime temperatures.

3.3 Spanish Orchard Spraying Case

As shown in Table 7, the retrofit autonomous system used in LSP Spain reduced labour use by 42% while significantly lowering pesticide-related input costs.

Table 7. Machinery Utilization, Labour Use, Fuel Use and Annualized Cost: Spanish Orchard Spraying Case

Indicator	Unit	Conventional tractor	Retrofit system
Effective field capacity	ha/h	1.729	1.33
Farm area per day	ha/day	13.83	15.96
Scaling farm size	Ha	97	112
Operation hours	h/ha/year	12.15	15.79
Extra machinery capacity	h/year/farm	514.17	368.42
Labour time	h/ha/year	13.20	7.66
Fuel consumption	L/ha/year	42	52
Annualized private cost of weeding/spraying	€/ha/year	2155	1903
Annualized extra societal cost ('C02'+'Pesticide')	€/ha/year	178	139

Although machinery costs were substantially higher than those of conventional tractors, the reduction in labour and pesticide costs, including input cost savings of about €502/ha/year, more than compensated for these additional investments. The robotic system generated considerable annual savings in non-machinery inputs, making it economically attractive under both baseline and alternative scenarios.

The Spanish case demonstrated that autonomous spraying systems become particularly viable when pesticide costs represent a large share of total operational expenses. Precision application technologies capable of reducing chemical use therefore play a central role in improving economic performance.

3.4 Dutch Sugar Beet Weeding Case

The Dutch pilot evaluated the Robotti platform for mechanical sugar beet weeding. Compared with conventional tractors, the robotic system exhibited substantially lower operational efficiency due to its narrower working width and slower speed. Table 8 presents the machinery utilization, labour, and fuel indicators for the Dutch sugar beet weeding case. Although labour use decreased by 20%, the robotic system required more operational time and consumed more fuel than the conventional alternative. Machinery costs were almost double those of the tractor-based system.

Table 8. Machinery Utilization, Labour Use, Fuel Use and Annualized Cost: Dutch Sugar Beet Weeding Case

Indicator	Unit	Conventional tractor	Robotti
Effective field capacity	ha/h	2.4	1.2
Farm area per day	ha/day	19.20	14.40
Scaling farm size	ha	134	101
Operation hours	h/ha/year	2.08	4.17
Extra machinery capacity	h/year/farm	737.50	675.00
Labour time	h/ha/year	2.20	1.76
Fuel consumption	L/ha/year	17	25
Annualized private cost of weeding/spraying	€/ha/year	418	747
Annualized extra societal cost ('C02'+'Pesticide')	€/ha/year	5	7

Results from alternative scenarios shows that under most scenarios, the robotic system was not economically competitive. Only under conditions involving large farms and large fields did the robotic system approach economic viability. The use case indicates potential long-term advantages related to farm structure. Dutch farms are generally larger and often involve multiple crops and operations, which may improve annual machinery utilization and support future adoption of autonomous systems.

4. Discussion

The findings across all four pilot areas demonstrate that autonomous agricultural robots can significantly reduce labour requirements in European farming systems. Labour savings ranged from 20% in the Netherlands to 48% in France, confirming that automation has strong potential to address labour shortages.

However, the study also revealed that labour savings alone are insufficient to guarantee economic viability. High investment costs remain one of the primary barriers to adoption. Economic performance depends heavily on machinery utilization rates, operational efficiency, pesticide savings, and farm size.

The spraying cases in Spain and Greece particularly emphasized the importance of reducing pesticide use. Because pesticides account for a substantial share of total spraying costs, autonomous systems become economically attractive only when they significantly improve application efficiency.

Fuel savings were inconsistent across the pilots. Only the French robotic system reduced fuel consumption substantially, while the other robotic systems consumed equal or greater amounts of fuel compared with conventional tractors. This finding indicates that further technological optimization is necessary.

Farm size emerged as another critical determinant of economic feasibility. Large farms are generally better positioned to distribute high machinery costs across larger operational areas. Small farms may struggle to justify robot ownership unless cooperative arrangements, contracting services, or machinery sharing models are available. The study highlights the importance of maximizing machinery utilization. Because robots involve high upfront costs, economic viability improves substantially when systems are used across multiple crops, operations, or farms, a finding consistent with previous work on robotic machinery economics and farmer perspectives on field robots (Lowenberg-DeBoer et al., 2021; Spykman et al., 2021; Vahdanjoo et al., 2023).

Beyond farm-level economics, the report also examined broader social and environmental implications. Autonomous systems may reduce worker exposure to pesticides, decrease physically demanding labour, and mitigate soil compaction due to their lighter weight. The technology may also contribute to lower greenhouse gas emissions when operational efficiency improves. However, pesticide reduction and wider agricultural transformation also depend on social, behavioural, and institutional factors beyond technology availability alone (Hossard et al., 2022; Young et al., 2022).

At the same time, adoption barriers remain substantial. Farmers may hesitate to invest in unfamiliar technologies because of concerns regarding reliability, servicing availability, infrastructure limitations, internet connectivity, and regulatory uncertainty. The report stresses that technological innovation alone cannot guarantee adoption; institutional, social, and economic conditions strongly influence behavioural change.

5. Broader Socio-Economic and Environmental Implications

Beyond farm-level profitability, the Robs4Crops study highlights broader socio-economic and environmental implications associated with the transition toward autonomous farming systems. One of the most important findings is that the value of robotic technologies cannot be evaluated solely through short-term machinery cost comparisons. Instead, the technology should be understood within the broader context of agricultural sustainability, labour transitions, environmental stewardship, and rural resilience.

Labour scarcity remains one of the strongest drivers behind interest in agricultural automation across Europe. In many agricultural regions, the availability of skilled machinery operators is declining while labour costs continue to rise. Autonomous systems therefore offer the possibility of stabilizing farm operations under increasingly constrained labour conditions. However, the study also emphasizes that robotic systems are unlikely to fully replace human labour in the foreseeable future. Human supervision, technical monitoring, planning, transport logistics, and maintenance continue to require skilled operators. Consequently, agricultural automation may lead less to labour elimination and more to labour transformation, where traditional machinery operation shifts toward supervision, digital management, and technical service provision.

The environmental implications of robotic systems are similarly multifaceted. Reduced pesticide application through precision spraying technologies may lower chemical exposure risks for both workers and surrounding ecosystems. In addition, smaller robotic platforms may contribute to lower soil compaction compared with heavy conventional tractors, potentially improving soil structure, water infiltration, and long-term productivity. Nevertheless, environmental gains depend strongly on operational context and system design. The findings showed that fuel savings were not consistently achieved across all case studies, indicating that technological optimization remains necessary before broad environmental benefits can be guaranteed.

Another important issue concerns technology accessibility and adoption inequality. High investment costs may create barriers for smaller farms, particularly in regions dominated by fragmented landholdings and family-based farming systems. The study therefore stresses the importance of alternative ownership and access models such as machinery-sharing cooperatives, leasing arrangements, and agricultural contracting services. Such approaches may allow smaller farms to benefit from robotic technologies without bearing the full burden of ownership costs.

The findings also point toward the growing importance of institutional and infrastructural readiness. Autonomous farming systems rely heavily on reliable internet connectivity, positioning systems, data exchange platforms, technical servicing infrastructure, and clear regulatory frameworks. In regions where these supporting systems remain weak, large-scale diffusion of autonomous technologies may be constrained despite technological progress.

The study highlights the importance of trust and social acceptance in shaping adoption decisions. Farmers may hesitate to adopt robotic systems because of uncertainty regarding reliability, maintenance, safety, and long-term economic performance. Demonstration activities, farmer networks, cooperative learning environments, and transparent policy support may therefore play a critical role in accelerating responsible adoption. Overall, the findings suggest that autonomous agricultural robots should not simply be viewed as machinery innovations, but rather as components of a broader agricultural transformation involving technological, economic, institutional, and social change.

6. Conclusion

The Robs4Crops study provides one of the most comprehensive evaluations of the economic feasibility of autonomous agricultural robots currently available in Europe. The findings demonstrate that robotic systems can significantly reduce labour requirements and potentially contribute to more sustainable farming systems.

However, the study also reveals that economic viability varies considerably across operational contexts. Autonomous systems are most attractive under conditions characterized by high labour costs, significant pesticide expenditures, large operational areas, and opportunities for high machinery utilization. Among the four pilot cases, the Spanish spraying system showed the strongest economic performance, while the Dutch sugar beet weeding case remained less competitive because of lower operational efficiency. The French and Greek cases demonstrated moderate economic potential, particularly under conditions involving labour scarcity or improved pesticide management.

Successful implementation will depend not only on technological advancement but also on supportive policies, cooperative business models, farmer trust, and the development of robust service ecosystems. Widespread adoption will further depend on technological maturity, improved machinery utilization, and reliable cooperative access models capable of reducing the burden of high upfront investment costs. As technologies mature and operational costs decline, autonomous systems may become increasingly important components of resilient and sustainable agricultural production systems.

Acknowledgements

The ROBS4CROPS project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101016807. The authors are deeply grateful for the invaluable contributions of project partners especially LSP managers (Bertrand Pinel and Luc DeJonghe (Terrena, France), Thanos Dritsopoulos and Markos Legas (PEGASUS), Oriol Serra and David Martin (Serrater), Han Hilbrands (SmartAgri Technology), Klaas-Jan and Nard Savelkouls (ABEMEC), Alea Scovil (AgroIntelli), who provided data, feedback and insights from the farmers' perspective. We are also grateful to the entire ROBS4CROPS consortium for any reflections on earlier versions of the economic model. The study has also benefited from comments by seminar participants at the Department of Food and Resource Economics, University of Copenhagen, Denmark.

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