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Article

Does precision technologies adoption contribute to the eco-nomic and agri-environmental sustainability of Mediterranean wheat production? An Italian case study

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Abstract: The European Green Deal has set a concrete strategic plan to increase farm sustainability. At the same time, the current global challenges, due to climate change and fuels and commodity market crisis, combined with the Covid-19 pandemic and the ongoing war in Ukraine, comprise the need for quality food, but also the reduction of negative external effects of agricultural production, with fair remuneration for the farmers. In response, precision agriculture has great potential to contribute to the sustainable development. Precision agriculture is a farming management that provides a holistic system approach to managing the spatial and temporal crop and soil variability within a field to improve the farm's performance and sustainability. However, farmers are still hesitant to adopt it. On these premises, the study aims to evaluate the impacts of precision agriculture technologies on farm profitability, agronomic and environmental management by farmers adopting (or not) these technologies, using the case study method. In detail, the work focuses on the period 2014-2022 for two farms that cultivate durum wheat in Central Italy. The results suggest that the implementation of precision technologies can guarantee economic and agri-environmental efficiency. Results could serve as a basis for developing a program to start training in farms as well as suggest policy strategies.

Keywords: precision agriculture; durum wheat; Italy; case study; economic impact; agro-environmental im-pact; sustainability; nitrogen efficiency; profitability

1. Introduction

The transition towards a sustainable agricultural system is a priority to ensure the Sustainable Development Goals (in particular, SDGs 2.3 and 12.4) of the United Nations Agenda 2030, as well as the European Green Deal objectives. In particular, the European Commission has set a concrete strategic plan to reduce the use of chemicals and fertilizers, enhance biodiversity and assist farmers in decision-making processes to increase farm sustainability. In addition, the current historical period and geopolitical framework lead to significant impacts to the agricultural sector. In particular, the wheat production is currently affected by a significant stocks' depletion and price volatility. Starting with the Covid-19 in 2020, the unexpected spread of the pandemic and the resulting lockdown and closures around the globe led to an unavoidable critical situation, related to the export restrictions and the changes into the purchasing behavior of wheat derivatives, like flour [1]. These circumstances have put Europe and countries like Italy in severe deficit conditions in terms of stocks, deriving also from the increased price volatility. Price volatility can be partially traced to uncertainty over the flow of supplies, depending principally to current production and existing stocks. The U.S. Department of Agriculture estimates that global wheat ending stocks for the 2022/23 marketing year will be around

267 million metric tons. More than half of these stocks will be held by China, while EU, USA, and other major exporters account only for 20%. China's wheat stocks increased by over 160% between 2012 and 2020. This was largely due to changes in China's agricultural policy, which increased producer support prices, resulting in the accumulation of large government stockpiles [2]. By contrast, wheat stocks held by the rest of the world declined by 12% over same period.

Moreover, the ongoing war in Ukraine has contributed to reduce the wheat production in the country, disrupting the markets worldwide. The Russia-Ukraine war has caused the highest increase, since 2008, in levels and volatility of prices in agricultural markets, for wheat, creating an ongoing vulnerability for global food security [3,4,5,6]. One difference between the two periods is the scale of the disruptions in staple food markets. While the period of initial pandemic lockdowns saw some isolated volatility, the Russia-Ukraine war is affecting all major food staples [7]. The relative tightness of global stocks suggests that price volatility will continue to remain high relative in respect to the past 10 years. Going forward, rebuilding inventories of wheat and other key global crops would help to reduce both prices and price volatility. By the same token, tight stocks mean that an unforeseen production shortfall in a major wheat producing region would likely send prices sharply higher again (as in 2010/11 and 2012/13) and result in increased price volatility.

In addition, fertilizer prices are a determinant factor more now than at the beginning of the pandemic, where the situation was already compromised. Even if the prices were at extremely high levels before the war began, they are still continuously rising; nonetheless Russia, an important fertilizer producer, is considering an export ban. Furthermore, the energy crisis due to the high prices for natural gas, an essential feedstock to produce nitrogen-based fertilizers such as urea and ammonia, is contributing to boost fertilizer prices as well [8]. Higher fertilizer prices could depress production, leading to less grain on the market in 2022 and putting further upward pressure on already-high food prices [9,10]. In this context, it is important to analyze the cereal sector, with reference to the wheat production, which remains a mainstay of nutrition both in Italy and worldwide. This is because it is essential to understand how to cope with current crises, considering the market dynamics that are being determined such as the rise in fertilizer prices and the volatility of wheat prices, factors that would make the cultivation of wheat (and cereals in general) unprofitable.

As a consequence of the global instability, the implementation of sustainable resilient strategies in agriculture is crucial. This entails the implementation of innovative agricultural practices that increase the productivity and income of farmers and, at the same time, can help to maintain ecosystems. Therefore, one of the actions to implement is reducing the quantity of inputs, in particular fertilizers, while maintaining production to protect both the environment and the income of farmers [11,12].

A key factor for sustainable agriculture is the introduction of digital technologies, which can help farm management through better-informed and timely decisions. These new technologies are known by the term Precision Agriculture Technologies (PATs), a farming management concept based on observing, measuring, and responding to inter and intra-field variability in crops [13]. According to an official report jointly published by ITU and FAO in 2020 [14] "digital agriculture has the potential to contribute to a more economically, environmentally, and socially sustainable agriculture, while meeting the agricultural goals of a country more effectively".

From the beginning of the '90s, different authors have discussed about the agri-environmental and economic effects derived from the application of PATs [11,15,16,17,18,19 ,20,21]. In detail, most of the papers deals with environmental sustainability. The environmental benefits of precision agriculture (PA) derive mainly from the optimization of the management of crop inputs as seeds, fertilizers (especially the efficient use of nitrogen), pesticides, irrigation water and diesel, which often results in a reduction in their consumption, without a decrease of the yield. It is notable that some studies report how the quantity of inputs does not decrease, but their use is optimized to avoid waste and pollution [12,22]. In addition, it emerges that, from an environmental point of view, through PATs it is possible to improve the soil proprieties (sustainable nutrient management) and reduce greenhouse gases emissions [23,24,25]. Finally, the optimal management of weed is underlined [26,27].

The research on precision agriculture applied to the cereal farming started later, in 1997. In this scenario, it is notable from Figure 1 the increasing interest of the academia in this topic, with an exponential increase in the number of documents (articles and reviews) available per year. The most producing countries regarding PA adoption in cereal farming cultivation are the United States, China, and Australia, while Italy ranks just fifth.

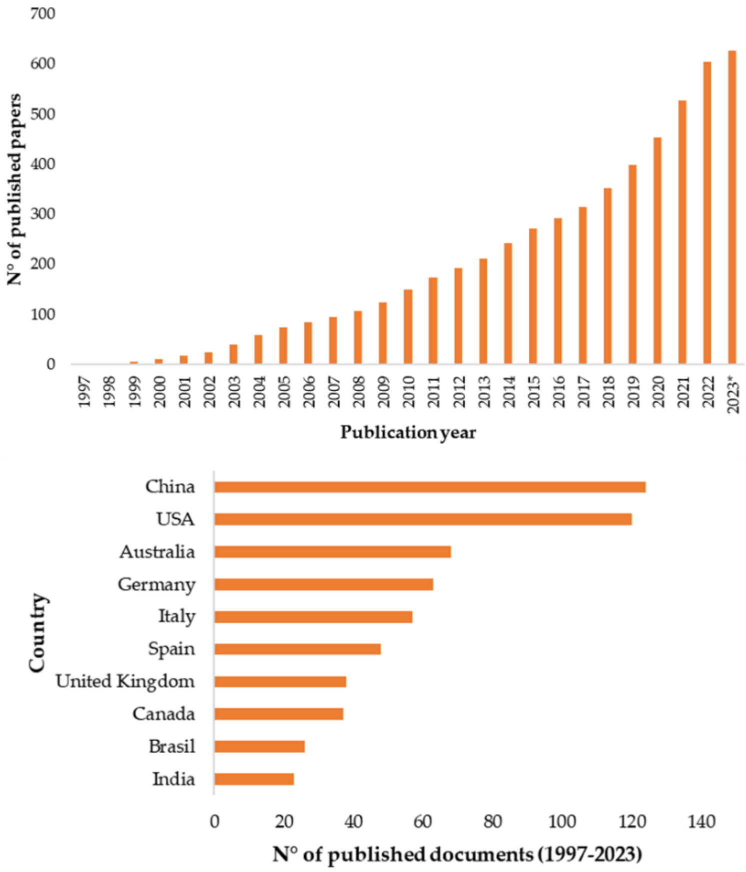

Figure 1. Number of available papers (articles and reviews) and top 10 countries about PA applications in cereal/wheat production (*Papers published as of March 2023).

Considering the growing population and the necessity of safe food, establishing methods to increase the yield of staple crops, like wheat, without compromising the sustainable development of future generations, is a challenging task. The implementation of PATs, like variable rate application systems, could improve productivity, proving support to both producers and consumers [28,29,30,31,32,33]. In the pool of available documents, only few studies assess the economic sustainability of PA application in the cereal sector [34,35,36,37]. The economic benefits regard a general reduction of production costs, especially due to the correct management of crop inputs (reduction of pesticides and nitrogen) and an increase of productivity of the farm. The major economic benefit is recorded in the decrease in labor costs and cost saving of fuel. However, an increase in total costs due to the capital invested in technology is highlighted.

However, adoption of PA tools is yet far behind expectations, in part due to limitations in quantifying and demonstrating its economic and environmental benefits, insufficient detailed knowledge on technological functions, small farms managed by older farmers and the deficiency of an incentive system [13,38,39,40,41,42,43,44,45,46].

On these premises, this paper evaluates the impacts of PATs on farm profitability, agronomic, and environmental management by farmers adopting (or not) these technologies, using the case study method proposed by Yin (2009). In detail, the work focuses on the period 2014-2022 for two farms (A and B) that cultivate durum wheat in Central Italy. Farm A uses PATs since 2018; farm B has conventional agronomic management. The farm profitability is explored using economic Key Performance Indicators (KPIs). In addition, to understand what will happen to farm B if it decides to adopt the PATs package of farm A, a simulation was performed for the year 2022.

On the other hand, from an agri-environmental perspective, fertilization management is one of the most relevant targets of the PA. In particular, the nitrogen (N) deriving from fertilizers, when inefficiently used in crop production systems, can move from agricultural fields, contaminated surfaces, and groundwater resources, and contribute to greenhouse gas emissions (GHG) [47]. Since the interaction between the N rate, soil, weather, and crop response is a complex system, the management of this nutrient is the key aspect that distinguishes PA from conventional management [48,49]. Thus, the N environmental and agronomic efficiency is measured in this paper with the estimation of the nitrogen agronomic efficiency (NAE) index. This paper is structured as follows: Section 2 describes materials and methods; Section 3 presents the results and discussion. Finally, Section 4 concludes.

2. Materials and Methods

2.1 Study area and data set

The work focuses on the period 2014-2022 (9 years) for two farms (A and B) that cultivate durum wheat (*Triticum turgidum* subsp. *Durum Desf*) in the Marche Region (Central Italy) (Figure 2).

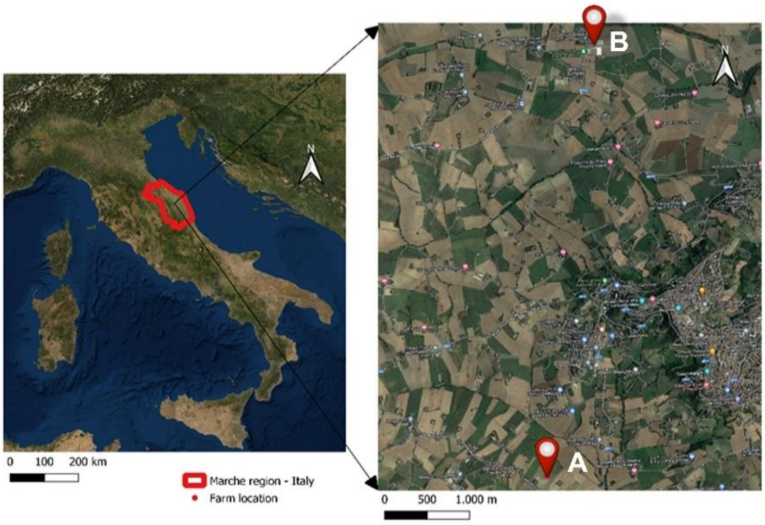

Figure 2. Marche region and experimental farm's location.

The climate of the study area is meso-Mediterranean based on the Walter & Leith Climate Class (Figure 3), which is characterized by mean annual precipitation of about 768 mm and a mean annual temperature of 17.2 °C with monthly means ranging from 9 °C in February to 29 °C in August. There is a potential frost from February until March and a period with a high probability of drought from June to August. The soil of the study area is classified as silt-clay texture.

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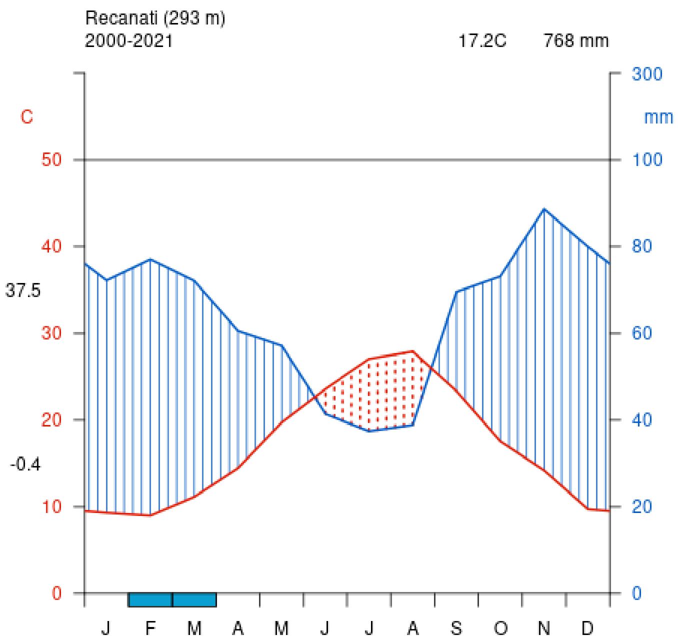

Figure 3. Walter and Lieth climate diagram of the study area (2000–2021 long-term series).

The two farms are agronomically managed differently; farm A acquired the first PA package in 2018, starting to adopt it in 2019. This period is considered the years of "technical change", in which farm A has fully implemented the use of the PAT package considered in the present study. In line with the subdivision made by Finco et al. [21], the PA package acquired by farm A includes:

i. Guidance systems (driver assistance, machine guidance, controlled traffic farming).
ii. Recording technologies, (soil mapping, soil moisture mapping, canopy mapping, yield mapping).
iii. Reacting technologies, (variable-rate irrigation and weeding and variable rate application of seeds, fertilizers, and pesticides).

On the other hand, farm B has conventional agronomic management in all the years of this study. Figure 4 represents the experimental design of the case study.

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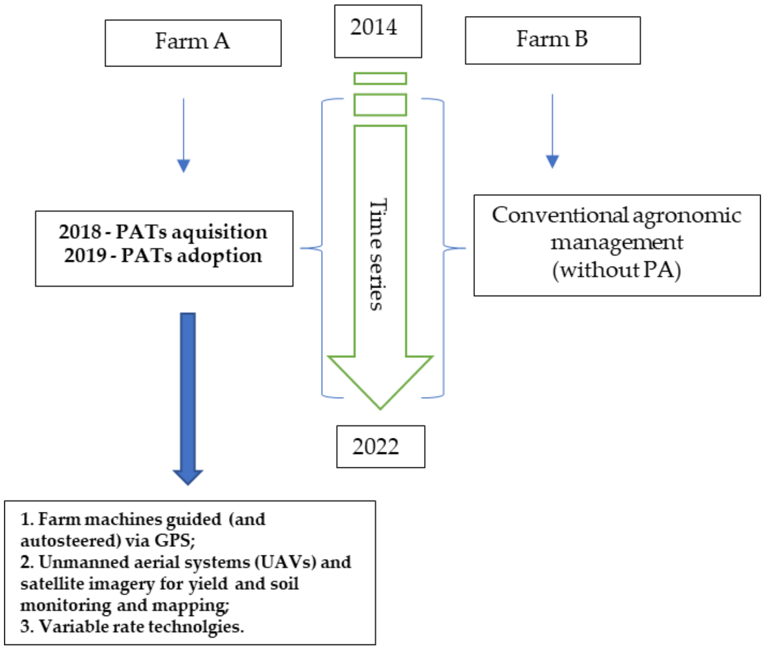

Figure 4. Experimental design.

We outline that farm A was selected as it represents one of the few pioneering Italian farms that decided to adopt PATs. On the other hand, farm B was chosen as it is similar to farm A in nature, size, work, location, and objectives. In the logic of this study farm B works like a "control" case for not yet adopting PA technology. Although it does not have a specific drive for innovation, farm B is still a big farm in size (compared to the regional and national median). Moreover, as it can be seen from the data (Table 1), farm B is capable of levels of profitability almost in line to the median operating profit per hectare (calculated net of European CAP supporting payments applied to the durum wheat production) obtained by the farms larger than 40 hectares and specialized in cereal farming in Central Italy.

Farm A and Farm B, while both producing durum wheat, are different from each other both structurally and from the point of view of the entrepreneurial and management logic that guides the strategic and operational choices. Farm A is a farm of about 400 hectares cultivated using minimum tillage regime and almost entirely irrigated. Three quarters of the hectares are positioned in flat areas, and the rest in hilly areas. Farm A's mission is explicitly oriented towards technological innovation. About half of the farm UAA is used for the cultivation of cereals, including corn, while about a quarter of the UAA is used in the production of industrial legumes. It is important to note that farm A is integrated up-stream along the supply chain with an important Italian seed industry. Besides, farm B is a farm of about 110 not-irrigated hectares cultivated using conventional tillage regime, located in hilly areas, and almost entirely occupied by cereal and forage crops.

For contextualizing the two case studies in the territorial framework, a comparison between them and our elaboration on the FADN sample of cereal farming in Central Italy was carried out using basic profitability indicators – i.e., productivity, average value (price), gross profit, operating profit (Table 1). The historical series analyzed in Table 1 is divided into two periods according to the year of adoption of the PA by farm A in 2018.

Table 1. Performance indicators comparison between FADN database and the two selected case studies. Indexes' base value: Central Italy.

	UAA durum wheat	Average yield	Average yield index	Average durum wheat price	Average durum wheat price index	Gross profit	Gross profit index	Operating profit	Operating profit index
	ha	**t/ha**		**€/t**		**€/ha**		**€/ha**	
Central Italy farms > 40 ha (210-2018)	15.2	4.7	1.00	222	1.00	478	1.00	295	1.00
Farm A (2014-2018)	87.6	5.66	1.18	257	1.16	776	1.62	498	1.69
Farm B (2014-2018)	54.2	6.2	1.31	213	0.96	494	1.03	294	0.99
Farm A (2019-2022)	103.0	5.4	1.14	392	1.76	1,401	2.93	1,019	3.45
Farm B (2018-2022)	57.0	5.9	1.26	369	1.66	1,275	2.67	1,075	3.64

Based on Table 1:

1. Productivity: for both periods considered (2014-2018 and 2019-2022), the two case studies are both considerably more productive than the median value of productivity referred to the sample of farms (greater than 40 hectares) producing durum wheat in Central Italy. Nevertheless, in the period 2019-2022, that is the period after the acquisition of the PA technology by farm A, both farms A and B slightly lost productivity compared to their levels in the previous period.
2. Price of the durum wheat produced: in the period 2014-2018, farm A proves to possess a capacity to enhance production with a notable premium price compared to Central Italy (+16%) and farm B (+20%). This difference in price is due to the fact that farm A markets its product as seed wheat, a niche market in respect to the mainstream production of semolina wheat. In the period 2019-2022, post-PA adoption by farm A, the world changed drastically due to the double crisis (pandemic and the war in Ukraine) which, as we know, has led to a shock on the commodity market. Therefore, the surge in profit margins per hectare experienced by both case studies is due to the short-term economic prospects.

3. Profitability (2014-2018): in the period 2014-2018, the operating income generated by every hectare of durum wheat produced by farm A is 69% higher than that of Central Italy and 70% higher than that of farm B. This evidence indicates a much greater cost efficiency experienced by farm A in its PA pre-adoption period with respect both to the median context and to farm B. On the other hand, during 2019-2022, both case studies show an operating income which increases considerably because of the supply shock within the European market. At this regard, it is interesting to note that the difference in competitiveness between the two case studies observed in the previous period has disappeared as indicated by the operating income settling on the same level for both the farms.

The economic results obtained by farm A to produce durum wheat in the pre-adoption period (2014-2018) in comparison to that of the reference context are not surprising; in fact, from a managerial point of view, farm A is a farm characterized for being explicitly oriented towards efficiency and for having a very high propensity to innovate which is an atypical attribute in the agricultural context investigated as confirmed by the Smart AgriFood Observatory in 2021, the Italian UAA managed with precision agriculture techniques is around 4%.

Farm A relies on a managerial structure given by 3 managers – i.e., the managerial structure coincides with the farm ownership – plus three full-time workers (all three highly skilled agricultural technicians). One of the three managers is a young, specialized technician responsible for the computerized and automated farm management since the acquisition of the PA technology in 2018.

Instead, despite being a larger and more profitable wheat producer compared to the median value of the sample of cereal farms in Central Italy, farm B is characterized by a traditional management structure which does not employ full-time workers and where the management work and the work in the fields are both carried out directly by the entrepreneur and his family.

Finally, focusing on nitrogen management, Table 2 lists all the practices applied by both farmers, acquired through the field notebooks.

Table 2. Agronomic management practices of the farms.

Farm A	
Field Activities	**Period**
Ploughing (40 cm)	October
Harrowing	November
Sowing	November
Pest control: Azoxystrobin, Cyproconazole	March
1st N fertilization – VRT[1]	March
2nd N fertilization – VRT[1]	April
Harvest	July
Farm B	
Field Activities	**Period**
Chisel (25 cm)	October
Harrowing	November
Sowing	November
Pest control: Azoxystrobin, Cyproconazole	March
1st N fertilization	March
2nd N fertilization	April
Harvest	July

[1]VRT: Nitrogen fertilization performed with the Variable Rate Technology

2.2 Economic analysis

The economic analysis aims to explore farm profitability in adopting or not PATs through indicators, by comparing two case studies (farm A and B) based on Yin's case study design [50]. This approach was chosen because the focus of the study is a contemporary phenomenon characterized by a small number of pioneering adopting PA.

To carry out this study, a profitability analysis was performed, employing financial ratios [51,52]. This analysis allows comparing the two farms, A and B, similar in size, locality, and crop system; in this way, the understanding of the discrepancies in the results, determined by a different management approach and in the propensity to adopt new technologies, can emerge [53]. We restate that farm A invested in precision farming technology since 2018, while farm B has not (yet) invested in precision farming technology but operates under the conventional management system, and it is considered a possible "target farm" that could adopt PA.

Thus, we designed our case study as follow:

- The profitability of durum wheat production performed by the PA adopting case study (farm A) has been assessed by comparing how the profitability indicators evolve before and after the adoption period (2014-2018 vs. 2019-2022).
- Besides, the incidence of Pats adoption in terms of IC results has been assessed comparing the indicators of the PA adopting farm (farm A) to that of the not-adopting farm (farm B).

By being limited to a specific crop, the analysis has been conducted using margin ratios (income statement analysis) as indicators of profitability but not return ration (balance sheet analysis), since this type of indicators would have required an analysis of the profitability of the farm business taken as a whole. Instead, this study focuses only on durum wheat profitability, meeting the objectives of the Operational Group SMART AGRICULTURE TEAM financed by the Rural Development Program (RDP) Marche 2014/2020, sub-measure 16.1.

It is also important to point out that this economic analysis was not constructed as an experimental field trial but as a comparative case study conducted within real farms operating on the real market. In fact, our goal is not to directly (experimentally) evaluate the effect of some PA device on the crop profitability; rather, the objective is to analyze basic crop profitability measures and indices during the period of PA adoption process. At this regard, while supporting the necessity of carrying out experimental trials to verify the economic *efficacy* of adopting specific technologies to specific crops, we underline that also the economic *effectiveness* evaluation of technology adoption carrying it out in the “real farm” productive space can generate further elements of analysis useful to understand the determinants of the adoption process. Our work falls into this second category of studies on technology adoption *effectiveness*.

The efficiency and effectiveness have been measured against the KPIs listed below:

- Productivity
  - T/ha
- Gross Profit (per hectare)
  - Revenues (RV) – Variable Costs (VC)
- Gross profit Margin
  - (RV – VC)/RV
- Operating profit (per hectare)
  - Gross Profit – (PA capital depreciation quota – land for rent quota – administrative and general expenses quota
- Operating profit margin
  - Operating profit/RV

All the data useful for this analysis were obtained by mean of in-depth interviews to the agribusiness entrepreneurs of the two farms.

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2.3. The nitrogen agronomic efficiency index (NAE)

To measure the environmental and agronomic efficiency, the nitrogen agronomic efficiency (NAE) index was calculated by the following formula (Eq. 1):

$$NAE = \frac{Yield\ harvested\ (kg/ha)}{Nitrogen\ provided\ to\ the\ crop\ (kg/ha)} \quad \text{(Eq. 1)}$$

The NAE is the ratio between the total yield harvested (kg/ha) and the nitrogen provided to crop (kg/ha). The higher the NAE value, the greater the nitrogen use efficiency for production purposes. At crop maturity, the yield data was collected with a combined harvester for the entire durum wheat production area. The yield data (t/ha) was calculated from measurements taken at the time of delivery to the consortium.

3. Results and discussion

3.1. Economic results

In this paragraph, the main economic results will be presented. Table 3 shows the comparison between farm A and B from 2014 to 2022 in terms of productivity, cost efficiency of the production process, and profitability.

Table 3. Economic analysis.

Harvest year	Productivity (t/ha)		Durum wheat price (€/t)		Variable costs (€/ha)		Variable cost ratio (A/B)	Gross profit (€/ha)		Gross profit ratio (A/B)	Operating profit (€/ha)	
	A	B	A	B	A	B		A	B		A	B
2014	6.40	6.20	287.30	230.00	580.40	702.50	0.83	1,183.32	598.50	1.98	889.89	398.50
2015	4.90	5.80	306.40	240.00	600.50	712.50	0.84	817.86	554.50	1.47	511.60	354.50
2016	5.70	5.80	213.00	180.00	588.80	672.50	0.88	576.30	246.50	2.34	409.28	46.50
2017	5.60	6.00	245.00	200.00	564.85	677.50	0.83	753.84	397.50	1.90	377.41	197.50
2018	5.20	7.00	234.00	215.00	600.55	709.50	0.85	548.99	670.50	0.82	300.90	470.50
2019	5.60	5.50	270.00	245.00	572.80	662.50	0.86	898.87	560.00	1.61	410.22	360.00
2020	5.90	6.50	326.60	270.00	592.58	698.50	0.85	1,296.09	93.,50	1.39	965.21	731.50
2021	5.30	5.80	480.00	470.00	605.00	692.50	0.87	1,879.00	1,908.50	0.98	1,528.29	1,708.50
2022	4.70	5.50	490.00	490.00	771.40	1017.50	0.76	1,531.60	1,699.50	0.90	1,170.97	1,499.50

1) Productivity: land productivity is a very complex indicator that depends on many variables involved. In our case study, the data show that the most productive farm is the one that does not adopt the PA: farm B. Moreover, what is noted is also a slight declining trend in productivity for both farms, and perhaps this evidence could be related to the change in atmospheric and climatic conditions in the medium term. However, this is a hypothesis that should be verified using statistically representative samples of cultivated areas. Then, focusing the attention on the post adoption period, we note that farm A shows an increase in productivity in the 2019-2020 period followed by a decrease in productivity in the period 2021-2022. Again, the owners/managers of farm A attribute these trends as essentially linked to environmental conditions and not directly linked to the use of PATs which, among other things, should not be a factor of productivity increase but of cost optimization for any given level of productivity.

2) Cost efficiency: regardless of the use of the PATs, looking at the trend of variable costs and the variable costs ratio, it emerges that farm A is a farm structurally more efficient than farm B, while in terms of PA cost effectiveness, until 2021, the variable costs ratio remains substantially constant. Therefore, no signs of PA adoption efficacy are observed. Things change in 2022. Indeed, the variable costs ratio between farm A and farm B falls from 0.83-0.87 (in trend) to 0.76. Although this is an observation of only one year, so not very meaningful if seen in isolation, it still allows us to make a hypothesis: with raw material prices at the levels of 2022, the cost optimization of the production process using PATs could become significant and relevant. Obviously, this hypothesis should be tested experimentally; nevertheless, our data indicate that the farm that adopts a PAT management shows a resilience in terms of increase in the production cost per hectare, much greater than the case study that does not adopt.

3) Gross profitability: interesting information can emerge if observing the gross profi. First, in the pre-adoption period, farm A shows to be capable of much higher profitability than the "control" case study (farm B). Since 2018, in conjunction with the investment in the PAT package, farm A apparently loses its profitability advantage with respect to farm B. Indeed, in the period 2021-2022 the gross profit ratio between the two case studies is reversed compared to previous years – the wheat produced by farm becomes more profitable than that produced by farm A – and this is due to three underlying forces acting simultaneously: wheat selling price, productivity, contingency of exceptional environmental conditions.

a. Selling price: Since 2018, the difference between the two case studies in terms of average revenue is narrowing until it disappears in 2022. The exceptional increase in prices in the three-year period 2020-2022 has favored an upward squeezing of the price differentials, previously linked mainly to product quality.

b. Productivity: farm B remains a structurally more productive farm even in the post-adoption period of the PA package by farm A. The higher productivity of the durum wheat produced by farm B lies in the genetics of the seeds used. Farm A produces durum wheat for seed. This varieties used are generally less productive than semolina varieties, but they usually tend to have a higher market value even if, as we have seen, in the 2021-2022 the price of the two case studies flattens out on the same level due to the market shock.

c. Environmental conditions: although the use of PATs allows a greater timeliness of action in crop management, even without the use the technologies farm B was able to manage the 2021 sowing period more effectively than farm A. The 2021 sowing was very difficult in the survey area due to exceptionally prolonged rain events. Farm A was unable to sow before December 2021 (two months of delay) and this strongly influenced the low productivity of the 2022 harvest, while farm B found useful windows for sowing in the right period, i.e., October 2021.

4) Operating profit: the fundamental information contained in the comparison between the two case studies, in terms of operating profit, is the incidence of the depreciation share of the PA capital invested by farm A in 2018. This factor, combined with the alignment of the prices of wheat sold starting from 2020 and the higher productivity of farm B, determines an inversion of the profitability of the two case studies in 2021-2022 when farm B becomes more profitable than farm A. The weight of the share of depreciation of the PA capital on the profitability per hectare of farm A also emerges from the joint comparison of the gross margin and the operating margin (Figure 5). In fact, the narrowing of the distance between the two indicators that can be seen when passing from the gross margin to the net margin is essentially due to the depreciation rate of the PA capital discounted by farm A.

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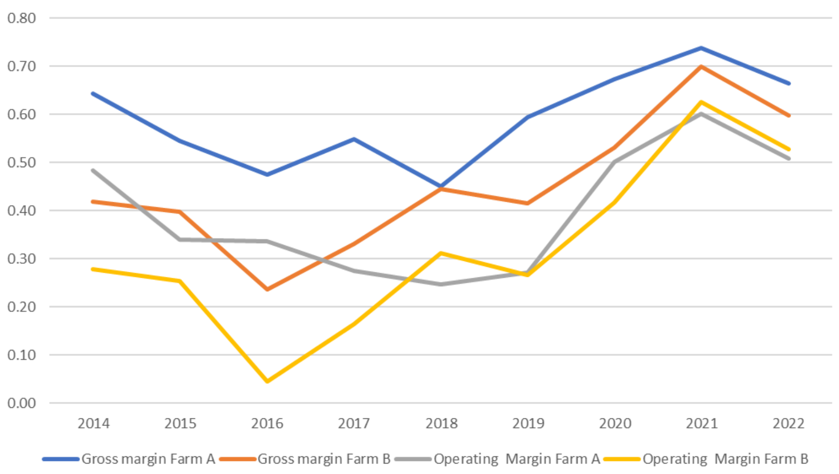

Figure 5. Variation of gross and operating margin for farm A and B in the considered period (2014-2022).

In 2020-2022, the operating profit of farm A improved to levels far above pre-adoption conditions, and this is especially due to the market price trend (Figure 6).

Figure 6. Durum wheat market prices trend 2014-2022 in Central Italy. J: January; M: May; S: September (Source: Borsa Merci Bologna).

In addition, farm adopting PATs creates advantages over traditional farming in terms of better management of resource efficiency. This aspect is particularly relevant for the use of N fertilizer. In fact, after covid pandemic and for the Russia-Ukraine war, this input increased its price by 176% from January 2020 to December 2022 (Figure 7).

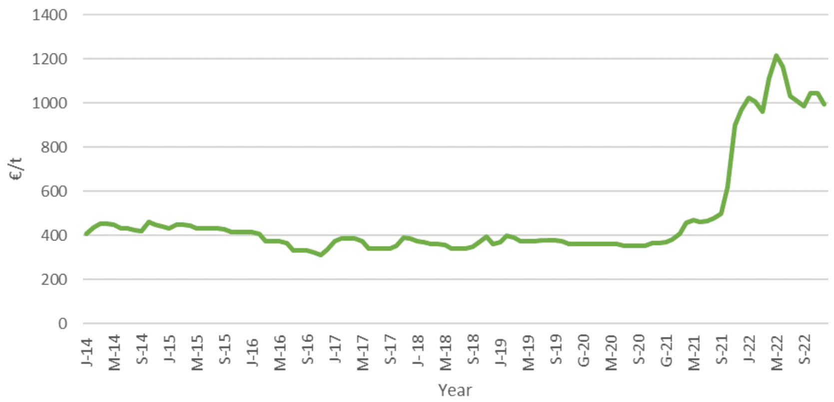

Figure 7. Urea 46% N market prices trend 2014-2022 in Italy. J: January; M: May; S: September (Source: Borsa Merci Mantova).

In this scenario, PATs allowed farm A to optimize N distribution according to the specific necessity of the crop as shown in the following paragraph (NAE index).

In this way the farm A works achieving both a better quality of production and minimizing the negative impacts on the environment.

Finally, to understand what will happen to farm B if it decides to adopt the PATs package of farm A, a simulation was performed for the period 2020-2022 (Table 4). A depreciation cost of the same PA capital acquired by farm A is considered with a variating depreciation rate according to the durum wheat farm UAA.

Table 4. Simulation of PAT adoption for farm B for the period 2020-2022.

Year	Average yield (t/ha)	Durum wheat price (€/t)	Variable costs (€/ha)	Operating profit (€/ha)	Operating margin
2020	6.50	270.00	698.50	444.77	0.25
2021	5.80	470.00	692.50	1,416.56	0.52
2022	6.00	490.00	1017.50	1,202.24	0.42

It emerges that, if farm B had acquired the same PA package as farm A, the operating margin of farm B improves thanks to the new market conditions in the period 2020-2022 despite the cost of PA capital. This evidence suggests that PA adoption by farm B could be feasible in economic terms thanks to a sufficiently profitable, productive, and extensive farm structure in which implementing the new technologies in this new market conditions (which, however, are constantly changing).

Nevertheless, despite the favorable economic situation, farm B is currently not prone to technological change. The motivation could not be purely economic, but it could be linked to the characteristics of the owner. As the literature suggests [54,55,56], older farmers show a lower propensity to adopt as compared to their younger counterparts. Old farmers' may be loath to changes and they may not see longer-term benefits perhaps because they lack training and their bond to conventional agricultural management [57]. Moreover, access to credit is certainly another possible constraint to adoption.

3.2 Agronomic results

Farm A supplied less nitrogen (-38%) than farm B for each year under analysis (Table 5). While evaluating the average yield, during the five growing seasons, shows that farm B and farm A reached the same yield level of 5 t ha^{-1}.

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The NAE index, which is an index designed to assess nitrogen fertilizer use efficiency, shows that the Farm A obtained a higher value (+0.15) than the Farm B (Table 5).

Table 5. Total nitrogen provided, crop yield, and NAE per farm each year.

Year	Farm	N provided (kg N / ha)	Tot. Yield (t/ha)	NAE
2017	A	136	4.60	0.34
2018	A	129	3.80	0.30
2019	A	114	6.00	0.53
2020	A	177	4.60	0.26
2021	A	125	4.70	0.38
Mean	A	136	5.00	0.36
2017	B	210	4.60	0.22
2018	B	230	4.20	0.18
2019	B	215	4.50	0.21
2020	B	223	5.10	0.23
2021	B	208	4.70	0.23
Mean	B	217	5.00	0.21

[1]NAE: Nitrogen Agronomic efficiency.

After water, nitrogen fertilization management is the most important plant nutrient [58]. Nitrogen fertilization contributes significantly to crop development, chlorophyll accumulation [59,60,61,62] and nitrogen content [63].

Mineral nitrogen contributes to better growth by giving the crop the nutrient when it needs it most, which results in higher production [59,64] and quality grain levels [65]. Farm B obtained a higher production level than farm A due to the higher nitrogen provided to the crop.

[66] with 20 years of data on durum wheat production shows that nitrogen is the key driver of the production. The authors have shown that increasing the nitrogen supplied to durum wheat allows a significant increase in yield.

It is also true that as the dose increases, the yield of durum wheat does not increase proportionally. [67] showed that nitrogen doses above 150 kg N/ha don't increase yield but, on the contrary, result in a higher protein percentage.

When the nitrogen is not absorbed by the crop, it can only have two fates, leaching [68] and denitrification [69], which have negative environmental impacts, without considering the economic damage suffered by the farmer and that such production inputs are less available and increasingly expensive.

Given its consequences at the agronomic, economic, and environmental levels, the management of nitrogen fertilization has always been an important topic of scientific research [28]. Today, to optimize nitrogen fertilization at the farm level, precision farming has a strong impact on both the environment and the economy [63,70,71].

Precision agriculture is agronomic management based on the spatial and temporal variability of agronomic components, such as the soil's chemical and physical variability [49] and crop needs. Analyzing spatial and temporal variability, prescription maps [62], [72] can be generated that allows the nitrogen dose to be adjusted according to crop needs and so improve the nitrogen use efficiency (NUE).

Several authors have reported that precision farming allows an increase in NUE. [73] in China showed yield and NUE results of the precision agronomic management. The authors report an increase in yield and NUE compared to conventional agriculture of 10% and 51-97%, respectively.

Also, in Switzerland winter wheat (*Triticum aestivum*) [74] it was reported that precision nitrogen management improved on average the NUE by 10%. Moreover, in Umbria, Italy, it was reported that the variable rate technology improved the NUE by 15% compared to the flat rate [75].

In according with all the previous works, an increase in the NUE was also achieved in our case study. Farm A which uses the variable rate technology obtained a higher NAE of 15% than farm B which distributes nitrogen evenly. Farm A is more environmentally and profit-friendly than farm B.

4. Conclusions

Being the adoption of the PA still at a pioneering state in central Italy, our case study can represent a useful benchmark for both agricultural entrepreneurs and policymakers with respect to the economic effects of PA technology adoption applied to durum wheat production. From the economic analysis, it emerges that, in terms of gross profit, there are substantial differences between the two case studies. Farm A is characterized by a gross profit that is on average higher than farm B in the pre-crisis period 2014-2020. Farm A' s economic indicators have been affected by the PATs depreciation schedule coinciding with the technological change. Despite this, the economic efficiency of farm A improved to levels above pre-adoption conditions, thanks to the new market conditions in the period 2020-2022. In addition, farms adopting PATs optimize the use of inputs like nitrogen fertilization, according to crop needs; at the same time, it favors the farm management's efficiency in terms of human resources. Given these results, policymakers are advised to encourage the adoption of these technologies given that the current market conditions generate incentives to adopt: very high costs of input, but very high prices of output. Finally, both from an economic and agronomic point of view it is important to consider these aspects, in order to appreciate all the advantages of this type of innovation that hinges on the automation of the production process. The farm deciding to adopt PATs must already possess both the characteristics and the philosophy of efficiency, since adopting promising and efficient technologies on obsolete or inefficient production systems – similarly to what happens in the field of automation of manufacturing production processes – does not mean innovating but automating the pre-existing inefficient production process. In addition, the adoption of PA technology requires training programs for farmers and farmworkers to acquire the right skills. In fact, the availability of training is a condition necessary for understanding and mastering the PA package characteristics as well as for fully exploiting its potential in terms of efficiency and effectiveness.

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