



Unleashing profitability of vineyards through the adoption of unmanned aerial vehicles technology systems: the case of two Italian wineries

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Abstract

Purpose Precision agriculture technologies play an important role in optimising practices to increase yields and reduce costs, contributing to socio-economic progress and environmental well-being, and playing a key role in addressing climate change. Viticulture is a strategic, input-intensive agricultural sector where precision technologies can make the use of resources more efficient without compromising profitability. The aim of this study is to evaluate the profitability of implementing precision farming systems, such as unmanned aerial vehicle surveying for the production of vigour maps, compared to the conventional cultivation system in two Italian wineries.

Methods The profitability of using precision farming tools in viticulture compared to conventional management techniques has been investigated in two Italian wineries over a four-year period, before and after the introduction of UAV technology.

Results The results demonstrate the usefulness and economic viability of precision agriculture technologies in viticulture. The vigour maps produced by the data collected with UAV technology allow both the identification of problems such as diseases, and consequently the planning of phytosanitary treatments, and selective grape harvesting, which allows a significant improvement in the quality of the harvested grapes.

Conclusion The results demonstrate the usefulness of precision technologies for cost-effective and sustainable vineyard management, satisfying a market segment made up of stakeholders who are increasingly sensitive to environmental issues.

Keywords Precision agriculture · Precision viticulture technologies · Economic efficiency · Gross profit analysis · Gross margin profit · Farm management · Viticulture

Introduction

Research background

The global agricultural production system today faces serious challenges related to climate change, rising energy and input costs, including those resulting from the conflict between Russia and Ukraine, the long-term effects of the 2020 pandemic crisis, the growing demand for food in the face of decreasing land availability due to increasing urbanisation rates and the exploitation of natural resources, to name a few (Abay et al., 2023; FAO, 2023; Galanakis, 2023). A polycrisis that has led to a profound rethink of production and operations in the global food chain, with the aim of making the sector resilient and sustainable. In this complex scenario, it is essential for farms to implement policies and strategies aimed at optimising the use of natural resources and inputs in order to increase productivity, reduce the environmental impact of production processes and remain competitive in the market (Hedley, 2015; Finger, 2023). A potential response to these farmers' emerging needs can be provided by precision agriculture technologies, particularly predictive analytics tools (Ancev et al., 2004; Jerhamire et al., 2022; Roj et al., 2021). Precision agriculture has been defined by the International Society of Precision Agriculture as “*a management strategy that gathers, processes and analyzes temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production*” (ISPA, 2021). Precision agriculture is the combined use of artificial intelligence (AI) and information technology (IoT) tools to provide constantly updated information on soil parameters, crop growth, water status, air quality and climatic conditions, improving management decision-making by making more efficient use of resources, reducing costs and mitigating negative environmental impacts (Jensen et al., 2012; Tey & Brindal, 2012; Carrer et al., 2015, 2022; Ballesteros et al., 2020). Precision technologies in agriculture play an important role in several respects. They optimise practices to increase yields and reduce costs (Beyer et al., 2016; Yost et al., 2017; Zangina et al., 2021) and, as emphasised by several authors, they contribute to socio-economic progress and environmental well-being and play an important role in addressing climate change (Balafoutis et al., 2017; Bucci et al., 2020; Rose et al., 2021). However, there are cultural and economic barriers to the transition of farms to precision farming systems, related to the size of the farm and the specific technologies used (Balafoutis et al., 2017; Sumiahadi et al., 2019; Mizik et al., 2023a, b).

In recent years, a large number of precision agriculture technologies (PATs) have been developed, which Balafoutis and co-authors (2017) classify into three main categories: (i) Monitoring technologies, remote/proximal sensing for soil, canopy, and weather monitoring; (ii) Guidance technologies, Controlled Traffic Farming, Machine Guidance, Driver Assistance; (iii) Acting technologies, Variable Rate Irrigation “VRI”, Variable Rate Weeding “VRW”, and Variable Rate Application “VRA” technologies. Alongside these technologies there is a small sector that includes Decision Support Systems (DSS), Mobile Applications, Machine Learning applications (Harel et al., 2022; Adamides et al., 2023; McFadden et al., 2023), and autonomous robots equipped with sensors and cameras (VineRobot project, 2015; Wall-ye project, 2015; Vitirover project, 2015). These latest advances in technology,

while not yet widespread, are transforming precision agriculture to increase efficiency and productivity on farms.

Research gap, aim of the study and contribution

Precision agriculture has received considerable attention from academics in recent years, with the aim of understanding the benefits and barriers to the adoption of modern technologies on farms. In particular, numerous studies have evaluated the return on investment of precision farming tools in relation to the influence this information can have on farmers' decisions to adopt and invest in new technologies (Tey & Brindal, 2012; Finger et al., 2019, 2023). Depending on the situation, the results show an increase in profits as a result of higher yields or a reduction in operating costs, particularly those related to the use of pesticides and fertilisers (Koch et al., 2004; Baio et al., 2017; Casa et al., 2018). However, as observed by some authors, the farm profitability of adopting some of the PATs varies depending on the technologies adopted, crop types, production systems and other socio-economic and environmental characteristics (Balafoutis et al., 2017; Sumiahadi et al., 2019; Hanson et al., 2022). Socio-economic barriers and investment costs may hinder adoption, particularly for smallholder farms (Mizik et al., 2023a, b). In addition, most studies have evaluated the economic viability of adopting precision farming tools in herbaceous crops (cereals, maize, soya, etc.) and mainly in the USA, while little attention has been paid to the profitability of adopting precision farming tools in tree crops, and in particular in viticulture, compared to conventional farming systems. The limited data available show that the adoption of precision technologies in vineyard management generates significant cost savings, as a result of the reduction in fertiliser costs and the increase in profits (Bramley et al., 2011a, b; Maynard et al., 2015; Schimmelpfennig et al., 2016). However, these benefits show considerable variability and in some cases turn out to be rather small and by no means do not justify the winegrowers' investment (Di Gennaro et al., 2019; Bellvert et al., 2021; Tziolas et al., 2023). In this scenario, the available data are not sufficient to make a clear assessment of feasibility, especially in relation to the highly variable conditions of the vineyard (pedo-climatic characteristics, varieties, working conditions, duties and taxes). Under this scenario, an additional profitability analysis, based on real data, is needed in order to allay winegrowers' concerns.

In view of the above, this study aims to fill this gap by assessing the profitability of implementing precision farming systems, such as unmanned aerial vehicle (UAV), for the production of vigour maps, compared to the conventional cultivation system in two Italian wineries. In particular, the profitability analysis was based on real data obtained through interviews with vineyard owners and agronomists involved in vineyard management. According to the results of the 7th Agricultural Census (Istat, 2022), only 11% of Italian farms have made at least one innovative investment (related to precision agriculture, but also to the use of technologically advanced machinery, equipment, hardware and software or other technologies) between 2018 and 2020. Therefore, the acquisition of data on the impact of precision farming technologies on costs and profitability is very important in the Italian scenario to support the choices of entrepreneurs. Given the preliminary nature of the research, the case study approach was considered to be the most appropriate and suitable to explore a contemporary and complex phenomenon that is not yet widespread at a national level. In addition to enriching the current literature on the profitability of precision agri-

culture, our findings have relevant managerial implications. Indeed, the knowledge of the economic benefits resulting from the adoption of PAT in viticulture, either through increased production or through reduced inputs, is a key driver for agricultural entrepreneurs to invest in innovative and sustainable solutions.

Literature review

Backgrounds on precision agriculture technologies challenges and opportunities

The diffusion of precision technologies in agriculture is influenced by three main factors, as pointed out by Mizik and colleagues (20–23): efficiency, technology and people. Technological development and digitalisation have contributed significantly to improving the efficiency of production processes, particularly in terms of reducing inputs and their associated costs, increasing crop yields and farm profitability, and promoting the development of green, environmentally friendly agriculture. Numerous studies have been carried out to identify the benefits and barriers associated with the adoption of innovative technologies in agricultural production systems, particularly in herbaceous crops. Casa and co-authors (2018), looking at ten Spanish wheat farms, found that ISOBUS on-board computer systems for variable-rate pesticide application reduced pesticide use by an average of 30% and increased profits by 20%. Precision farming tools are also widely used in fertiliser distribution. In this area, several empirical studies have shown that the adoption of VRA technologies reduces operating costs by cutting fertiliser charges by between 10% and 41% and increases profit margins (Baio et al., 2017; Dilon and Kusunose, 2013; Robertson et al., 2007; Koch et al., 2004). However, as stated by Dilon and Kusunose (2013) and Robertson et al. (2007), the cost savings from VRA depend on different variables such as farm size, soil type and crop production level.

Technologies, in particular their type, reputation and ease of use, play a key role in the diffusion process. Some studies show that user-friendly technologies encourage their adoption (Mizik et al., 2023a, b; Michels et al., 2021). For example, Michels and colleagues (2021) found that farmers who have a high level of confidence in the use of drones, particularly for harvest data management, perceive their efforts as less burdensome and are more likely to adopt precision technology. This finding confirms the central role of human capital, and in particular education levels, in facilitating the transition to the adoption of precision technologies in agriculture. However, the existing literature on education reports inconsistent results, highlighting that, in most cases, the adoption of precision technologies is more frequent among farmers with a high level of formal agricultural education, but above all with computer or technological skills that increase awareness and the ability to understand the information and data derived from these technologies (Kendall et al., 2022; Paxton et al., 2016; McBride and Daberkow, 2003). Some scientists note that the complexity of these technologies can be a challenge for managers and workers unfamiliar with advanced precision systems, especially with data interpretation methods lag behind, due to limited computer skills and technological apprehension (Orr et al., 2001; Babin et al., 2022). However, proximity to and interaction with adopters can affect technology adoption, with clear evidence of success (Abadi & Pannell, 1999; Lamb et al., 2008). In keeping with this, Blash and colleagues (2022) emphasize that the adoption process is facilitated by the exchange of

information and knowledge with the external environment, particularly through interactions with other farmers using precision technologies, i.e. by their degree of openness to innovation. In general, the greater the ability of farmers to absorb relevant external information and knowledge and use by combining it with internal farm resources, the greater the likelihood of adopting new technologies (Micheels and Nolan, 2016).

Overall, the complex nature of precision agriculture and the variety of factors influencing its adoption are clear. Key factors include the education and skill levels of farmers, the ability to create linkages to absorb and capitalise on new knowledge, and the technical and economic efficiency of the precision technologies that can be implemented. The latter is particularly important as it can reduce scepticism and risk perceptions associated with the adoption of innovation in agriculture. Furthermore, the demonstrability of results in technical and economic terms, i.e. demonstrating how real the benefits are, increases the confidence of potential adopters by facilitating the diffusion of innovative technologies.

Economics of precision viticulture technologies

As noted above, little attention has been paid to analysing the economic viability of adopting PATs in the viticulture sector, despite it being a strategic input-intensive agricultural sector (Ammoniaci et al., 2021; Singh & Sharma, 2022). Precision viticulture technologies (PVTs), which use advanced tools such as tailored irrigation and data-driven decision making, provide detailed insights into crop and soil health, improving vineyard management (Verdugo-Vásquez et al., 2021), grape quality and wine production, while increasing farm profitability (Tisseyre & Taylor, 2005; Mazzetto et al., 2010; Matese et al., 2015). In addition, PVTs allow the use of technology and data for sustainable and efficient practices, contributing to socio-economic progress, stability, and environmental health (Lamb and Bramley, 2002; Proffitt & Bramley, 2010; Ferro et al., 2023; Tziolas et al., 2023).

Among the PVTs, monitoring technologies, including remote and proximal sensing, provide accurate observations of changes in vineyard conditions. For example, it is possible to monitor the response of the canopy to light absorption and reflection (obtained from multispectral images) by calculating different vegetation indices, such as normalised difference vegetation index (NDVI), normalised difference red edge (NDRE) and leaf chlorophyll index (LCI) (Matese & Gennaro, 2018; Matese et al., 2019). In addition, these technologies can assess thermal and water stress (obtained from thermal sensor images) by calculating other water stress indices, such as the Crop Water Stress Index (CWSI). This approach improves management efficiency, quality and sustainability (Matese et al., 2015; Santesteban et al., 2019; Gokool et al., 2023). More specifically, studies show a positive impact of the adoption of precision technologies on grape quality management. Bonilla et al. (2015) found that the use of vigour maps based on the NDVI vegetation index, obtained from aerial photographs, and the consequent zoning of vineyards, is a very useful tool for the efficient management of vineyard operations. In particular, the authors observed a positive relationship between the NDVI index and some variables related to organoleptic characteristics and grape quality (anthocyanins, sugar content), including pH, which could be useful for selective grape harvesting. For example, the Bolgheri project in Italy aimed to obtain vigour maps for selective grape harvesting. The use of vigour and zoning maps allowed grapes to be harvested from areas with different vigour levels and vinified separately to produce higher quality wines. Similarly, the adoption of proximity sensors has shown advantages

in terms of spatial resolution and timeliness in predicting the quality of table grapes and therefore identifying the most appropriate time for harvesting (Anastasiu et al., 2018). For example, dos Santos Costa et al. (2019) used a spectroradiometer and mathematical models to assess grape quality attributes (total soluble solids, anthocyanins, flavonoids), identifying different stages of grape ripening, allowing grapes with similar quality characteristics to be grouped together to obtain wines with high added value. Better grape quality translates into a higher price and higher quality finished product (Mizik, 2023a, b). With this in mind, Bramley et al. (2011a, b) conducted a study in the Murray region of Australia comparing conventional and selective harvesting methods. The results show that in the case of conventional harvesting, all production was allocated to ‘premium’ wines sold at \$10 per bottle. Conversely, selective harvesting differentiated grapes by vigour, with low-vigour areas used to produce “super premium” wines sold at \$15 per bottle, and high-vigour areas used for the “premium” category. With selective harvesting, total revenue was 12.4% higher than with conventional harvesting. In line with this, Casson et al. (2022) highlighted the positive effect of PVTs on grape quality, finding an increase in income from grape sales due not only to an increase in the quantity produced, but also to an improvement in quality that allowed the unit selling price to increase by 12.5%.

Given the range of technologies available, several authors have examined the economic viability of the different instruments. A comprehensive cost and profitability analysis, taking into account various exogenous and endogenous factors affecting the implementation of PVTs, is essential to assess the economic feasibility and to understand the financial implications and benefits of PVT implementation. Indeed, as some authors point out, the implementation of PVTs is hampered by the low resolution of satellite and aerial images, the high operating costs and the experimental stage of robotics, while the training of technicians remains a crucial factor for the widespread implementation of these technologies.

Previous studies have mainly used both cost-benefit analysis (CBA) (Borgogno-Mondino, 2017; Finco et al., 2022; Allegro et al., 2023) and gross margin analysis (Proffitt & Pearce, 2004; Maynard et al., 2015; Tziolas et al., 2023) to assess the feasibility and profitability of PVTs. For example, Andújar and colleagues (2019) evaluated economically viable fertiliser application techniques using different plant yield mapping methods in relation to vegetation cover. They found that ground-based precision techniques (LiDAR-based) provided the better details, but were more expensive than aerial imagery. UAVs, which are affordable due to their ease of use and wide coverage, result in a cost saving of €6.1 per hectare compared to the conventional technique. Furthermore, when site-specific spraying was applied based on the maps generated from UAV imagery, the dosage was reduced by up to 80% compared to the total amount used in conventional application methods. However, as Maynard (2015) found, the benefits of aerial imagery surveys and proximal grape yield monitoring technologies depend on the size of the vineyard, being economically feasible for medium sized vineyard producers (71–360 ha, excluding vineyards of 15 ha or less), with potential savings of \$290 per hectare. On the other hand, very large vineyards (> 1430 ha) tend to see fewer benefits, as they encounter a relatively flat payback curve due to the high variability of environmental factors in their fields. Other authors have instead compared conventional and innovative vineyard management techniques. For example, Di Gennaro et al. (2019) found that high-resolution RGB imagery from UAVs is efficient and accurate for vineyard yield estimation, resulting in cost savings of \$3.1 per hectare in field yield monitoring, without considering the purchase price of adopting UAV systems. Similarly,

Schimmelfennig and colleagues (2016) demonstrated cost savings of -\$25.01 per hectare associated with the production of soil maps using remote sensing imagery compared to traditional soil mapping methods, particularly for subsequent spraying operations using variable rate technologies. The increased efficiency in terms of resource use and consequent cost reduction was also highlighted by Andrenelli et al. (2013), who evaluated the cost of applying monitoring technologies using automatic resistivity profiling technology for soil surveys in a Tuscan vineyard. They found this technology to be very effective compared to conventional systems, identifying a reduction in sampling and laboratory analysis costs of €206–309 per hectare for large vineyards (30–60 ha) and €409–549 per hectare for smaller farms (≤ 15 ha). Practical experience has shown that the adoption of remote sensing and variable rate application (VRA) technologies can lead to significant economic profit gains, ranging from 10 to 30%, mainly due to cost reductions (Bramley et al., 2005, 2011a, b).

Precision technologies have found wide application in the field of vineyard irrigation and fertilisation, offering both environmental benefits and improved economic outcomes. Casson et al. (2022), comparing six different scenarios associated with different approaches to variable rate irrigation and fertiliser technology (ranging from older traditional methods to innovative approaches), observed a reduction in CO₂ emissions of over 50% and a 30% increase in water use efficiency in a single year compared to traditional methods. This resulted in a significant 23% increase in revenue through improved grape yield and quality. In line with these findings, Bellvert and co-authors (20–21) found that, in the area of precision irrigation (PI) efficiency, the adoption of a regulated deficit irrigation (RDI) strategy in a 100-hectare vineyard during two consecutive growing seasons (2016 and 2017) allowed a net benefit (calculated as the difference between the PI cost savings and the cost of acquiring the technology and the labour required to apply it in the field) of between €20.0 per hectare in 2016 and €48.7 per hectare in 2017, compared to conventional methods. In terms of environmental benefits, PI resulted in a 14–38% reduction in water use and a 35% reduction in energy use, ultimately benefiting the farmer. However, as highlighted by Casson and co-authors (20–22), the transition to precision irrigation requires access to on-demand water sources, which can increase costs and environmental concerns. Sarri and colleagues' study (2020) also emphasises the enhanced efficiency that can be accomplished through the utilisation of precision irrigation tools. The authors focused their attention on the evaluation of telemetry data collected during the application of pesticides in a vineyard and showed that approximately 9.53% of the total kilometres travelled during the spraying phase were methodologically incorrect, which affected the efficiency of fertilisation. This resulted in a high variability in fuel and pesticide costs ranging from €0.01 to €0.03 per metre, with a total cost impact of €1,941.10. These results highlight the importance of precision sensor data in reducing both the economic and environmental costs of farm management (Sarri et al., 2020).

Recent research has led to significant advances in the design of autonomous robots tailored to viticulture, which are transforming vineyard operations. However, these are cutting-edge technologies that are being applied on an experimental basis, with limited uptake due to the high investment costs required. Tziolas and colleagues (2023) evaluated the economic aspects of using robots, called “cobots”, compared to conventional labour for four different grape varieties in Greece. Cobots showed significant potential in certain viticultural operations, leading to cost reductions of up to 11.5% compared to their conventional counterparts. In particular, the average savings associated with the use of cobots in some operations were

194.22 €/ha for weed control, 75.17 €/ha for tying, 71.74 €/ha for pruning and 35.90 €/ha for herbicide treatments, although in some operations the use of the robot proved to be poorly effective (i.e. defoliation and tying operations). Similarly, McCorkle et al. (2016) investigated the use of robots as an alternative to human labour in vineyard operations in Texas, USA. They found that the use of robots in both large and small vineyards allowed for a reduction in labour hours per hectare and associated costs, highlighting the goodness of the investment as demonstrated by the highly positive net present values in both cases. While the potential cost savings from the use of robots were noted, the study did not analyse their ability to perform complex manual processing tasks, such as grape selection, efficiently for the production of high quality wine.

The results of these studies show the economic viability of adopting precision technologies in viticulture, with a reduction in costs and an increase in profits. However, there is considerable variability depending on factors such as the technologies used, the size of the farm, the varieties grown, to name but a few. In this sense, further empirical analyses on the profitability and management costs of precision technologies can contribute to enriching the literature, but at the same time can provide useful pointers to practitioners on the potential and benefits of digitisation.

Table 1 Summarises the main economic perspectives, methods and findings found in the literature on precision viticulture.

Materials and methods

The cases under study

The profitability of using precision farming tools in viticulture compared to conventional management techniques has been investigated in two Italian wineries (Fig. 1): Torre Bisenzio and Mulini di Segalari. Although the choice of two case studies is a risky option in management studies due to the impossibility of generalising the results, it offers the possibility of studying a new and complex phenomenon through the direct collection of high quality data. This exploratory approach makes it possible to carry out a detailed analysis of each case study and, at the same time, to identify the variables that distinguish one case from another (Yin, 2003; De Massis et al., 2015). In the literature, several authors (Silva et al., 2007; Meyer-Aurich et al., 2008; Bramley et al., 2011a, b; Capmourteres et al., 2018; Bellvert et al., 2020; Bucci et al., 2020) have used case studies to investigate the economic feasibility of implementing precision farming technologies. Focusing on one or a few farms allows for a deeper investigation of a real phenomenon, which is fundamental in a complex sector such as agriculture, and for more precise results. Moreover, the efficiency of PVTs involves several aspects that need to be studied at the plot level (Sassu et al., 2021), which makes the case study suitable for exploring this area of research.

The Torre Bisenzio winery, located in Umbria, Italy (42°84'48"63"N., 11°95'47"81"E., 460–580 m above sea level, 118 km from the coast), covers a total area of 273 hectares, of which 6.21 hectares are vineyards. The winery benefits from a Mediterranean climate and loamy-clay soils with a gentle slope of 20%, creating an ideal environment for growing a variety of grape varieties such as Sauvignon Blanc, Grechetto, Pinot Nero, Sangiovese, Syrah, Cabernet Franc, Petit Verdot, Cabernet Sauvignon and Merlot. Three hectares of

Table 1 Relevant economic overviews, methodologies, and findings from the precision viticulture literature. (Source Our elaborations on data collected from scientific databases as science direct, Scopus, web of Knowledge)

Author(s)	Year	Country	Precision Viticulture technologies used on case studies	Economic Analysis	Economic indicators	Results
Tziolas et al.	2023	Greece	Acting technologies (Collaborative Robots for vineyard operations)	This study conducts an economic assessment by comparing the use of collaborative robots (cobots) and conventional labor considering four cultivar vineyards. It employs the Life Cycle Costing (LCC) framework to evenly distribute the total cost of a product or activity across its entire lifecycle.	<ul style="list-style-type: none"> • Total Costs for each cultivar (TCi) • Total factor productivity (TFP) • Human labor costs using robots 	<ul style="list-style-type: none"> ■ -10.6% of an-nualequivalent TCi ■ +10% of TFP ■ -30% of human labor costs
Allegro et al.	2023	Italy	Acting technologies (Precision Pruner Machinery)	This study analyzes vine performance and the costs associated with various levels of mechanization during winter pruning over a five-year trial spanning from 2011 to 2015, using Pruning Cost estimates.	<ul style="list-style-type: none"> • Field Working Capacity– Ca (ha/h) • The pruning costs (€/ha) 	<ul style="list-style-type: none"> ■ 0.24+0.01 ha/h of Field Working Capacity (Ca) ■ -800 €/ha of pruning cost

Table 1 (continued)

Author(s)	Year	Country	Precision Viticulture technologies used on case studies	Economic Analysis	Economic indicators	Results
Finco et al.	2022	Italy	Acting technologies (Precision Irrigation System with an image processing software to monitor the hydric stress status of the vineyard).	This study investigates the economic justification for irrigation strategies and aids decision-making through a software platform prototype. It employs cost-benefit analysis (CBA) and simulates the impact of irrigation costs over two years.	<ul style="list-style-type: none"> • Water Productivity (WP) • Economic Water Productivity (EWP) • Precision Irrigation's total cost (€/ha) 	<ul style="list-style-type: none"> ■ 6.2 kg/m³ of WP in 2020 and 5.1 kg/m³ of WP in 2021 ■ 0.6 €/m³ of EWP in 2020 and -0.3 €/m³ of EWP in 2021 ■ 760 €/ha of Precision Irrigation's total cost
Bellvert et al.	2021	Spain	Acting technologies (Precision Irrigation System using the NDVI maps for regulated deficit irrigation strategies)	This study assesses the effectiveness of an integrated approach that combines a vine water consumption model with remote sensing data to optimize precision irrigation (PI) and It conducts a cost-benefit analysis (CBA) to compare this approach with a conventional irrigation strategy.	<ul style="list-style-type: none"> • Water Productivity (WP) • Agronomic Water Productivity (AWP) • Irrigation Efficiency (i.e.) • Cost for conducting a PI management (€/ha) • Operating profit with PI systems (€/ha) • Operating saving cost with PI systems (€/ha) 	<ul style="list-style-type: none"> ■ 0.58–0.83 kg/m³ of WP ■ 2.56–5.64 kg/m³ of AWP ■ 0.74 to 0.76 m³/m⁻³ of i.e. ■ 50,9 €/ha of total cost for conducting a PI management ■ +70,90 €/ha (2016) and +99,60 €/ha (2017) of operating profit ■ 70.95€/h of operating saving cost in 2016 and 99.63€/h of operating saving cost in 2017

Table 1 (continued)

Author(s)	Year	Country	Precision Viticulture technologies used on case studies	Economic Analysis	Economic indicators	Results
Borgogno-Mondino E.	2017	Italy	Monitoring technologies (UAV's sensor)	The study offers insights into the potential costs and the remote sensing market for Synthetic Aperture Radar (SAPR) applications within the Italian wine sector. The unit cost of flight for four distinct scenarios has been calculated using a model specifically designed for estimating unit costs	<ul style="list-style-type: none"> • UAV flight costs (€/ha) • UAV productivity (ha/day) 	<ul style="list-style-type: none"> ■ 127.60 €/ha of unit cost of UAV's flight ■ -25 ha/day of productivity of a continuous area by UAVs
Maynard et al.	2015	Australia	Monitoring technologies (Remote Sensing Images for Vigour Zone Identification)	The study assessed Precision Viticulture (PV) technology's influence on fruit and wine quality, pricing, and costs. It used case studies and a Levelized Cost Model with a Partial gross margin analysis), incorporating industry cost data and existing literature.	<ul style="list-style-type: none"> • Gross Margin Return • Levelised Cost on Investment (ROI) 	<ul style="list-style-type: none"> ■ 37–3,134\$/ha of Gross Margin Returns ■ 5–20% of Levelised cost/tonne of products ■ 1–23% of differences in Return on Investment (ROI)
Prof-fitt and Pearse	2004	Australia and New Zealand	Monitoring technologies (Airborne Digital Multi-Spectral Imagery (DMSI) sensor).	This study outlines the economic advantages of employing precision viticulture technologies. It utilized the total gross retail production value and computed gross returns (\$/ha) across various yield zones.	<ul style="list-style-type: none"> • Gross Returns (\$/ha) for four contrasting scenarios • Total gross retail value of wine production (\$/ha) 	<ul style="list-style-type: none"> ■ 12.84 \$/ha of Gross Return using precision technologies ■ +139,480 \$/ha of wine production's total gross retail value

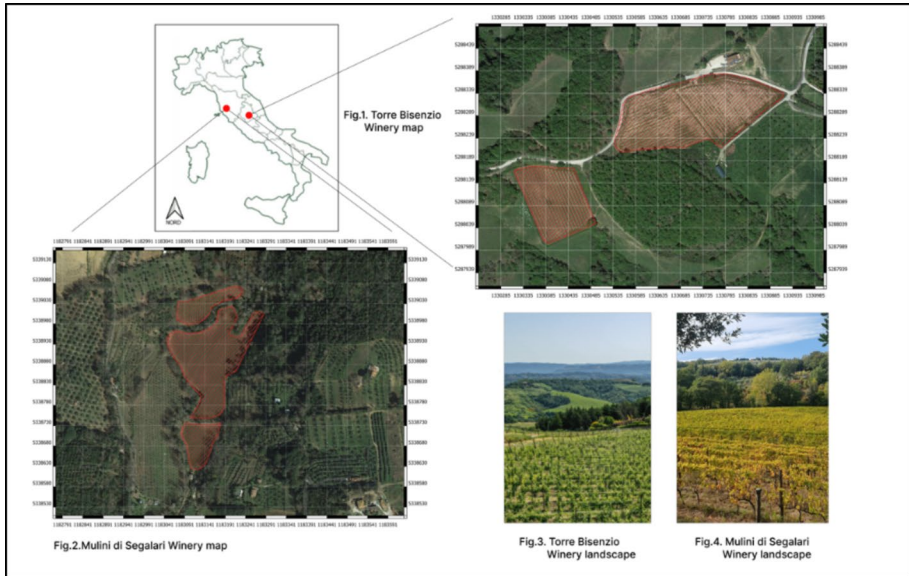


Fig. 1 Location of study areas

vineyards are farmed organically, using techniques such as spurred cordon and Guyot training, along with a fixed drip irrigation system from a well. The winery operates as an agricultural limited liability company and is directly managed by the agricultural entrepreneur, with the support of seasonal workers.

The Mulini di Segalari winery is located in Tuscany, Italy ($43^{\circ}17'32''58''\text{N}$., $10^{\circ}62'68''29''\text{E}$., 90–130 m above sea level, 15 km from the coast). The climate here is temperate (in terms of temperature and rainfall), which makes it ideal for growing vines. Compared to Torre Bisenzio, this is a small farm, with a total surface area of 7.13 hectares, of which 4.04 are vineyards and 3.06 are olive groves. From a pedological point of view, the soil is sandy-clayey, with varying gradients, and is exclusively devoted to the following vines Sangiovese Nero, Cabernet Franc, Cabernet Sauvignon, Merlot, Syrah, Vermentino. The three hectares of vineyards included in the study are certified organic and mainly use the spurred cordon training form. The Mulini di Segalari winery is an agricultural general partnership and is directly managed by the agricultural entrepreneur, with seasonal workers contributing to its operations.

Both wineries, although unique in their locations and characteristics, share a commitment to sustainable farming practices, careful vineyard management and the production of high quality Italian wines with DOC and IGT certification. In addition, the vineyard areas in both case studies fall within the two most common UAA (Utilised Agricultural Area) classes for vine cultivation, between 3 and 10 hectares, i.e. 30% of the total vineyard area (ISTAT, 2012).

Data collection and analysis

The collection of technical and economic data for the profitability analysis of wineries before and after the adoption of precision farming technologies was carried out through direct interviews with wine-growers, using a specially prepared questionnaire that took into account the structural and managerial aspects of the two wineries studied. Specifically, the first step was to identify wineries operating in Tuscany, one of the most agricultural regions in Italy, that were using precision technologies, by contacting companies that provide technical advice on the implementation of innovative technologies, and on the basis of articles published in the grey literature. The next step was to contact each winery on the list to confirm: (i) the actual use of precision technology; (ii) the specific type of technology used; (iii) the period of use of the technology, which for the purposes of the study had to be longer than one crop year; (iv) the willingness to participate in the study. From an initial list of 29 wineries, only 7 met the above criteria, of which two of the wineries had similar characteristics and both were using UAV technologies, albeit with different objectives. For each of the two wineries, interviews and informal speeches were conducted with both the owners and agronomists of the wineries between April and August 2023. Each interview lasted between 60 and 90 min. The interviews were followed by communication by e-mail and telephone in order to verify the data and, above all, to validate the results obtained.

The collected data refer, for both case studies, to four harvest years (from 2018/19 to 2021/22) and concern both the costs of the inputs introduced into the production process and the relative production values obtained. In order to proceed with the reconstruction of the company balance sheets it was necessary to gather information (technical and economic) both through the knowledge and experience of the technical representatives of the 2 wineries and with the support of official documents such as the holding file and the logbook. When prices (about technical means or production) were not available, they were estimated by means of handbooks and official agricultural price lists or by resorting to professionals (i.e. agronomists) and commercial managers of farm supply stores. The information of a technical nature concerned on the one hand the quantity and type of inputs (raw materials, capital and labour) introduced into the production process and on the other hand the grape yields obtained in the various agricultural years covered by the investigation.

On the other hand, the economic aspects concerned the unit prices applied by the wineries in the purchase of goods and services from outside the company, within the liabilities of the balance sheet, and the average unit prices at which the company's production was sold. With regard to the latter, since both companies do not sell the grapes but only the wine obtained from their processing, the companies' technicians were asked to estimate the average price paid for grapes of the same quality in the areas under investigation. In this way, the labour input required to manage the vineyard and the machinery used to carry out the cultivation operations (owned or hired, where appropriate) were reconstructed year by year. The labour rates for temporary agricultural workers were obtained from the official bulletins in force for each of the 4-year periods.

To assess the profitability of grape growing, the gross profit (GP) and gross margin profit (GMP) were calculated based on the data collected for each of the four harvest years (from 2018/19 to 2021/22), using Eqs. (1) and (2).

The first index, the GP, is obtained by deducting the direct production costs of grapes from revenues and measures how well a company is performing by monitoring its produc-

tion costs. More specifically, the GP indicator ignores the contribution of fixed capital and depreciation to the company's profitability. This methodology promotes data-driven decision-making and simplifies the comparative analysis of conventional and precision farming systems (Abadi, 2000; Kasmioi & Ceulemans, 2012).

The basic formula for computing the GP is:

$$GP = \sum_{i=1}^{12} REV - \sum_{i=1}^{12} DC \quad (1)$$

The second indicator, the GMP ratio, is obtained by subtracting explicit costs from sales, dividing the result by net sales and multiplying by 100%, giving the percentage of sales in excess of the cost of goods sold. The basic formula for calculating gross profit is:

$$GMP = \left[\sum_{i=1}^{12} REV - \sum_{i=1}^{12} DC \right] / \sum_{i=1}^{12} REV \times 100 \quad (2)$$

In Eqs. (1) and (2): GP and GMP are expressed in € and % respectively; REV is the revenue and specifically the production value, expressed in €; DC are the direct costs (labour wages, machine rentals, fertiliser, pesticide and fungicide prices, water, electricity, fuel and lubricant consumption, insurance, product maintenance fees) incurred during a crop year, expressed in €; i is an index ranging from 1 to 12, where 1 indicates the beginning of the crop year (1 November of the year) and 12 corresponds to the end of the crop year (31 October of the following year).

To measure the impact of precision technology adoption on direct costs, the operating ratio was also calculated. The operating ratio calculates the proportion of variable costs in the total revenue generated by the winery.

$$\text{Operating ratio} = \text{Directcosts} / \text{Revenue} \quad (3)$$

An index of less than 1 indicates that the income generated is able to cover the cost of the winery's variable inputs; the lower the index, the more profitable the business.

Quantitative data was integrated with qualitative information from interviews and secondary data, including filing records and logbooks, to ensure the validity of the research and to eliminate researcher subjectivity in the interpretation of quantitative data.

Results and discussion

An economic analysis of the adoption of Unmanned Aerial Vehicles (UAV) as a precision agriculture technology was carried out in two Italian wineries, Torre Bisenzio and Mulini di Segalari, which can be considered as early adopters of these modern technologies as a decision support tool. The benefits and costs were evaluated over a period of four harvest years, comparing the situation before and after the use of UAV systems to produce vigour maps.

For the Torre Bisenzio winery, the annual operating costs and revenues for the four harvest years studied are shown in Table 2. The results show that the conventional scenario has higher labour and material costs. Following the introduction of UAV systems for pest control, a gradual reduction in operating costs related to phytosanitary treatments is observed in 2020/21. Specifically, the data show a reduction in the frequency of phytosanitary treatments, from 11 times per year in the 2019/20 crop year, the year immediately preceding the adoption of the new technology, to 8 times per year in the 2021/22 crop year. This reduction led to a decrease in labour costs from 350 €/ha to 142 €/ha (−59%) and in pesticide and fungicide costs (from 214.5 €/ha in the 2019/20 crop year to 203.7 €/ha in the 2021/22 crop year), as shown in Fig. 2. The good results obtained, as stated by the interviewee, are linked to the adoption of precision technologies, despite a significant influence of adverse climatic conditions. As shown in Fig. 3, these surveys identify areas of varying vigour, helping managers to target phytosanitary treatments in vulnerable areas. According to a local online newspaper, this allows the company to make informed decisions to ensure the highest quality grapes in different vintages (Orvietoviva, 2023). This is also a company philosophy rooted in sustainability, which includes environmental responsibility and a constant focus on the quality of the grapes and wines produced (Orvietonews, 2022). The reduction in the use of pesticides is also in line with the European Directive on the Sustainable Use of Pesticides (EU Directive 2009/128/EC), which encourages a reduction in the application

Table 2 Profitability analysis of the “torre Bisenzio” case study. (Source Our elaboration on collected data)

Crop year	2018/19	2019/20	2020/21	2021/22
Unit	(€/ha)	(€/ha)	(€/ha)	(€/ha)
Revenue	9,433.99	6,883.99	10,633.99	12,133.99
Direct costs	4,873.46	4,949.26	5,416.86	5,668.72
Labor wages	3,829.79	3,863.13	3,829.79	3,813.13
Machine rental	50.00	50.00	50.00	50.00
Cost of the UAV surveys	0.00	0.00	498.07	758.23
Materials	513.67	556.14	559.00	567.36
Fertilizer	41.91	70.92	75.00	36.77
Pesticides and Fungicides	186.4	214.5	201.5	203.7
Fuel and Lubricant oil	93.73	79.09	90.80	135.25
Electricity	33.33	33.33	33.33	33.33
Insurance vineyard adverse climatic events	158.33	158.33	158.33	158.33
Maintenance fees	476.00	476.00	476.00	476.00
Insurance	4.00	4.00	4.00	4.00
Gross profit (€)	4,560.53	1,934.73	5,217.14	6,465.27
Gross margin profit (%)	48.34	28.10	49.06	53.28
<i>Labor cost related to phytosanitary treatments</i>	150.00	550.00	150.00	133.33
<i>Operating ratio (Direct costs/Revenue)</i>	0,52	0,72	0,51	0,47
<i>Operating ratio (Materials/Revenue)</i>	0,05	0,08	0,05	0,05
<i>Operating ratio (Labor wages/Revenue)</i>	0,41	0,56	0,36	0,31

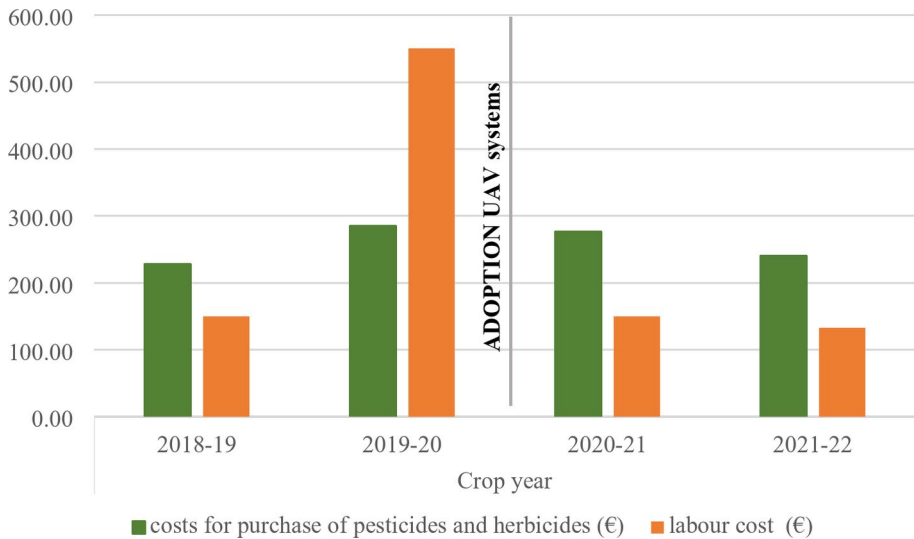


Fig. 2 Trend of phytosanitary treatments costs (€/ha) in the “Torre Bisenzio” case study

rate per hectare by improving the quality of nutrient deposition in the soil and reducing environmental pollution. The results of the first case study corroborate the findings of previous empirical investigations (Campos et al., 2020; Andujar et al., 2019) revealing that the precise guidance provided by UAV systems reduces the use of plant protection products in vineyards compared to conventional systems. However, our findings partially contrast with those of Maynard et al. (2015), who found that only medium-sized wineries benefit from the adoption of aerial imagery surveys and proximal grape yield monitoring technologies. In fact, our case studies highlight the effectiveness and efficiency of adopting these new technologies even in small and micro wineries. Having calculated the operating costs, the next step was to assess the revenue based on the average grape price in the reference area. Revenue from grape sales has consistently shown an annual growth, with a significant difference of 39.5% between the two years before and the two years after the adoption of precision technologies, due to the increasing volumes of grapes harvested.

Finally, we used the GP and GMP indicators to assess the profitability of the vineyard and the impact of the adoption of precision farming technologies. The results show that, as a result of using UAVs to obtain vigour maps and monitor plant health, the profitability of the vineyard cultivation increased both in terms of GP (+44.4%) and GMP (from 48.3% in the 2018/19 crop year to 53.28% in 2021/22), as described in Table 2. Furthermore, the operating ratio shows that the adoption of precision technologies has led to an overall reduction in the ratio, i.e. the ratio of direct costs to revenue produced, mainly due to a reduction in labour costs. These results confirm the positive impact of the adoption of precision technologies in reducing costs, improving efficiency and increasing profitability, and corroborate previous findings that the adoption of precision technologies, even in small vineyards, leads to increased profit margins as a result of higher yields, but mainly a reduction in pest control costs, with benefits that can vary from \$37 to \$3,134 per hectare compared to conventional management (Bramley et al., 2011a, b; Maynard et al., 2015; Schimmelpfennig et al., 2016).

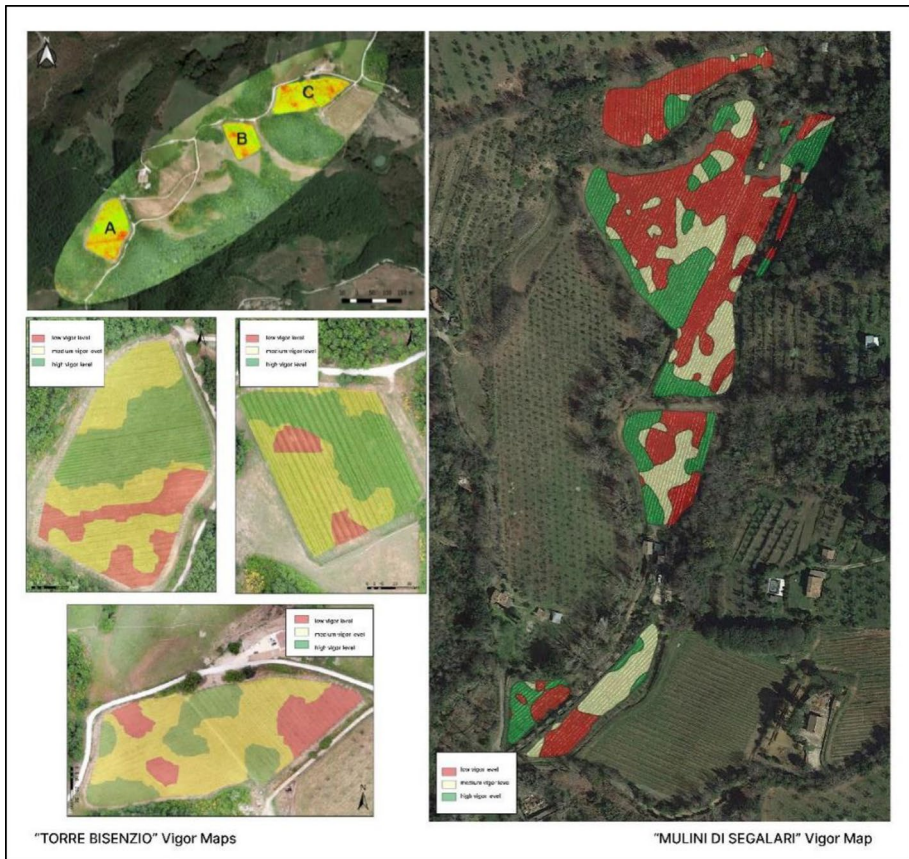


Fig. 3 Vigor Maps of vineyards examined

For the Mulini di Segalari winery, the costs and benefits of adopting precision farming technologies are shown in Table 3. It is evident that a significant proportion of the total direct costs are attributable to labour, accounting for 73.9% of the total. The material costs, on the other hand, account for 16.5% of the direct costs. In more detail, with reference to labour costs, the adoption of drones, as early as the 2019/20 crop year, resulted in a low gradual increase in labour costs of 15.7% (from 3,280.40 €/ha in the 2018/19 crop year to 3,891.25 €/ha on average in three years of adoption) and, at the same time, an increase in materials costs of 15.4% (from 544.27 €/ha in the 2018/19 crop year to 643.44 €/ha in three years of adoption). However, if we look at the different labour cost components, the results show that labour costs for phytosanitary treatments decreased by 29.7% (from €243.56 per ha in the 2018/19 crop year to €187.74 per ha in three years after adoption), while expenditure on pesticides and fungicides increased by 32.9% (from €182.95/ha in the 2018/19 crop year to €272.70/ha in three years after adoption) due to the adoption of more expensive, higher quality products. This conclusion is supported by data from the farm file and log-book, which show a reduction in phytosanitary treatments from 16 to 11 times per year. Also in the second case study, and in line with what other authors have found, the adoption of

Table 3 Profitability analysis of the “mulini Di Segalari” case study.
(Source Our elaboration on collected data)

Crop year	2018/19	2019/20	2020/21	2021/22
Unit	(€/ha)	(€/ha)	(€/ha)	(€/ha)
Revenue	9,200.00	14,300.00	9,200.00	7,500.00
Direct costs	4,260.90	5,248.93	5,312.12	5,240.60
Labor wages	3,280.40	3,901.40	3,901.40	3,870.96
Machine rental	0.00	0.00	0.00	0.00
Cost of the UAV surveys	0.00	296.30	296.30	296.30
Materials	544.27	615.00	678.19	637.12
Fertilizer	0.00	0.00	0.00	0.00
Pesticides and Fungicides	182.95	275.98	320.33	221.78
Fuel and Lubricant oil	113.61	91.31	110.15	167.63
Electricity	87.15	87.15	87.15	87.15
Insurance vineyard adverse climatic events	0.00	0.00	0.00	0.00
Organic and biodynamic certifications	160.56	160.56	160.56	160.56
Maintenance fees	344.68	344.68	344.68	344.68
Insurance	91.55	91.55	91.55	91.55
Gross profit (€)	4,939.10	9,051.07	3,887.88	2,259.40
Gross margin profit (%)	53.69	63.29	42.26	30.13
<i>Labor cost related to phytosanitary treatments</i>	243.56	197.89	197.89	167.44
<i>Labor cost related to grape harvest</i>	656.9	1313.9	1313.9	1313.9
<i>Operating ratio (Direct costs/Revenue)</i>	0,46	0,37	0,58	0,70
<i>Operating ratio (Materials/Revenue)</i>	0,06	0,04	0,07	0,08
<i>Operating ratio (Labor wages/Revenue)</i>	0,36	0,27	0,42	0,52

precision technologies makes it possible to reduce the number of treatments and the quantities of pesticides used (Campos et al., 2020; Andujar et al., 2019).

In contrast to the reduction in labour costs for treatment operations, the results indicate a 13.7% increase in grape harvesting costs following the introduction of precision technology. Indeed, in this second case study, UAV technology is being used not only for pest control but also for selective grape harvesting, reflecting a significant shift in business management. Insights gained from interviews with the CEO reveal a comprehensive overhaul of harvesting methods, with vigour maps from UAV systems as the driving factor. These results delineate different levels of vigour within the vineyards, which have been categorised as low, medium and high vigour, as visually depicted in Fig. 3. This diversity within the vineyard led to a shift from row-based harvesting to targeted harvesting within homogeneous zones, focusing on grapes with advanced ripeness. According to the winery’s CEO, the grapes harvested first were destined for the production of premium wines, which commanded a higher market price, resulting in increased wine sales revenue for the company. Precision technologies, according to an online article on the winery’s history, have clearly demonstrated their ability to improve product quality and operational efficiency, revolutionising the

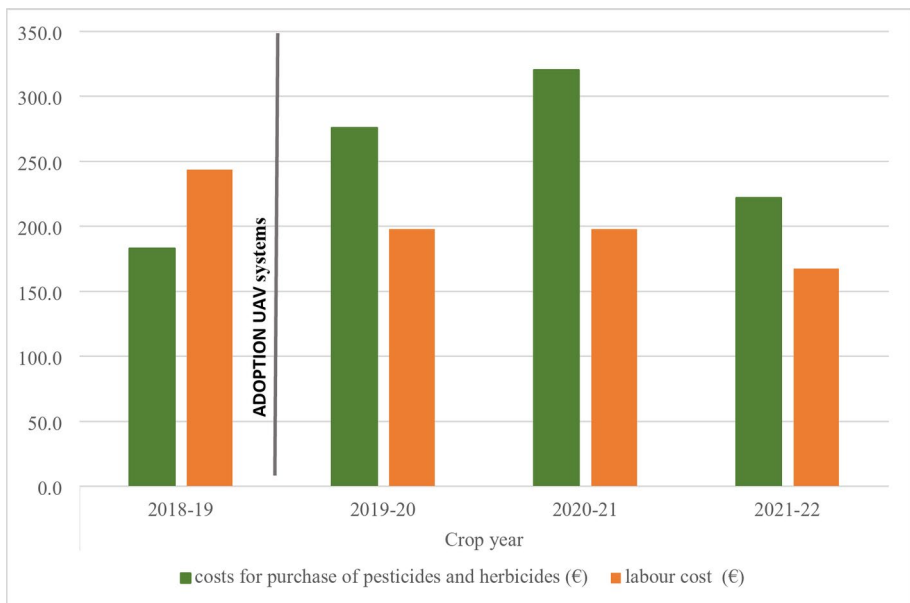


Fig. 4 Trend of phytosanitary treatments costs (€/ha) in the “Mulini di Segalari” case study

management aspect (Intoscana, 2023). The adoption of precision technologies, depending on their use in the field, can result in higher labour costs, as found by Bramley et al. (2011a, b), who reported a 47.13% increase in labour costs following the adoption of precision technologies. Furthermore, only with reference to precision technologies for yield monitoring, Di Gennaro et al. (2019) point to limited cost savings without considering the cost of purchasing or renting UAV systems

Comparing productivity levels before and after the introduction of precision UAV systems in our second case study, the GP showed an apparent reduction. This result is partly due to selective grape harvesting, but also to unfavourable weather conditions, especially in the last crop year. Similarly, the GMP decreased from 53.6% in the 2018/19 wine year to an average margin value of 45.23% over the last three years (−8.4%), as shown in Table 3. The analysis of the operating ratio for the second winery shows that the share of direct costs in revenue has also increased as a result of the adoption of precision technologies. In fact, as can be seen from the data in Table 3, the incidence of materials increases due to the increase in the price of the inputs used, and the operating ratio that takes into account the cost of labour increases significantly due to the higher cost of selective harvesting. In this second case study, the adverse climatic conditions experienced in the 2019/20 and 2020/21 crop years lead to a significant increase in costs related to herbicides and pesticides (Fig. 4). Insights gathered from interviews with vinegrowers, alongside phytosanitary regional reports, underscore a marked escalation in pest infestations in the studied areas, a phenomenon exacerbated by climate change. In recent years, climate change has exacerbated critical stresses such as water shortages and increased temperatures, which have compromised the physiological integrity of vines, making them more susceptible to pests and diseases (Petriashvili et al., 2023). Especially higher temperatures can accelerate pest life cycles, leading to more frequent and severe infestations (Burchett & Burchett, 2017), reducing yields and

negatively impacting profitability. (Campos et al., 2019; Sassu et al., 2021). In response to these challenges, the adoption of precision technologies, particularly for plant health monitoring, can make a significant contribution to reducing negative impacts, as demonstrated in the Torre Bisenzio case study. Vigor maps generated by UAVs provide actionable insights that enable timely interventions, ultimately supporting sustainable practices while mitigating the economic impact of climate change on vineyard profitability (Campos et al., 2019; Matese et al., 2019; Pádua et al., 2019).

The analysis of the two case studies confirms the profitability of using precision farming tools to monitor vine cultivation and the versatility of these tools, not only for weed control but also for targeted selective harvesting to improve the quality of the harvested grapes. However, the adoption of UAV technologies presents numerous barriers that can hinder their uptake and long-term sustainability. The high cost of deployment, which includes not only the purchase price but also maintenance costs, necessary software and operator training, can be prohibitive especially for small wineries (Bawa et al., 2024). There is also a rapid learning curve for UAV use and data interpretation, which can deter farmers who lack specific skills from integrating drones into their farming practices (Makam et al., 2024). Not insignificant, as Singh and colleagues (2024) point out, are barriers of a technical nature (including stability and reliability, drone sensor quality, drone payload capacity, flight duration), and regulatory nature, which can be complex and restrictive. As a result, especially for smallholder farmers, the adoption of PATs, and UAVs in particular, requires supportive policies to address cost and technological challenges (Santesteban et al., 2019; Rose et al., 2021; Carrer et al., 2022). Our case studies shed light on these barriers, paving the way for future technological solutions.

Implications

Based on our results, we can draw both theoretical and practical implications. From a theoretical point of view, the study contributes to enriching the literature on the benefits of adopting precision farming technologies in a strategic sector such as wine grape production, based on real data. More specifically, the profitability analysis, based on the temporal analysis of gross profit and gross margin, confirms the results of previous empirical studies, demonstrating the potential of UAV technology for pest monitoring and selective harvesting, and revealing gross margin values that justify the commitment of winegrowers in the digital transition process. The possibility of reducing vineyard management costs or improving product quality and reducing environmental impact is in line with the principles of sustainability and responsible management.

The empirical results of the present study provide significant insights for winegrowers wishing to improve their business performance in terms of sustainability. The results highlight the versatility of certain precision farming technologies, like the UAV technology used in the two cases to monitor plant health for pest control, but also for selective grape harvesting to achieve high levels of harvest quality. The significant reduction in labour costs, due to a reduction in the number of phytosanitary treatments and the quantities of pesticides and fungicides used, demonstrates the effective and efficient use of this technology. This makes it possible to improve the quality level of the grapes and to reduce the consumption of resources such as labour and materials, with environmental benefits. Therefore, these results

can be an incentive for many growers and non-growers to manage their farms in a more responsible and sustainable way. Although the results demonstrate the profitability of precision farming techniques, confirming previous findings, there remains a general reluctance among farmers to adopt these technologies due to the cost and difficulty of using them. The high investment and maintenance costs of precision technologies, including UAVs, are a major challenge, especially for small and medium-sized enterprises. Funding in the form of subsidies or low-interest loans from governments could overcome this initial barrier. These subsidies could be complemented by support from agricultural and rural development policies to compensate for the adoption of technologies that reduce the environmental impact of vineyard management techniques. To reduce the financial burden on farms, one solution is to turn to companies that offer drone services at reasonable prices. As the two case studies show, the adoption of precision technologies is dependent on specialised technology companies that can provide IT support and help farmers and technicians to assess different situations accurately, efficiently and cost-effectively. In light of this, it is essential that both companies and scientific research invest in defining simple, intuitive, low-cost and functional technological solutions to achieve business objectives. For example, projects such as VineRobot, Wall-Ye, Vitirover, VinBot, Agrimet have developed or are trying to develop field robots equipped with sensors and cameras that allow precise vineyard monitoring, productivity improvement and autonomous tasks, marking a significant leap in vineyard management practices. With this in mind, and considering that for farmers these data-driven economic benefits can positively influence their decision to adopt precision technologies, agricultural extension services could be offered to them. These services can play a key role in providing farmers with the knowledge and tools they need to access and use precision technologies, from using the technologies themselves to reading and interpreting the data provided. This would raise awareness among managers and workers of the potential of these innovative technologies in relation to specific business needs, and increase the skills required to adopt precision technologies. In addition, traditional extension systems can be complemented by digital, mobile or tablet-based systems to facilitate information sharing and learning. These services are in line with the objectives of the EU's rural development programmes, in particular the need to promote knowledge transfer and innovation in the agricultural sector in order to increase the profitability and competitiveness of businesses in the sector. In this context, governments and institutions can play a key role in the diffusion process. For example, several EU programmes support the introduction of precision technologies in agriculture. Some measures of the Common Agricultural Policy 2023–2027 provide incentives for the adoption of technologies that rationalise the use of fertilisers, plant protection products and irrigation water. These priorities were confirmed at the end of December 2024 by the Council of the European Union on the future of agricultural policy after 2027. In fact, the Council considers it necessary to support farmers in the adoption of innovative and intelligent technologies that can facilitate the digital transition and contribute to the achievement of environmental and climate objectives. However, the issue of purchasing precision technology or the cost of the service of reading and analysis remains a problem, particularly for very small wineries. For the latter, which have difficulty in accessing subsidies and funding, the possibility of using these precision technologies through consortia could be explored. In this case, technology companies could help small enterprises to collect, manage and analyse data.

Conclusions, limitations and future research direction

In this study, the economic impact of the adoption of one of the many existing precision agriculture technologies, the UAV, for the production of vegetative vigor maps, was examined in two Italian wineries. Through a time profitability analysis of the vineyard, before and after the adoption of this technology, our results show the usefulness and economic viability of this technology in the viticultural field, and especially its versatility. The results confirm the positive influence of the adoption of precision technologies in terms of reducing variable costs, in particular labour and treatment costs. In addition, as the analysis of the two case studies suggests, UAV technology is used with a dual purpose. On the one hand, for the production of vigour maps, which make it possible to identify problems such as diseases and, consequently, to plan phytosanitary treatments so that the problem can be tackled in good time. On the other hand, for selective grape harvesting, which allows a significant improvement in the quality of the grapes harvested, resulting in a better overall quality of the wine, which commands higher prices on the market.

The profitability analysis has shown how the use of UAV technologies can improve the profitability of grape growing, as a result of greater efficiency in the use of resources. As observed in the Torre d Bisenzio case study, the improvement in economic performance can be attributed to the reduction in vineyard management costs, despite the cost of renting the drone, due to the reduction in the number of phytosanitary treatments for pest control. This inevitably has an impact on the sustainability dimension of the use of precision farming tools. Conversely, as shown in the case study of the Mulini di Segalari winery, the adoption of selective harvesting technology leads to an increase in direct costs and consequently to an increase in the time required to carry out the harvest, with a reduction in the gross profit margin. This result should not be interpreted negatively, bearing in mind that, as already mentioned, a selective harvesting system makes it possible to obtain grapes of better quality for the production of premium wines.

This study is not without limitations, mainly related to the analysis of two case studies and one precision farming technology, compared to the plethora of tools currently available on the market, which do not allow the generalisation of results. Indeed, the paper has the limitations of case study research, which suffer from the statistical representativeness and generalisability of the results. However, the richness of the data and results can be useful for other wineries besides those studied. Managers of companies with similar characteristics in terms of size and pedo-climatic conditions can use the results of the study to understand the potential benefits of adopting UAV technologies and versatility, starting from real data, and evaluate the potential implementation. In addition, it is important to note that the results of the profitability analysis are closely related to the environmental context in which the two companies operate, the uncertainty of environmental conditions, the dynamics of market prices of technical inputs and products. As demonstrated in the second case study, the variability of climatic conditions (temperature, rainfall, humidity, solar radiation) can have a significant impact on the spread of pests and insects, affecting yields and the quality of the grapes harvested. However, the results highlight the usefulness of precision technologies for cost-effective and sustainable vineyard management. The possibility of reducing production costs through the rational use of resources is a real opportunity for companies operating in the sector, enabling them to obtain higher quality and more sustainable grapes

and thus satisfy a market segment made up of consumers who are increasingly sensitive to environmental issues.

Future studies should analyse business cases that integrate multiple precision technologies in addition to UAVs to verify the combined economic and environmental impacts. In particular, with regard to the environmental sustainability of precision farming technology, it would be useful to scientifically measure the environmental impact of conventional farming systems and systems managed with precision farming tools. Finally, given the high cost of acquiring data collection services, it would be useful to study the propensity and willingness of winegrowers to pay for the adoption of precision farming tools.

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

Declarations

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

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