



Conventional management vs. precision viticulture: A comparison of different levels of mechanization and their impact on vineyard profitability

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Abstract

Purpose Viticulture is one of the most input-intensive agricultural sectors, in which the adoption of precision technologies could contribute significantly to reduce environmental impacts and operating costs. Previous studies have primarily focused on technical aspects, often examining individual farm operations or specific technologies using hypothetical data, rather than assessing economic impacts. To fill this research gap, this study evaluates the profitability of adopting varying levels of precision technologies in an Italian vineyard, focusing on two key farming operations - fertilisation and harvesting - using empirical data.

Method This study adopted a partial budgeting approach comparing three differently managed vineyards: (a) conventional management (conventional spreader and manual harvest); (b) low-innovative management (VRT spreader and self-propelled harvester); (c) high-innovative management (VRT spreader and selective self-propelled harvester).

Results The findings show that high-innovative management achieved the highest profitability value of 10,732.82 € ha⁻¹ year⁻¹, which is twice that of conventional management. This is due to both direct cost savings (-66.1%) and increased revenues (+33.6%). However, precision technologies are only economically viable for farms larger than 25.81 ha (high-innovative management) and 16.42 ha (low-innovative management).

Conclusion In this context, as the results of this study demonstrate, the provision of public subsidies aimed at reducing the high investment costs could represent a valid instrument to promote the adoption of precision agriculture technologies among winegrowers, thereby reducing the minimum farm size for their adoption. This study enriches the economic literature on precision agriculture technologies, also providing useful insights for winegrowers and policymakers.

Keywords Break-even point · Extended gross margin · Partial budgeting · Selective harvester · Tuscany · Variable rate technology

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Introduction

Research background

In recent decades, population growth has driven intensified agriculture to boost crop yields, often leading to resource overuse and environmental harm (Feisthauer et al., 2024; Roberts et al., 2023). Additionally, rising input costs and volatile agricultural prices, partly due to recent wars, have hurt farmers economically, sometimes forcing them to stop farming (Boungou & Yatié, 2024; Mustafa et al., 2024). In this scenario, innovative solutions, among which precision agriculture technologies (PATs), are emerging as a strategic solution to a number of unresolved environmental and economic issues in the agricultural sector (Abbasi et al., 2022; Cisternas et al., 2020). PATs can provide farmers with knowledge for site-specific conditions (i.e., soil or weather conditions, crop vigour, yield forecasting), enabling targeted and tailored farming operations that optimize inputs use and save labor (Feisthauer et al., 2024; Islam et al., 2024; Jovarauskas et al., 2021). Adopting PATs enhances production sustainability by reducing agrochemical use, soil erosion, groundwater contamination, and greenhouse gas emissions (Jovarauskas et al., 2021; Ranjan et al., 2019). Moreover, by tailoring operations to plant-specific needs, PATs can increase yields while lowering production costs through more efficient input use (e.g., Feisthauer et al., 2024; da Silveira et al., 2023). As a consequence, PATs adoption contributes to increase farm profitability and plays a crucial role in shifting towards more responsible and sustainable management of farming systems (Feisthauer et al., 2024; Papadopoulos et al., 2024). In viticulture, the adoption of PATs encompasses a suite of site-specific farming operations, such as fertilisation, pesticide and weed control, irrigation, soil tillage and harvesting (Mizik, 2023; Moreno & Andújar, 2023; Tardaguila et al., 2021), optimizing yields and production costs, improving grape quality and overall value creation, as well as increasing environmental benefits (Mizik, 2023; Tardaguila et al., 2021).

Research gap and aim of the study

Research on PATs in viticulture has mainly focused on technical features and optimal parameters for site-specific operations, including agrochemicals dosage, drop size and drift effect of treatments, field capacity of farming operations, and efficacy of proximal and remote sensors (Pascoal et al., 2024; Moreno & Andújar, 2023). Empirical evidence indicates that PAT adoption can increase yields while reducing inputs. Vineyard yields have been shown to rise by 10% with variable-rate irrigation (Sanchez et al., 2017) and up to 40% when combined with variable rate fertilization (Balafoutis et al., 2017). Variable rate technology also reduces water use by up to 20% (Nadav & Schweitzer, 2017), copper by 44% (Garcia-Ruiz et al., 2023), and total pesticide volumes by around 22–25% (Gil et al., 2013; Román et al., 2020).

Despite evidence that PATs adoption can result in input savings and yield gains in vineyards, the economic benefits of doing so are rarely discussed in the extant literature (Sofia et al., 2025; Testa et al., 2025; Tardaguila et al., 2021; Lowenberg-DeBoer et al., 2020). Furthermore, most of economic analysis on PATs adoption in viticulture focus on a single farming operation, i.e. irrigation, crop protection, fertilization, yield monitoring, and harvesting, or on a specific technology adopted, thereby providing only a partial information

of overall vineyard management (Papadopoulos et al., 2024). In the field of crop protection, studies consistently show that implementing targeted technologies reduces operating costs. However, the magnitude of these savings varies according to the technology used. For example, adopting a VRT sprayer can generate savings of €118.16 per hectare (Pagliai et al., 2023), while Unmanned Aerial Vehicle (UAV) sprayers reduce costs from €31 to €22.50 per hour (Morales-Rodríguez et al., 2022). Retrofitted intelligent sprayers have been shown to lower annual costs by \$307 per acre (Signorini & Ivey, 2023), and telemetry systems can save up to €2,104.09 per hectare annually, mainly through reduced fuel, pesticide, and water use (Sarri et al., 2020). Concerning the irrigation techniques, Bellvert and co-authors (2021) have shown that the implementation of a precision irrigation system, based on NDVI maps, can yield financial savings ranging from €70.9 to €99.6 per hectare. Variable drip irrigation leads to an increase of the revenues by 23%, due to improvements in both grapes yield and quality (Casson et al., 2022). However, Finco et al. (2022) highlighted that using sensor-based software platforms to monitor vineyard water stress can raise production costs by €760 ha⁻¹, regardless of yield gains. In harvesting, selective harvesters can increase revenues by up to 12.7% over conventional ones, primarily due to higher grape quality (Bramley et al., 2011; Sofia et al., 2025).

In contrast, few studies have compared the economic performance of multiple PATs or directly against traditional techniques, leaving a gap in understanding their relative financial impacts across technologies and conventional practices (Galati et al., 2025). The Andújar et al. (2019) study has shown that while the adoption of aerial imagery techniques for fertilization purposes can engender cost savings of 6.1 € ha⁻¹, the on-ground technologies are still not cost-effective compared to the conventional spreader. Tona et al. (2018) found that VRT sprayers with ultrasonic or LIDAR sensors can cut pesticide costs by 18.7% and 33%, respectively, compared to conventional systems. Similarly, Testa et al. (2025) reported that annual pesticide costs per hectare drop from €499.50 with conventional sprayers to €324.68 with VRT or €334.67 with UAV sprayers. Moreover, few studies have identified the minimum vineyard size at which PAT adoption becomes advantageous. These studies have produced very different results, varying by technology and conditions. For instance, VRT sprayers with ultrasonic sensors are viable above 10 ha (Tona et al., 2018), while optical VRT sprayers require 17.02 ha (Testa et al., 2025). For UAVs, yield estimation is cost-effective above 60 ha, or 5 ha excluding purchase (Di Gennaro et al., 2019), and UAV sprayers using multispectral maps are advantageous for farms over 2.27 ha (Testa et al., 2025). Unlike previous work, the authors also assess how incentives affect PAT adoption, showing that with public subsidies the UAV sprayer remains cost-effective at all vineyard sizes, and the break-even point for VRT sprayers can fall to as low as 3.03 ha.

One notable finding from the literature is that only a limited number of studies rely on empirical in-field data (Pagliai et al., 2023; Morales-Rodríguez et al., 2022; Bellvert et al., 2021), while the majority are based on hypothetical settings or scenarios, providing findings that may be affected by many research assumptions and bias (Testa et al., 2025; Signorini & Ivey, 2023; Casson et al., 2022). In this respect, only one study to date has examined the combined adoption of multiple PATs on vineyard profitability using real data (Sofia et al., 2025). The Authors found that UAVs for crop protection reduced pesticide costs from €214.5 to €203.7 per hectare, while UAVs for harvesting increased revenue by 12.3% through higher-quality grape yields.

With this in mind, the paper aims to answer the following research questions (RQ):

RQ1. Does the introduction of PATs increase the wineries' profitability?

RQ2. Does combining multiple PATs for vineyard management improve profitability?

RQ3. What is the minimum area required for vine cultivation to be economically viable at various levels of precision of mechanization?

In view of the aforementioned points, the objective of the present study is to assess the profitability of introducing PATs in a Tuscan vineyard, considering three different levels of mechanisation under the same soil, climate and environmental conditions. The study will focus on two farming operations, fertilisation and harvesting. In detail, three differently managed vineyards have been compared: (a) conventional management (conventional spreader and manual harvest); (b) low-innovative management (VRT spreader and self-propelled harvester); (c) high-innovative management (VRT spreader and selective self-propelled harvester). A partial budgeting analysis using three years of techno-economic data estimated the average gross margin per vineyard. Given that investment costs are a key barrier for small and medium farms (Feisthauer et al., 2024; da Silveira et al., 2023; Abbasi et al., 2022), the minimum economically viable vineyard area for adopting precision technologies was also determined, accounting for public subsidies.

This study advances the literature on PAT economics in viticulture by comparing mechanization levels in fertilization and harvesting and their effects on overall farm profitability. Practically, it offers winegrowers insights into mitigating investment risks, a key barrier to adopting innovative technologies.

Materials and methods

Case study and adopted PATs

The profitability analysis of adopting precision technologies in viticulture compared to conventional management practices was investigated by adopting a case study approach. The adoption of a case study in management literature is a widespread method to evaluate business performance in various sectors of activity and investigates recent phenomena for which a quantitative approach cannot be adopted due to the lack of a significant amount of data (Yin, 2009). Scholars, by means of case studies, perform in-depth analysis providing useful insights for managers and policymakers (George and Bennet, 2005). Although some concerns could arise from the adoption of a single case mainly due to the representativeness and replicability of the results obtained, as well as selection bias, case studies are a valid approach to identify new hypotheses or to validate theories or to perform the evaluation of a new sector or technology (Yin, 2009; Bennett, 2004). For this reason, the case study is particularly well-suited to evaluating the profitability of PATs, given that their adoption rates among farmers are currently in an embryonic phase (Feisthauer et al., 2024).

This research focused on a case study, Tenute Ruffino S.r.l. Società Agricola, an organic winegrowing farm spanning 150.70 hectares and consisting of three main vineyards situated in the "Chianti area", a region of Tuscany (Central Italy). This area is bordered by the Tyrrhenian Sea to the west and by the Apennines to the east (Fig. 1).

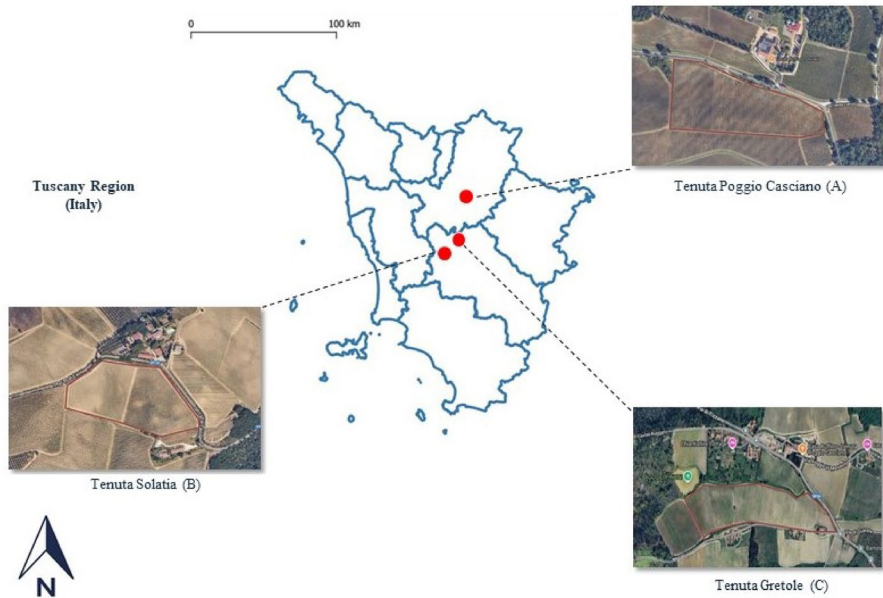


Fig. 1 Location of the three estates under study

This area is famous for producing “Chianti Classico” wine, an Italian Protected Designation of Origin (PDO) that is highly regarded worldwide for its exceptional quality (Sarri et al., 2020). The Chianti Classico area is characterized by a sub-oceanic Mediterranean climate, in which the warm season is dry and the cold season is wet, with an average annual temperature of about 14 °C and average precipitation of less than 700 mm (Costantini et al., 2012). The vineyard was located between 290 m and 350 m above sea level and the most representative cultivar was the red grape variety Sangiovese, which was grown using a cordon spur pruning system. The average plant density accounted for 5000 plants ha⁻¹ (2.50 m between rows and 0.80 m in the row).

The Ruffino winery consisted of six prestigious estates stretching from the Chianti Classico area to Montalcino. The analysis focused on three vineyards located in the Chianti Classico area under similar environmental conditions, in order to enable a comparison of the results. These three vineyards were differently managed for fertilization and harvesting in terms of mechanization and PAT adoption: conventional management, low-innovative management, high-innovative management (Table 1).

The first vineyard (A) covered 24.2 hectares and a conventional management (CM) was used for both fertilization and harvesting operations. Specifically, fertilization was carried out by means of a conventional spreader (Cosmo VNA600, Busca, Italy) mounted on a 75-kW tractor (Lamborghini Spire S105, Pieve di Cento, Italy). The spreader administered a uniform dose of fertilizer to all plants, regardless of site-specific conditions and fertilization requirements. Harvesting was carried out manually to minimize damage to the grapes and to select fruits according to their different degrees of ripeness. This approach guaranteed the production of high-quality wine.

Table 1 Vineyards according to management and PAT adoption

| Vineyard | Management | PAT adoption | Farming operations | |
|----------|-----------------|--------------|-------------------------------|------------------------------------|
| | | | Fertilization | Harvesting |
| A | Conventional | No PATs | Tractor+Conventional spreader | Manual harvest |
| B | Low-innovative | One PAT | Tractor+VRT spreader | Self-propelled harvester |
| C | High-innovative | Two PATs | Tractor+VRT spreader | Selective self-propelled harvester |

The second vineyard (B) covered an area of 64.8 hectares. Fertilization was the only operation involving the adoption of PATs, which is indicative of a low-innovative management (LIM) approach. For this farming operation, in fact, a variable-rate technology (VRT) spreader (KUHN SAS, Saverne, France) was installed on the same 75-kW tractor. Unlike a conventional spreader's constant rate, the VRT spreader enabled farmer to adjust the fertiliser dose in real time, thus allowing to apply products site-specifically according to changes in canopy conditions, while reducing the time and inputs required for fertiliser application. The harvesting was carried out by means of a 120-kW self-propelled harvester (New holland Braud VL660, Torino, Italy), which significantly reduced labour time compared to manual harvesting with limited losses and damages.

The third vineyard (C) covered 61.7 hectares. A high-innovative management (HIM) can be detected as both farming operations adopted PATs. In particular, while the aforementioned VRT spreader was used for fertilization, a 134-kW selective self-propelled harvester (New holland Braud 9090 - Enocontrol, Torino, Italy) was employed. Unlike the conventional harvester, this selective harvester had the capacity to separate grapes into two bins based on the variability of grape quality among plants, slightly reducing the field capacity. This process enabled the selection of optimal fruits for the production of high-quality wines, while reducing harvest losses when compared with conventional harvesting methods.

The technical characteristics of the agricultural machinery and the adopted PATs are detailed in Table 2.

All adopted PATs were equipped with GPS technology and were based on prescription maps obtained by means of multispectral unmanned aerial vehicle (UAV) flights provided by a third-party service provider. Specifically, a single flight with Phantom 4 drone (DJI Technology Co., Shenzhen, China) was utilized for both fertilization and harvesting operations, generating specific maps based on the normalised difference vegetation index (NDVI). This index was able to highlight the spatial variability among plants thanks to the geometric reconstruction of their canopy. It provided georeferenced NDVI maps with the aim of assessing the canopy vigour as well as grape ripening (Ferro et al., 2023; Daglio et al., 2022). Subsequently, NDVI maps provided, following data processing, specific prescription maps that were loaded onto PATs via USB flash drive, thereby empowering farmers to perform targeted and tailored farming operations through the utilisation of GPS technology (Garcia-Ruiz et al., 2023; Di Gennaro et al., 2019).

Table 2 Technical characteristics of agricultural machinery and adopted PATs

| Items | Tractor | Conventional spreader | VRT spreader | Self-propelled harvester | Selective self-propelled harvester |
|--|---------|-----------------------|--------------|--------------------------|------------------------------------|
| Power (kW) | 75 | | | 120 | 134 |
| Purchase price (€) | 58,000 | 3,500 | 7,500 | 170,000 | 242,500 |
| Life-time period (hours) | 16,000 | 1,200 | 1,200 | 2,500 | 2,500 |
| Annual working hours (h year ⁻¹) | 1,066 | 120 | 120 | 250 | 250 |
| Field capacity (ha h ⁻¹) | | 0.66 | 1.16 | 0.50 | 0.47 |

Economic analysis

The survey was carried out in May 2024 through face-to-face interviews with the winegrower to collect technical and economic data on vineyard management using a specially designed questionnaire (Appendix A). The information requested in the data collection form was aimed at assessing the impact of different management practices across three distinct vineyards. All collected data (i.e. inputs, yields, labor, field capacity, machinery costs) refer to the 2020/21–2022/23 crop years. When market prices were not provided directly by winegrower, they were determined on the basis of a market survey, in some cases using the price lists of the inputs employed in the production process (Sofia et al., 2025). To compare the profitability of the three vineyards, an economic analysis was performed. This analysis took the form of a partial budgeting, with the focus being on the changes that occurred in the two aforementioned farming operations across the three vineyards. The rationale behind this lies in the inherent nature of partial budgeting which clearly identifies the disparities between different farming systems when some changes in management practices are introduced, as opposed to the systems being in their original state (Lowenberg-DeBoer et al., 2020; Plastina et al., 2020). Therefore, this method constitutes a highly suitable approach to evaluate the profitability of PATs adoption (Rahim et al., 2022; Karatay & Meyer-Aurich, 2020).

Specifically, the Extended Gross Margin (EGM) for each vineyard was calculated as follows (Rajmis et al., 2022; Schroers et al., 2010):

$$EGM = R - TC \quad (1)$$

where EGM is the extended gross margin (€ ha⁻¹ year⁻¹), R represents the annual revenues of vineyard and TC identifies the total annual costs.

The mean value was computed following the calculation of the EGM values for each of the three crop years (see Appendix), to obtain an economic parameter with minimal susceptibility to weather conditions or market fluctuations (Rahim et al., 2022).

Regarding the annual revenues, the yields (Mg ha^{-1}) were multiplied by the prices of organic grapes (€ Mg^{-1}) sold for use to produce Chianti Classico wine (CCIAA Arezzo-Siena, 2024). In detail, the highest market price was found for manual harvest as the fruits were not damaged (CM), while the lowest prices for the conventional harvester (LIM). For the selective harvester, given that fruits were divided into two different bins based on their quality, half of the grapes were sold at market prices for manual harvesting and the other half at prices for conventional harvesting.

With regard to the total annual costs, these were comprised of both direct costs and machinery costs as outlined below:

$$TC = DC + MC \quad (2)$$

where *DC* identifies the direct costs, and *MC* represents the machinery costs. Both *DC* and *MC* included the labour required to perform the farming operations, considering a worker salary of 15.00 € h^{-1} (CCIAA Arezzo-Siena, 2024). Direct costs encompassed expenses related to fertilizers, manual harvesting, mapping and georeferencing. The cost of fertilizers was determined for all vineyards, by considering both the amounts of inputs used and the corresponding market prices provided by winegrower. Manual labour cost for harvesting was calculated exclusively for conventional management practices by applying the worker's salary to the hours worked on the farm. In addition, mapping and georeferencing costs were applied to vineyards that adopt PATs, by considering the market values per flight (pilot included) of the third-party service providers.

Machinery costs were determined in accordance with the ASABE standard of hourly equipment cost (€ h^{-1}), encompassing both fixed and variable costs (ASABE, 2015a; 2015b). The fixed (or ownership) costs constituted all annual expenses (€ year^{-1}) that the farmer is obliged to pay, regardless of whether agricultural machinery is used. These costs encompassed depreciation, interest on invested capital, housing, and insurance. The hourly cost was then calculated by dividing the aforementioned fixed costs by the number of annual working hours of each machinery provided by manufacturers. Specifically, a straight-line depreciation was calculated on the basis of the purchase price (provided by winegrower), the remaining value (estimated at 10% of purchase price) and the economic life of the machinery based on the international literature (Testa et al., 2025; Rahim et al., 2022; Pezzi & Martelli, 2015). The interest on invested capital was estimated as half of the sum of the purchase price and the residual value, by applying an average real interest rate of 1.5% (ECB, 2024). The housing and insurance costs were estimated as percentage of the purchase price, with values of 75% and 25%, respectively.

The variable costs referred to the hourly expenses associated with the utilization of agricultural machinery. Such expenses encompassed the costs of repair and maintenance, fuel and lubricants and labour involved in operating the tractor as well as self-propelled harvester. Fuel and lubricant costs were determined by dividing the annual costs provided by winegrower by the annual working hours of agricultural machinery, while the hourly salary of an employee was adopted for labour costs. Repair and maintenance costs were calculated based on specific repair factors applied to the purchase values of agricultural machinery and

then divided by their estimated lifetime in hours (Testa et al., 2025; Pezzi & Martelli, 2015). After determining the hourly equipment cost, the fixed and variable costs were multiplied by the effective field capacity (ha h^{-1}) of each agricultural machinery, considering both working and turning times provided by winegrower. This was done in order to calculate the hourly machine cost per hectare.

Therefore, Eq. (1) can be rewritten as follows:

$$EGM = R - \left[DC + \left(\frac{FC}{h} + VC \right) \cdot C_a \right] \quad (3)$$

where FC represents the fixed costs, VC identifies the variable costs, h is the annual working hours of agricultural machines and C_a their field capacity.

In conclusion, to provide a more comprehensive economic evaluation, the minimum vineyard area (break-even point) for which the PAT adoption is convenient, compared to conventional management, was calculated. Specifically, the total annual costs ($\text{€ ha}^{-1} \text{ year}^{-1}$) of the three vineyards managed in different ways were compared. Direct and variable machine costs were referred to one hectare, and annual fixed machine costs were divided by farm size (Testa et al., 2025; Rajmis et al., 2022; Tona et al., 2018). Furthermore, the minimum vineyard area was recalculated based on the public subsidies granted by the Italian government for PAT diffusion. This resulted in a 65% reduction on the purchase cost up to a maximum of 35,000 euros (IRP, 2024).

Results and discussion

The objective of the present study was to analyse the profitability of adopting precision agriculture technologies in viticulture. To this end, a comprehensive analysis was conducted of the costs and benefits of three different levels of precision technology adoption between vineyards managed under the same environmental conditions.

Hourly machinery costs

Hourly machinery costs were calculated to compare the economic viability of three vineyards with different levels of PAT adoption. Accurate cost allocation and financial planning require winegrowers to be aware of hourly machinery costs, since the total cost of farming depends not only on the required inputs (direct costs), but also on the machinery used to carry them out (Rajmis et al., 2022).

As shown in Table 3, the average hourly machinery cost ranged from 41.57 € h^{-1} for CM, to 201.06 € h^{-1} for HIM, confirming that costs increase in proportion to the level of innovation introduced for vineyard management (Testa et al., 2025; Rahim et al., 2022; Rajmis et al., 2022). As previous studies have shown (Cavalari et al., 2023; Martinez-Guanter et al., 2020; Tona et al., 2018), the highest average hourly cost values in the most innovative management (HIM) were due to the higher incidence of fixed costs, strictly linked to the high investment costs of PATs. In this study, fixed costs accounted for up to 57.7% of the total cost of a vineyard with a VRT spreader and a selective harvester, whereas in conventional management they represented only 17.8% of the total cost. In more detail, depreciation

Table 3 Average hourly machinery cost of vineyards (€ h⁻¹)

| Items | Management | | | | | |
|---------------------------|--------------|--------------|----------------|--------------|-----------------|--------------|
| | Conventional | % | Low-innovative | % | High-Innovative | % |
| Depreciation | 5.89 | 14.2 | 70.09 | 43.9 | 96.19 | 47.8 |
| Interest | 0.69 | 1.7 | 6.57 | 4.1 | 8.97 | 4.5 |
| Housing | 0.63 | 1.5 | 5.98 | 3.7 | 8.15 | 4.1 |
| Insurance | 0.21 | 0.5 | 1.99 | 1.2 | 2.72 | 1.4 |
| Fixed costs | 7.41 | 17.8 | 84.63 | 53.0 | 116.02 | 57.7 |
| Repair and maintenance | 5.11 | 12.3 | 29.85 | 18.7 | 39.26 | 19.5 |
| Fuel and lubricants | 14.04 | 33.8 | 30.18 | 18.9 | 30.78 | 15.3 |
| Labour | 15.00 | 36.1 | 15.00 | 9.4 | 15.00 | 7.5 |
| Variable costs | 34.15 | 82.2 | 75.03 | 47.0 | 85.04 | 42.3 |
| Total hourly costs | 41.57 | 100.0 | 159.66 | 100.0 | 201.06 | 100.0 |

accounted for the largest proportion of total hourly costs in both low and high-innovative managed vineyards, reaching 43.9% and 47.8%, respectively. Conversely, depreciation accounted only for 14.2% of the CM's total hourly costs, which were primarily made up of labour, fuel and lubricants, which together accounted for 69.9%. With regard to companies that adopt PATs, labour accounted just for 8.4% on average of the overall hourly cost, thanks to the superior efficiency of the VRT spreader and grape harvester in comparison to the conventional management system. These results highlight how the adoption of PATs leads to a reconfiguration of vineyard operational costs, with the incidence of required labor progressively decreasing as the level of mechanization increases. On the one hand, this finding points to greater process efficiency. On the other, it prompts reflection on the reorganization of work dynamics within farms. Indeed, the introduction of these technologies requires new skills, reduces physical strain, and reshapes labor demand in terms of both quantity and qualification.

Regarding fuel and lubricants, although the cost doubled in vineyards with PATs for the adoption of the grape harvester, its relative cost decreased from 33.8% (CM) to 15.3% (HIM). This result confirms that the adoption of precision technologies makes it possible to optimize the use of resources as well as production and quality efficiency. In this specific case, the efficiency in the use of fuel and lubricants helps reduce the carbon footprint of production processes. Therefore, despite both labour and energy costs were the most significant variable costs in CM, in accordance with the conclusions of Martinez-Guanter et al. (2020) and Sarri et al. (2020), their importance diminished with the adoption of PATs. This result aligns with the findings of Pagliai and colleagues (2023) who demonstrated that the implementation of VRT sprayer in vineyard reduced the fuel costs by 28.3%. Similarly, even in sectors as diverse as wheat, Jovarauskas et al. (2021) highlighted that the VRT spreader increased the energy efficiency (approximately 9%) and productivity compared to conventional one. Instead, the repair and maintenance costs ranged from 12.3% of total hourly cost (CM) to 19.5% (HIM), highlighting their proportional increase in proportion with the level of PAT adoption. This finding is consistent with the conclusions of Cavalari et al. (2023), who noted that these costs varied from 11.3% of variable costs for a conventional sprayer to 17.9% for a UAV sprayer.

Profitability analysis

The profitability analysis showed that the machinery costs ratio per hectare was very low for conventional vineyard management (3.5%) compared to a value of 40.4% for HIM (Table 4). However, despite machinery costs increased in vineyards with PATs, total annual expenses were on average 50.4% lower than conventional management, standing at 1,798.11 € ha⁻¹ year⁻¹. This finding was due to the savings in direct costs in vineyards adopting PATs (-68.6% on average), accounted for 501.81 € ha⁻¹ year⁻¹ (LM) and 587.64 € ha⁻¹ year⁻¹ (HIM).

Specifically, most of the savings in direct costs were attributable to the adoption of the grape harvester showing that manual labour for harvesting was one of the main costs of a conventional vineyard (59.5% of annual expenses). This is because adopting a grape harvester considerably reduced the harvest time from 68.4 h per hectare (h ha⁻¹) for CM to 2.00 h ha⁻¹ for LIM, which confirms the findings of Strub et al. (2021). The authors showed that manual harvesting requires approximately 37 times more working hours than mechanised management. Additionally, the reduction in direct costs was primarily due to savings in fertilisers (-39.8% on average), which far outweighed the costs associated with mapping and georeferencing. The study's findings confirm those of Andújar et al. (2019), who demonstrated that adopting a VRT spreader based on UAV prescription maps in vineyards could save up to 80% of fertiliser compared to conventional applications. This reduces production costs and creates environmental benefits, as well as in field crops (Rahim et al., 2022; Karatay & Meyer-Aurich, 2020).

In terms of revenue, the adoption of PATs resulted in an increase equal to 29.0% (LIM) and 33.6% (HIM), compared to the conventional management. This improvement was pri-

Table 4 Average extend gross margin of vineyards (€ ha⁻¹)

| Items | Management | | | | | |
|---|-----------------|--------------|------------------|--------------|-------------------|--------------|
| | Conventional % | | Low-innovative % | | High-Innovative % | |
| Revenues (A) | 8,768.50 | | 11,312.40 | | 11,718.75 | |
| Yield (Mg ha ⁻¹) | 4.50 | | 6.28 | | 6.25 | |
| Price (€ Mg ⁻¹) | 1,950.00 | | 1,800.00 | | 1,875.00 | |
| Direct costs (B) | 1,735.75 | 96.5 | 501.81 | 63.0 | 587.64 | 59.6 |
| Fertilizers | 665.04 | 37.0 | 397.16 | 49.9 | 402.99 | 40.9 |
| Mapping and georeferencing ^a | - | - | 104.65 | 13.1 | 184.65 | 18.7 |
| Manual labour for harvesting | 1,070.71 | 59.5 | - | - | - | - |
| Machinery costs (C=C.1 + C.2) | 62.36 | 3.5 | 294.51 | 37.0 | 398.29 | 40.4 |
| Fixed costs (C.1) | 11.12 | 0.6 | 156.70 | 19.7 | 232.89 | 23.6 |
| Depreciation | 8.83 | 0.5 | 130.04 | 16.3 | 193.39 | 19.6 |
| Interest | 1.03 | 0.2 | 12.05 | 1.5 | 17.86 | 1.8 |
| Housing | 0.94 | 0.2 | 10.95 | 1.4 | 16.23 | 1.6 |
| Insurance | 0.31 | 0.1 | 3.65 | 0.5 | 5.41 | 0.5 |
| Variable costs (C.2) | 51.24 | 2.8 | 137.82 | 17.3 | 165.40 | 16.8 |
| Repair and maintenance | 7.67 | 0.4 | 50.83 | 6.4 | 73.44 | 7.4 |
| Fuel and lubricants | 21.07 | 1.2 | 44.08 | 5.5 | 47.26 | 4.8 |
| Labour | 22.50 | 1.3 | 42.90 | 5.4 | 44.70 | 4.5 |
| Total annual costs (D=B + C) | 1,798.11 | 100.0 | 796.32 | 100.0 | 985.93 | 100.0 |
| Extended gross margin (A - D) | 6,970.39 | | 10,516.08 | | 10,732.82 | |

^a One UAV flight for low-innovative management and two flights for high-innovative management

marily due to the use of the VRT spreader, which, as demonstrated by previous studies in field crops, enhances yields by optimising fertilizer uptake for each individual plant. These findings found an average yield increase in vineyards of 39.2%, which is higher than the values reported by Rahim et al. (2022) for rice (+7.9%) and by Karatay and Meyer-Aurich (2020) for winter wheat (+1.9%). The adoption of the VRT spreader enables farmers to apply targeted, customized fertilizer doses based on the requirements of individual plants and the variability within the field, resulting in higher yields compared to conventional management (Rahim et al., 2022; Matese and Di Gennaro, 2015). This is because the VRT spreader relies on NDVI maps that detect plant vigor, allowing for an optimal nutritional balance and maximum efficiency, while also reducing the risk of diseases caused by over- or under-fertilization (Grasso et al., 2011). In addition, NDVI maps enable timely interventions, allowing plants to better adapt to unfavorable climatic conditions that have a detrimental effect on yields (Sofia et al., 2025; Jovarauskas et al., 2021). In particular, the greater increase in yield observed, compared to arable crops, confirms that the effectiveness of the VRT fertilizer spreader depends on the heterogeneity of the field, as it is based on spatial and temporal variability (Ahmad and Dar, 2020). In fact, vineyards are characterized by high spatial and temporal heterogeneity as plant canopies change during the growing season and, consequently, have specific nutrient needs for each phenological stage (Andújar et al., 2019; Matese and Di Gennaro, 2015).

In addition, the results show that the increase in yield enabled farmer to offset losses of grapes due to mechanized harvesting. These losses, in line with previous studies, were equivalent to a 2.5% and 5.0% reduction compared to manual harvesting, for selective and conventional harvester (Pezzi & Martelli, 2015; Bramley et al., 2011). It is evident that the enhanced revenue yield in the vineyard that adopted the selective harvester (11,718.75 € ha⁻¹) compared to the vineyard that used the conventional harvester (11,312.40 € ha⁻¹), were not solely due to reduced losses. In fact, the farmer sold half of the grapes at the same price as manually harvested fruits because the selective harvester, in contrast to the conventional one, was able to simultaneously divide the fruits into two bins according to their quality. In this regard, a study by Bramley et al. (2011) showed that the adoption of selective harvester can increase the revenues up to 12.7% compared to the conventional one thanks to the selection of the most optimal fruits to produce high-quality wines.

The results showed that the highest average EGM value (10,732.82 € ha⁻¹ year⁻¹) was reached for HIM, highlighting an increase of 54.0% compared to CM. This confirms that profitability increases with the PAT adoption as emerged also in previous studies. For example, Signorini and Ivey (2023) pointed out that a retrofitted intelligent sprayer could increase the Net Present Value of vineyard by 18.4%, while a gross margin of 9,861.34 \$ ha⁻¹ can be obtained by a winery that adopts a selective grape harvester to produce \$5–10/bottle wines (Bramley et al., 2011). Sofia and co-authors (2025) showed that the adoption of UAV to obtain vigour maps to monitor plant health and schedule phytosanitary treatments can increase the gross profit of vineyard by 44.4%. Additionally, the authors demonstrated the versatility of precision farming tools such as UAV technologies not only for treatment planning but also for selective harvesting. Similar results were achieved in other sectors. For instance, Rahim et al. (2022) emphasized that rice farmers could gain an additional income of 851.44 MYR ha⁻¹ by adopting a VRT spreader. Furthermore, pesticide treatments with VRT sprayer resulted in a 24.7% increase of extended gross margin for field crops (winter and spring wheat, and winter barley) as shown by Rajmis et al. (2022).

Therefore, adopting PATs increases efficiency by optimising the quantity and cost of inputs while increasing yields (Roberts et al., 2023; Jovarauskas et al., 2021). However, adopting a VRT spreader would deliver the best economic results when combined with mechanised harvesting. Indeed, if we assume that the LIM vineyard is harvested manually rather than mechanically, the average EGM would decrease from €10,516.08 to €10,219.52 per hectare (−2.8%) (Table 5). This is because, despite the reduction in machinery costs due to the absence of grape harvester (−86.9%) and the higher revenues obtained from manual harvesting (+8.3%), the direct costs would increase by 15.1% for grapes harvested manually. Conversely, although the grape harvester plays a key role in economic management of vineyards (Strub et al., 2021), the LIM reached an EGM similar to the HIM, confirming that the adoption of selective harvester compared to conventional one is still constrained by high investment costs (Segade et al., 2019; Bramley et al., 2011).

The minimum farm size for the adoption of PATs in viticulture

The study also sought to determine the minimum farm size required for the adoption of precision technologies for both farming operations, by comparing the total annual costs (direct and machinery costs) of the three vineyards managed in different ways (Testa et al., 2025; Rajmis et al., 2022; Tona et al., 2018). In fact, this is a well-established procedure in economic valuation aimed at assessing the most cost-effective option among several alternatives as farm size varies (Testa et al., 2025; Rajmis et al., 2022).

The findings showed that the minimum vineyard area required to introduce both PATs was equal to 25.81 ha, while a farm size of 16.42 ha was required to adopt only VRT spreader (Fig. 2).

The findings confirm that, at the current purchase prices, PATs adoption is only economically justified just for larger farms. This is consistent with a recent study by Testa et al. (2025) which showed that the introduction of VRT sprayer in Italian vineyards could be the

Table 5 Average extended gross margin of vineyard with VRT spreader and manual harvesting (€ ha^{−1})

| Items | Value | % |
|---|------------------|--------------|
| Revenues (A) | 12,255.10 | |
| Yield (Mg ha ^{−1}) | 6.28 | |
| Price (€ Mg ^{−1}) | 1,950.00 | |
| Direct costs (B) | 1,997.05 | 98.1 |
| Fertilizers | 397.16 | 19.5 |
| Mapping and georeferencing ^a | 104.65 | 5.1 |
| Manual labour for harvesting | 1,495.24 | 73.5 |
| Machine costs (C=C.1+C.2) | 38.53 | 1.9 |
| Fixed costs (C.1) | 9.48 | 0.5 |
| Depreciation | 7.64 | 0.4 |
| Interest | 0.83 | 0.0 |
| Housing | 0.75 | 0.0 |
| Insurance | 0.25 | 0.0 |
| Variable costs (C.2) | 29.06 | 1.4 |
| Repair and maintenance | 6.69 | 0.3 |
| Fuel and lubricants | 9.47 | 0.5 |
| Labour | 12.90 | 0.6 |
| Total annual costs (D=B+C) | 2,035.58 | 100.0 |
| Extended gross margin (A-D) | 10,219.52 | |

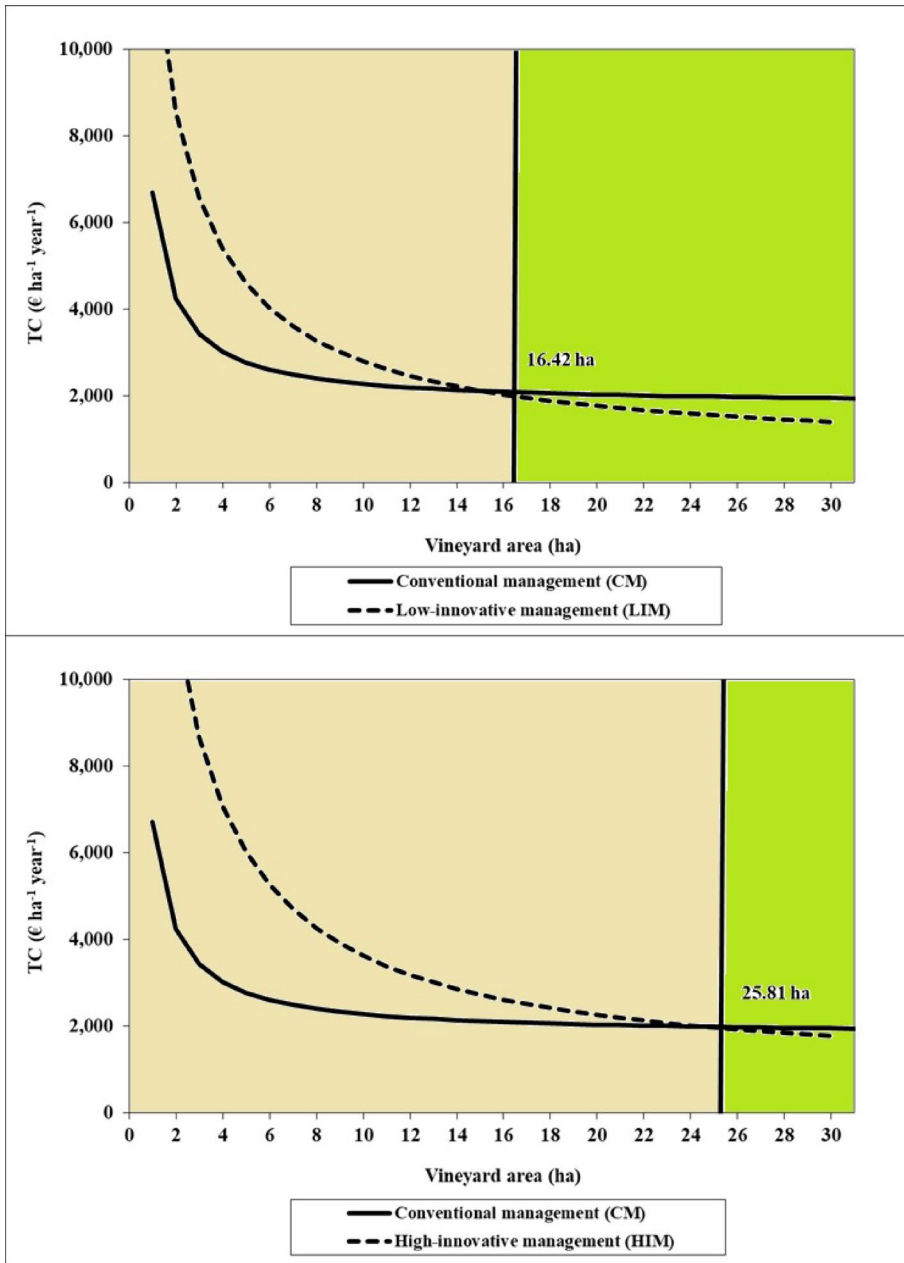


Fig. 2 Minimum farm size according to vineyard management

most viable option for farm larger than 17.02 hectares. However, while the farm area is also similar to the findings of Tona et al. (2018) regarding the cost-effectiveness of introducing a VRT sprayer (more than 10 ha), substantial differences can be found for field crops. Specifically, Rajmis et al. (2022) stated that the minimum area to introduce VRT sprayer in winter

wheat farms should be at least 300 hectares, while for Rahim et al. (2022) a 100-hectare rice farm would justify the introduction of VRT spreader.

Furthermore, the larger the number of PATs adopted simultaneously, the larger the farm needs to be, showing that the level of PAT adoption and its complexity also depend on farm size (Signorini & Ivey, 2023; Tona et al., 2018). For example, Signorini and Ivey (2023) highlighted that the net present value in a vineyard increased from 30 to 70 acres, reaching the highest value when a retrofitted VRT sprayer was adopted (17,627 \$ acre⁻¹) compared to a not-retrofitted one (17,273 \$ acre⁻¹). For their parts, Tona et al. (2018) demonstrated that the minimum area of vineyards could increase from 10 to 100 hectares, depending on the adoption of VRT sprayers with ultrasonic or LiDAR sensors.

In this scenario, financial support in the form of subsidies could encourage the adoption of PATs by reducing the high initial investment costs, making them accessible to smaller farms (Testa et al., 2025; Feisthauer et al., 2024; da Silveira et al., 2023). Based on this consideration, the impact of the current subsidies provided by the Italian government on the profitability of companies and the minimum company size was examined. More in detail, the findings showed that, thanks to a 65% reduction on the purchase cost provided by the IRP, the minimum vineyard area for the adoption of both PATs decreased to 18.98 ha, while VRT spreader was economically convenient also for farms larger than 13.57 ha (Fig. 3).

This result confirms the need to define effective measures to foster the adoption of precision technologies, allowing more winegrowers to obtain economic advantages while reducing environmental impacts (Feisthauer et al., 2024; Roberts et al., 2023). Nevertheless, it is worthing to note that the adoption of the PAT would remain uneconomical for the most winegrowers, as the minimum vineyard area would still exceed the average size of Italian vineyards (2.46 ha) (Istat, 2022). Therefore, for very small wineries struggling to access subsidies or financing, the adoption of innovations can be facilitated through modes of cooperation, supported by technology providers who assist with data management, interpretation, and analysis (Galati et al., 2025). From this perspective, Nguyen et al. (2024) highlight that agricultural cooperatives serve as innovation intermediaries, linking farmers with government bodies and lead firms, thereby shaping the impact of such support on farmers' intention to adopt PATs. Consistent with this, Wu et al. (2023) show that participation in cooperatives significantly promotes the uptake of a wide range of new technologies among Chinese family farms by enabling resource sharing, reducing transaction costs, and providing technical support. Farmers themselves, as highlighted by Barnes et al. (2019) and Balogh et al. (2021) view machinery rings, contractors, and shared-service schemes as crucial mechanisms for accessing precision agriculture tools without assuming the full costs and risks of individual ownership.

Conclusions, implications e future research directions

The study found that farm profitability increases with the level of adoption of PATs, with the EGM value rising from €6,970.39 per hectare per year (CM) to €10,732.82 per hectare per year (HIM). This is primarily due to the mechanisation of harvesting operations, which allows savings in direct vineyard costs of around 69%. These savings largely offset the increase in machinery costs. Although machine costs increased from 3.5% (CM) to 40.4% (HIM) of total annual costs, the latter were, on average, 50.4% lower than those for conven-

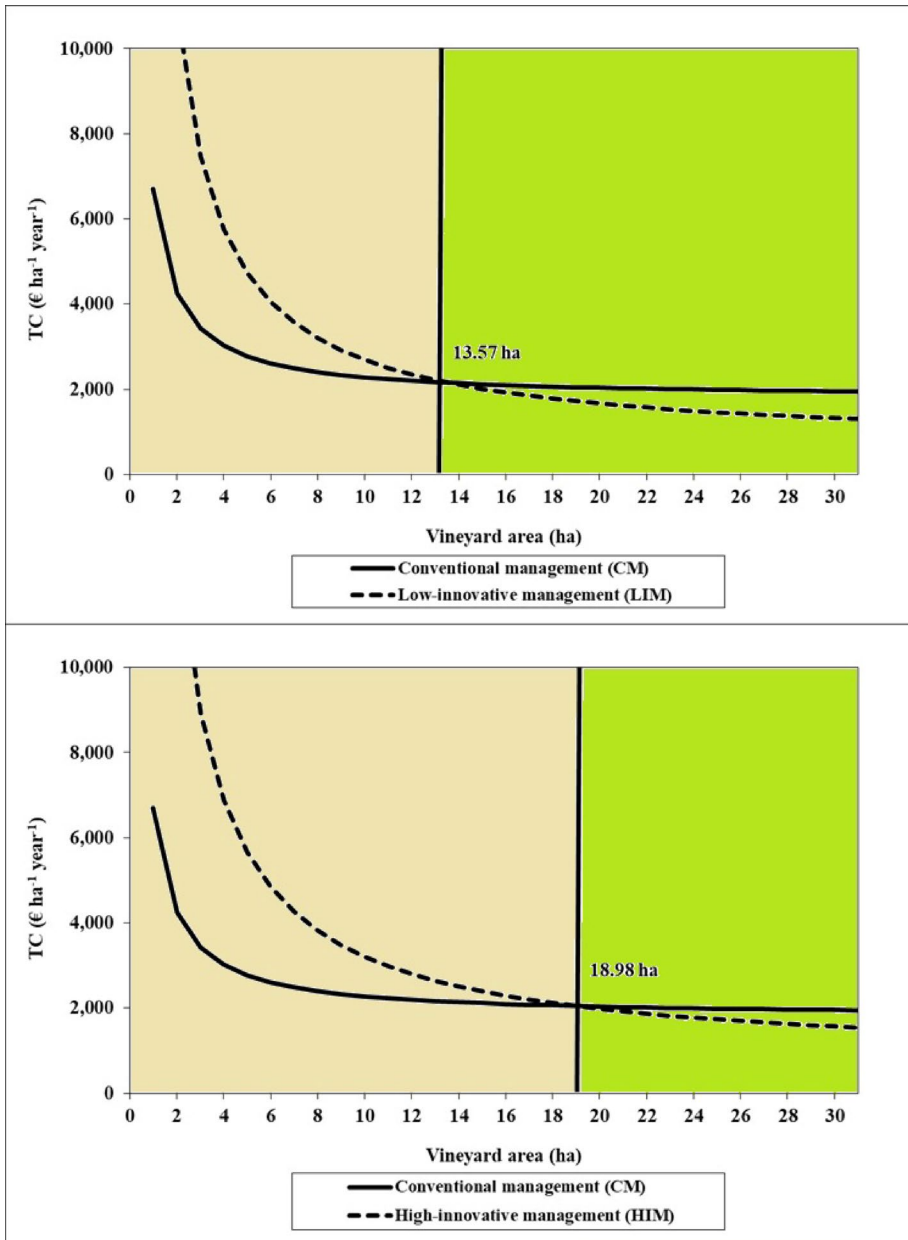


Fig. 3 Minimum farm size according to vineyard management without public subsidies

tional management. In a sector characterized by an aging farming population and a growing shortage of agricultural labor, the adoption of mechanical harvesting emerges as a potential solution to address the sector’s structural challenges. Furthermore, the results showed that digitalization implies an increase in revenues of 29.0% (LIM) and 33.6% (HIM) as a result of site-specific farming operations. With respect to the optimized fertilizer distribution, a

VRT spreader allows farmers to optimise the use of fertilizers, in relation to within-field variability, while increasing yield and grape quality. Compared with conventional practices, PAT reduces fertilizer costs by approximately 40%. However, the savings in fertilization are offset by higher expenses for mapping and georeferencing. Moreover, this study's findings show that PAT adoption is only economically justified for farms larger than 25.81 ha (HIM) and 16.42 ha (LIM). Nonetheless, when public subsidies are considered, the minimum vineyard area is reduced to 18.98 ha and 13.57 ha, respectively. This demonstrates that the larger the farm, the more site-specific farming operations can be adopted. This implies that, under current market conditions digitalization would increase the divide between small and large farms, as only the latter are able to make such investments economically viable.

A number of theoretical and practical implications can be drawn from this study. Theoretically, the study enriches the literature on the profitability of adopting precision technologies in viticulture. Compared to previous studies in this field, this study compares three levels of mechanization, two of which are precision-based, and their impact on costs and businesses' ability to generate profit, by using real rather than hypothetical data. Furthermore, the study identifies the minimum area required for the economically sustainable introduction of precision agriculture technologies (PATs) in wine-growing businesses for protection and harvesting operations, taking into account the possibility of obtaining subsidies.

The findings provide also useful managerial implications for winegrowers. The adoption of PATs, in particular the VRT spreader for treatments and the selective self-propelled harvester, contributes to reduce the direct costs of vineyard management and increases farms' profitability. Furthermore, as the study showed, the adoption of PATs makes it possible, on the one hand, to reduce the number of treatments and, on the other, to improve the quality of the harvested grapes. In detail, the reduction in both the number of phytosanitary treatments and the quantities of pesticides and fungicides applied highlights the effectiveness of precision technologies. Beyond enhancing grape quality through a lower reliance on chemical inputs, the adoption of PATs optimizes the use of labor and materials while reducing the environmental impact of production. By enabling more targeted applications, PATs limit chemical leaching into water bodies, protect ecosystems, and reduce pollution. Consequently, more efficient resource use also lowers greenhouse gas emissions, supporting environmental sustainability and climate change mitigation. We have also seen that, if we separate the effect of the VRT from the harvester, the reduction of costs of the VRT is offset by the increase of machinery costs and mapping and georeferencing. Therefore, these results demonstrate that there is a clear convenience for wine growers to introduce technological solutions that enable them to manage their vineyards in a responsible and sustainable manner, and this convenience increases with the size of the farm. The study, in fact, identifies the minimum area for which PATs are economically viable. This provides farmers with clear data on the economic advantages of these technologies and the farm size at which they are justified.

The study is able to shed light on some of the policy implications. On one side, the results of the study showed that the minimum farm size required to make the adoption of PATs economically viable is reduced thanks to government subsidies. In absence of subsidies, the polarizing effect of digitalization would be much more intense. At the same time, given that the bigger the size the greater the gains of digitalization, the reduction of the divide between small farms and larger farms would need measures targeted to small farms. For the latter, financial support provided by governments, such as grants or low-interest loans,

can facilitate the adoption of precision technologies by helping to overcome the barrier posed by high initial investment costs. These subsidies could also be accompanied by aid under rural development measures that could compensate farmers for the environmental benefits produced as a result of adopting precision technologies, including savings in natural resources and other production inputs such as pesticides, fertilizers, energy, and water. Financial incentives alone are not enough if the complexity of precision agriculture tools limits their use. It is therefore essential to align investment support measures with effective digitalization strategies that facilitate the removal of adoption barriers - particularly those arising from the transition from analog to digital systems, which requires operational reorganization, user training, and adequate technical support - and that integrate user education, advisory services, and specific incentives for the use of decision support systems (DSS). Moreover, a specific attention to small-scale farming should be given. In this regard, since farm profitability increases with the adoption of PATs, educational campaigns are essential to highlight both the economic advantages and the environmental benefits. These educational campaigns could increase trust in the technology, reduce perceived risks, and encourage its adoption, while also promoting joint purchasing among small farms and improving knowledge of the proper management of such tools. In this context, knowledge-sharing systems play a crucial role in promoting innovations and best practices across all actors in the agricultural sector. A prime example is the Agricultural Knowledge and Innovation System (AKIS), a cross-cutting objective and cornerstone of the EU Common Agricultural Policy, designed to foster and disseminate knowledge, innovation, and digitalization across agriculture and rural areas. Furthermore, for small wineries with limited access to funding, consortium-based approaches supported by tech companies can facilitate data management and analysis. In short, overcoming financial barriers, adopting innovative technologies, and fostering collaboration are essential strategies. These strategies can contribute to achieving more sustainable and resilient farming systems and contributing to the UN 2030 Agenda SDGs.

However, this study has some limitations mainly related to the case study approach which suffer from the generalizability of the results. In particular, the study considers different levels of mechanisation for specific operations. From this point of view, the economic evaluation of PAT adoption for a vineyard should take into consideration also other farming operations, such as pest control, irrigation or soil tillage. Moreover, since farm profitability depends on several factors such as yield, pedoclimatic conditions and market price volatility, a period longer than three years would be recommended to obtain more reliable results. Finally, considering that the adoption of precision technologies leads to a reduction in labour requirements on farms and the associated costs, future studies could compare different socio-economic and territorial contexts in order to verify the generalizability of the results.

Appendix A

Module for recording production processes related to winegrowing farm

Module for recording production processes related to winegrowing farm

| | |
|--|--------------------------|
| A. General information | |
| 1. Data collection information | |
| a. Data collector's full name | |
| b. Reference year of data (e.g., 2023) | |
| c. Date of the data collection (dd/mm/yyyy) | |
| 2. Company information | |
| a. Location of the company (City, Region, Country) | |
| b. Distance from the town center (km) | |
| c. Respondent's full name | |
| d. Respondent's role within the company (e.g., owner, manager, technician) | |
| 3. Corporate manufacturing activities | |
| a. Winegrowing cultivation | <input type="checkbox"/> |
| b. other cultivations (please specify) | <input type="checkbox"/> |
| 4. Employment and Labor Details¹ | |
| Family members: | |
| a. Number of family members working in the company (full-time) | |
| b. Number of family members working in the company (part-time) | |
| c. If part-time, specify the number of working days in a year | |
| Employees: | |
| d. Total number of employees | |
| e. Annual salary of employees in euro | |
| Seasonal workers: | |
| f. Number of seasonal workers | |
| g. Number of annual working hours | |

¹ If you have other operations different than winegrowing cultivation just report those directly involved in the farming operations of vineyards.

| | |
|--|--|
| B. Corporate structures | |
| 1. Surface | |
| a. Total farm land (hectares) | |
| b. Total area under cultivation (hectares) | |
| c. Owned cultivation area (hectares) | |
| d. Leased cultivation area (hectares) | |

| 2. Buildings, artefacts, and installations | | | | | |
|--|----------------------------|-----------------------------------|-----------------------|---------------------------------|---|
| <i>Please list all buildings, cultivation structures, and support installations related to winegrowing production (e.g., office, shelters, farming buildings, wells, irrigation system, ecc.).</i> | | | | | |
| Description (list) | Total area (square meters) | Year of construction (e.g., 2023) | Replacement value (€) | Presumed total duration (years) | Area used for winegrowing cultivation (square meters) |
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| 3. Machines and equipment | | | | | |
|---|-------------------------------|--------------------|---------------------------------|---|---------------------------------|
| <i>Please list all machines and equipment related to winegrowing production</i> | | | | | |
| Description | Year of purchase (e.g., 2023) | Purchase price (€) | Total annual employment (hours) | Annual employment for winegrowing cultivation (hours) | Presumed total duration (years) |
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| Items | Conventional Management | | | Low-innovative Management | | | Low-innovative Management | | |
|---|-------------------------|-----------------|-----------------|---------------------------|------------------|------------------|---------------------------|------------------|------------------|
| | 2020/21 | 2021/22 | 2022/23 | 2020/21 | 2021/22 | 2022/23 | 2020/21 | 2021/22 | 2022/23 |
| Direct costs (B) | 1,646.66 | 1,740.64 | 1,819.96 | 486.17 | 495.68 | 523.57 | 572.80 | 582.37 | 607.76 |
| Fertilizers | 620.71 | 671.12 | 703.29 | 381.52 | 391.03 | 418.92 | 388.15 | 397.72 | 423.11 |
| Mapping and georeferencing ^a | - | - | - | 104.65 | 104.65 | 104.65 | 184.65 | 184.65 | 184.65 |
| Manual labour for harvesting | 1,025.95 | 1,069.52 | 1,116.67 | - | - | - | - | - | - |
| Machine costs (C = C.1 + C.2) | 57.53 | 66.55 | 63.00 | 291.70 | 296.96 | 294.89 | 395.48 | 400.73 | 398.66 |
| Fixed costs (C.1) | 11.12 | 11.12 | 11.12 | 156.70 | 156.70 | 156.70 | 232.89 | 232.89 | 232.89 |
| Depreciation | 8.83 | 8.83 | 8.83 | 130.04 | 130.04 | 130.04 | 193.39 | 193.39 | 193.39 |
| Interest | 1.03 | 1.03 | 1.03 | 12.05 | 12.05 | 12.05 | 17.86 | 17.86 | 17.86 |
| Housing | 0.94 | 0.94 | 0.94 | 10.95 | 10.95 | 10.95 | 16.23 | 16.23 | 16.23 |
| Insurance | 0.31 | 0.31 | 0.31 | 3.65 | 3.65 | 3.65 | 5.41 | 5.41 | 5.41 |
| Variable costs (C.2) | 46.41 | 55.43 | 51.88 | 135.00 | 140.26 | 138.19 | 162.59 | 167.85 | 165.77 |
| Repair and maintenance | 7.67 | 7.67 | 7.67 | 50.83 | 50.83 | 50.83 | 73.44 | 73.44 | 73.44 |
| Fuel and lubricants | 16.24 | 25.26 | 21.71 | 41.27 | 46.53 | 44.46 | 44.45 | 49.71 | 47.64 |
| Labour | 22.50 | 22.50 | 22.50 | 42.90 | 42.90 | 42.90 | 44.70 | 44.70 | 44.70 |
| Total annual costs (D = B + C) | 1,704.19 | 1,807.19 | 1,882.95 | 777.87 | 792.64 | 818.46 | 968.27 | 983.10 | 1,006.42 |
| Extended gross margin (A - D) | 6,484.81 | 6,948.31 | 7,497.05 | 9,816.63 | 10,943.36 | 10,799.54 | 10,255.48 | 10,885.65 | 11,044.08 |

Author contributions Conceptualization: Antonino Galati; Methodology: Riccardo Testa; Data curation and formal analysis: Antonino Galati and Riccardo Testa; Validation: Antonino Galati and Gianluca Brunori; Writing-original draft: Antonino Galati, Riccardo Testa and Gianluca Brunori; Visualization: Riccardo Testa; Supervision: Antonino Galati. All authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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