Intelligent monitoring and control systems: a case study research to evaluate the profitability of measuring optimization in precision agriculture

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ABSTRACT

Precision Agriculture Technologies (PATs) offer the opportunity for farmers to improve the efficiency for the management of resources and the optimization of process inputs, thus increasing the whole-farm’s profitability. Despite these well-known benefits, the adoption of PATs is still challenged considering the socio-economic barriers and the individual characteristics of the farms: cropping systems, technical developments, field sizes and farm scale. The economic aspect is undoubtedly one of the most important aspect to consider before adopting technology. In most of the cases, in fact, farmers are reluctant to introduce precision farming systems, considering the costs needed to be addressed and for uncertainty about the profitability and advantages. This study aims to explore how PATs could affect the profitability of a representative Italian farm specialized in the production of cereals, as a case study research. In detail, an economic analysis was applied to determine the profitability of the farm. Measurable advantages for precision agriculture compared with conventional management of agricultural land were observed. Therefore, the potential gains from the adoption of PATs, challenges policymakers to design targeted interventions which could encourage their uptake. This paper is an extended version of the original contribution presented to the 2019 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgrifor) in Portici, Italy.

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1. Introduction

Defined by Leonard (2016) [1], as a means of producing on-site data to guide decision making, Precision Agriculture (PA) is a whole-farm management approach which allows to manage the growing of crops for better yield and quality, through the measurement of physical parameters and collection of data. Starting from the 1990s, several definitions of PA have been given in the literature [2,3,4,5,6], but all the authors agree that this practice matches the agronomic inputs and the practices to site-specific conditions within a field and the improvement of the accuracy of their application [7]. In detail, we can consider PA as an integrated information and production- based farming system, designed to deliver high-end technology solutions to increase farm production efficiency and profitability while minimizing environmental impacts. Precision Agriculture Technologies (PATs) are all of those innovations that incorporate recent advances in modern agriculture providing evidence for lower production costs, increased farming efficiency and reduced impacts. Accuracy and precision are two relevant factors to consider when taking data measurements. They both reflect how close a measurement is to an actual value, but accuracy refers to how close a measurement is to a known or accepted value, while precision reflects how reproducible measurements are. For a long time, in the field of PATs, digital devices able to take a more accurate and precise measurements generally corresponded to higher investment costs. This economic constraint initially caused a limited diffusion of PA. To date, a wide range of different low-cost devices is available on the market, which allows a to meet accuracy requirements in the measurements. However, even if there are affordable PATs available on the market, the application still remains circumscribed at few farms. In fact, in addition to the cost of investment, the adoption of the precision agriculture technologies has encountered other difficulties such as additional application or management costs and investment on new equipment, trained employees for the use of technologies and uncertainties found within the farming community, compared to the potential economic and environmental gains from their adoption [8,9,10,11,12,13,14,15]. Given these premises, this paper discusses the economic benefits of PA, in relation to the accuracy of the measurement taken by different technologies, trying to answer the following research question: “What is the economic effectiveness deriving from the adoption of high accuracy PATs?”. In order to reach this goal, we attempt to quantify the economic benefits of PA based on an Italian case study of a representative farm specialized in the production of cereals by means of the conservative system which has invested in high accuracy PATs. The case study method enables to explore and investigate a contemporary real-life phenomenon through detailed contextual analysis of a limited number of events or conditions, and their relationships. The methodology adopted for the evaluation of the profitability derives from the introduction of in PA technologies is a cost-benefit analysis. The remainder of the paper is organized as follows. Section 2 shows the main precision farming tools and their adoption. Section 3 presents the current policy framework for the support of PA. In Section 4, we present a brief literature review on the profitability of PA. Section 5 provides the methodology and data and section 6 discusses the results. Finally, conclusions and some policy implications are given in section 7.

1. PRECISION Agriculture TOOLS AND ADOPTION LEVEL

PA involves the use of digital technologies for the location, in a timely manner and in the right way to improve production while minimizing environmental impacts [16,17]. According to Pedersen (2017) [18], precision Agriculture Technologies for recording and mapping field and crop characteristics are divided into the categories below:

1. Global navigation satellite systems technologies (in fact these technologies record the actual position which can be used for different purposes such as guidance, mapping);
2. Mapping technologies;
3. Data acquisition of environmental properties (camera-based imaging, NDVI measurements, soil moisture sensors);
4. Machines and their properties Global navigation satellite systems (GNSS) technologies.

These technologies consent the recording of spatial differences in the factors relevant to crop growth, such as the quality of soil, the availability of water and fertilizers, or crop yield. This allows greatly improved efficiency of the resources made use of, leads to reduced waste of inputs and, in addition, improves the adjustability of biological-technical systems. The work of Guo et al., (2018) [19] highlights how positioning accuracy represents a key factor for the precise management of agricultural operations. In the engineering fields, accuracy refers to how close a measurement is to the true value, but a more rigid definition is applied by the International Organization for Standardization, (ISO), which defines accuracy as a measurement with both true and consistent results. The ISO definition means that an accurate measurement has no systematic error and no random error. A key component of the precision farming management approach is the use of a wide array of digital devices, which allow taking accurate measurement in agriculture: this includes GPS guidance, sensors control systems, robotics, drones, autonomous vehicles, variable rate technology, GPS- based soil sampling, automated hardware, telematics, and software. According to Perez-Ruiz and Upadhyaya (2012), [20], PA applications can be classified into three different categories, taking into account the different degree of accuracy in the positioning systems:

* low accuracy (meter level) can be used for asset management, tracking and tracing;
* medium accuracy (sub-meter level) can be used for tractor guidance, via manual control, for lower accuracy operations such as spraying) [18], spreading, harvesting bulk crops and for area measurement and field mapping);
* high accuracy (cm level) can be used for auto- steering systems on tractors and self-propelled machines (harvesters and sprayers.

Focusing on the adoption of PATs at worldwide level, the US are the top player in this sector, followed by Australia and Canada. Nevertheless, the percentage of PA adoption has also increased in Europe, with a rate of 15-20%. Based on region, the EU PA market is segmented into UK, Germany, Spain and France. In Italy only 1% of the agricultural surface is managed through precision farming techniques [21]. However, although the adoption rate of technology among farmers is still low due to socio-economic barriers [22,23,24], the market for smart agriculture technologies is growing, since technology providers are increasingly developing solutions that can cover the entire field of the agri-food supply chain (AFSC). In particular, the majority of the solution covers the first step of the AFSC, the production phase, starting from cultivation to storage of the product to processors. According to a recent survey conducted by the Osservatorio Smart Agrifood [25], currently, the available technologies on the market are those that support the growing phase of the crop (79%) followed by seeding/plantation phase (37%) and harvesting (33%) (Figure 1).

Figure 1: Main phases supported by PA

The most widespread technologies on the market are related to the soil mapping (29%), machine control (27%) and precision interventions (21%), such as planting, fertilizing and distributing pesticides. The remaining part of these technologies are reserved for the farm and crop management and monitoring, respectively 18% and 5 %. The main crops treated with PA are fruit and vegetables (38%) cereals (35%), wine (23%) and olive oil (4%). [26,27,28,29] (Figure 2).

Figure 2: Main crops treated with PA

For fruit and vegetable crops, machine vision methods allow growers to grade products and to monitor food quality and safety, with automation systems recording parameters related to product quality (as colour, size, shape, external defects, sugar content, acidity, etc.). Additionally, tracking of field operations, such as, the chemicals sprayed and the use of fertilizers, can be possible to provide complete fruit and vegetable processing methods. The use of PATs on arable land is the most widely used and most advanced amongst farmers. The technology allows the farmer to control the amount of inputs in arable lands, as the optimization of the use of fertilizers, as nitrogen, phosphorus and potassium. The development and adoption of PATs and methodologies in grape and olive orchards are more recent than in arable land. For these high-value crops, precise irrigation methods are developing rapidly to save water, while improving yields and fruit quality For example, grape quality and yield maps are of great importance during harvest to avoid mixing grapes of different potential wine qualities[30]. The "*Guidelines for the development of Precision Agriculture in Italy"* [31]*,* indicated as an objective for 2021, the extending of the management through precision agriculture up to 10% of the agricultural area cultivated nationally. Therefore, it becomes essential to identify the factors limiting their diffusion and the profitability of these technologies.

1. THE CURRENT POLICY FRAMEWORK FOR THE SUPPORT OF PRECISION AGRICULTURE

The support from Governments and other Public Institutions play an important role in a wider adoption of PA. For this reason, the European Commission started to develop several policies initiatives, including those relating to agriculture, environment, and R&D, to encourage the use of digital technologies, thus including PATs, among all the steps of the Agri-Food supply chain. In fact, all the actors of the supply chain require support to understand and take up new technologies to make decisions on the use of digital technology. The EC Communication (COM (2017)713) on “The Future of Food and Farming” recognized the huge potential that technological development and digitization have to address the current challenges for the sector, even if the level of digitalization “remains below expectations and unevenly spread throughout the EU, and there is a particular need to address small and medium-sized farms’ access to technology” [32,33]. Considering this low-digitalized scenario, policymakers set up a set of measures, both of European and national level. In Figure 3 we summarized the main initiatives up taken by Member States to facilitate the development and of PATs.

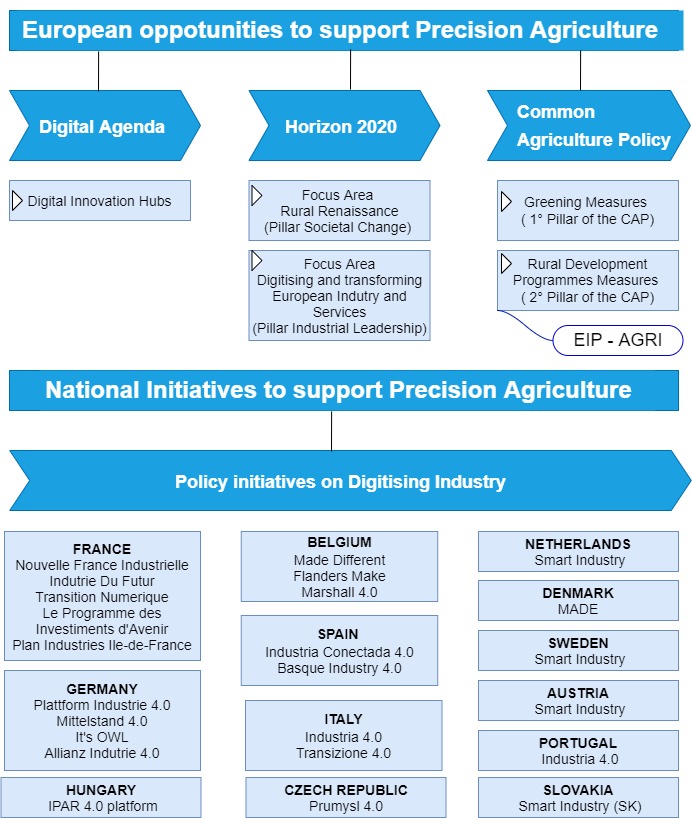


Figure 3: Policy instruments for PA adoption

Starting from the European level, the European Commission launched on 19 April 2016 the first industry-related initiative of the Digital Single Market package, which includes the Digital Agenda, aiming to make the agricultural sector and rural areas in Europe digitized and data-empowered. The strategy of the Digital Agenda for the Agricultural Sector, is the development of a network, so called Digital Innovation Hubs (DIH) to ensure SMEs to grasp the digital opportunities, improving processes and adapt their business models to the digital change. The EU supports the collaboration of DIHs to create an EU-wide network, where companies can access competences and facilities not available in the DIH of their region. From a total of 325 DHI, only 9 are the networks dedicated to the development of technologies for the Agrifood Sector.

Another fundamental contribution for the diffusion of these technologies is mainly provided under Horizon 2020 through the Societal Challenges and Industrial Leadership pillars, according to these specific calls:

* RUR-02-2018 - Socio-economic impacts of digitisation of agriculture and rural areas;
* RUR-13-2018 - Enabling the farm advisor community to prepare farmers for the digital age.
* RUR-20-2018 - Digital solutions and e-tools to modernise the CAP;
* DT-RUR-12-2018 - ICT Innovation for agriculture: Digital Innovation Hubs for agriculture.
* DT-ICT-08-2019 - Agricultural digital integration platforms;
* DT-ICT-09-2020: Digital service platforms for rural economies.

According to the CORDIS Database, there are already 25 EU-funded projects focused on the development of the precision farming solutions, thus including Internet of Food and Farm (IoF)

However, when we refer to the implementation and the adoption of precision agriculture technologies by end-users, and then by farmers, this is mostly channelled through the Rural Development Programmers under the 2nd Pillar of the Common Agriculture Policy (CAP). To date a number of Common Agricultural Policy (CAP) objectives that are relevant for precision agriculture have been introduced. For instance, different rural development measures under Pillar II of the CAP (Regulation EU No 1305/2013 of the European Parliament and of the Council of 17 December 2013) are suitable to play a role in fostering the development of this technology. Within the range of Pillar II, measures available for MS to support PA development through their RD programs are:

* Article 14 - Knowledge transfer and information actions. Member States could take these funds for training and knowledge transfer actions to foster the adoption of Precision Agriculture.
* Article 15 - Advisory services, farm management and farm relief services (FAS). The FAS is a system operating in all Member States to which any farmer can have access on a voluntary basis, and it is useful for the delivery of best agronomic practices and uptake of innovative solutions, including PA.
* Article 17 - Investments in physical assets. This measure aims at farm modernisation and intensification, as well as agri-environment-climate measures. So, this measure can help the farmer to purchase PA technologies. On the other hand, the adoption of PA could assist farmers in complying with the environment-related regulation (i.e: saving water, reduction of N fertilizers, etc).
* Article 28 - Agri-environment-climate. This measure supports farmers that undertake operations related to the agro-environment-climate commitments. PA can support farmers in participating in this scheme with more environmentally sustainable systems.
* Article 35 - Co-operation. Cooperation can relate to pilot projects and joint action undertaken with a view to environmentally friendly farming practices. PA may contribute to these requirements.
* Article 55, 56, 57 - European Innovation Partnership for Agricultural Productivity and Sustainability (EIP- AGRI). In particular, the EIP-AGRI can play an important role in both developing and mainstreaming precision farming in the EU, considering that there is a thematic focus Group on Precision Farming, made up of a cluster of experts and stakeholders, including scientists, farmers, advisers, and agribusiness to address current opportunities, limitations and transferable innovative solutions on the topic of Precision Farming. In particular, the EIP-AGRI Focus Group addressed the main question of how to organize data capture and processing to mainstream the application of Precision Farming for input and yield optimization, while trying to identify the main reasons behind the current lack of adoption, and identifying the key barriers to the implementation of Precision Farming on European farms.

In addition, PA can contribute to meeting the requirements put forward within the greening measures (1st of the CAP) in which farmers receive payment to undertake practices that benefit the environment and the climate. Farmers who are able to demonstrate an increase in their productivity (after the investments on precision farming technologies), while respecting cross-compliance requirements, would be rewarded with additional aids on top of the direct basic payments under the 1st Pillar of the CAP.

Finally, at national level, each member States, has developed Industry 4.0 policies with the aim of strengthening industrial competitiveness and modernization of the manufacturing sector, including the agriculture [34,35]. Industry 4.0 depends on a number of new and innovative technological developments: the application of information and communication technology (ICT) to digitize information and integrate systems at all stages of product creation and use (including logistics and supply), both inside companies and across company boundaries. This policy supports especially the digitalisation of agriculture based on the development and introduction of new tools and machines in production. From this review it is clear that there are still no specific measures for the diffusion of PATs in the sector, but there are generic measures to boost the innovation and digitization of the agri-food chain.

**4. THE PROFITABILITY OF PRECISION FARMING: A BRIEF REVIEW**

According to Busse et al, 2014 [36], three different PA research focus areas are represented in the literature. First, studies aim to prove the profitability and the positive environmental impacts of PA [37,38,39,40,41,42,43,44]. The second important research subjects include numerous investigations focused on the technical aspects of product development and process improvement. Finally, the third important research subject focus on the implementation of PA at the single farm level. Referring to the first aspect, PA has the potential to help farmers improve input allocation decisions, thereby lowering production costs or increasing outputs, and, potentially, increasing profits. However, there is still a scant knowledge about the relative magnitude of the overall benefits and costs of PATs on individual farms.

Previous studies [45,46,47,48,49,50] tried to evaluate the savings and revenues due to the application of precision agriculture, however considering the average savings from the application of the single technology, or for a specific growth phase of the crop. (Table 1)

Table 1: Economic benefits of Precision Agriculture

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Year** | **Author** | **PATs** | **Case study** | **Crop** | **Average savings** |
| 2000 | Bongiovanni and Lowenberg-DeBoer | RTV for fertilization | USA | Soya and corn | 17.60 €/ha |
| 2003 | Knight et al. | Assisted/Semi-Automatic Driving | UK | Arable crops | 25 €/ha |
| 2003 | Knight et al. | CTF | UK | Soft Wheat | From 18 to 45.5 €/ha |
| 2009 | Biermacher et al. | RTV for fertilization | USA | Soft Wheat | 13.2 €/ha |
| 2010 | Schneider and Wagner | RTV for fertilization | DE | Soft Wheat | 16 €/ha |
| 2011 | Lawes and Robertson | RTV for fertilization | AUS | Arable crops | 9.4 €/ha |
| 2012 | Shockley et al | RTV for seeding | USA | Soya and corn | 31.67 €/ha |

According to Zhang et al., (2002) [51], the impact of PA technologies on agricultural production is expected in two areas:

* profitability for farmers;
* ecological and environmental benefits to the public.

However, both the profitability and the environmental benefits of PA continues to be difficult to predict evaluate and measure [52, 53]. According to the literature, the profitability of PA depends on different aspects including: the farm size, the type of crop, the technology adopted, the degree of spatial variability of soil attributes (e.g. soil types, fertility and organic matter) and yield response [54,55,56,57,58,59]. Studies on PATs adoption emphasize that adopters tend to operate a larger agricultural area, and subsequently generate a higher income. This indicates the ability to accommodate some risk in investment of newer and larger technologies. Some studies highlighted that specialized farm in high-income crops such as vineyards and olive groves, are more likely to adopt PATs.

Major benefits of precision agriculture management derive from crop yield effects and reduced input use from more efficient farming; more efficient farm management with improved communication possibilities and higher quality of work with machine-guided systems. The implementation of precision farming concepts may mitigate production risks because inputs are applied only where they are needed. While risk mitigation with precision farming is intuitive, the implementation of precision farming typically requires substantial investments that may increase financial risk [60]. Investments in precision farming are further associated with irreversibility of the capital cost, which should be taken into account where appropriate. Farmers might prefer to wait for better information on the costs and benefits of the new technology before investing in precision farming technologies [61]. While the costs of precision farming technologies can, in many cases, be estimated precisely, it is more challenging to evaluate the response of the system to improved management.

A behavioural factor which is fundamental to have a positive effect is the willingness of farmers to trust the technology. Several studies found that a low level of trust in the technology could be a key limitation for PATs adoption, compared to other factors. Thus, farmers are waiting for research results on the profitability of various PA technologies before deciding to invest significantly to adopt more technologies. On the one hand, PA is aimed at large holdings with a farm and capital structure that enables them to invest in expensive systems. On the other hand, it is a means to get farm management back to small scale farming processes with detailed knowledge about small units and management zones and enable farmers to treat each unit, whether it is a piece of land or an animal, with the same care as farmers did in previous times. This development is facilitated by the help of smart technologies that allow the farmer to gain detailed knowledge about the field and subsequently to treat the field accordingly. Despite these advantages, precision agriculture is adopted only by innovative farmers and the intelligent usage of precision farming data is still rather limited. The introduction and uptake of technologies requires new skills and knowledge for farmers and advisers. Raising awareness and organising training on a regional/local level is essential, especially to reach small and medium-sized farms, where the use of digital technologies is not always thought of as profitable

However, taking advantages from PATs will depend, not only on the willingness of farmers to adopt new technologies, but also on each specific farm potential in terms of scale economies, as profit margin increases with farm size. This concept is widely explained in the work of Vecchio et al. (2020) [62], that analysed the socio-cultural and complexity factors that affect the probability to adopt PATs among Italian farmers. The authors found that the farmers most prone to technological innovation all had similar characteristics: big size farms (average dimension equal to 143 hectares), and young managers with the highest level of education.

**5. DATA AND METHODS**

In order to determine the profitability of the application of PA, a case study research was conducted. According to Yin [63] a case study research method is “an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used.” Due to the limited availability of other cases for replication, in this study, we adopt either a single-case design. While not making statistical representativeness, a single case study can contribute to scientific development through a deep understanding of a still rare context of inquiry such as that of PATs adoption in the Italian agriculture. The methodology adopted for the evaluation of the economic implications of PATs adoption is a cost-benefit analysis carried out referring to an innovative Italian farm specialized in the production of cereals. The analysis takes into consideration the production of durum and soft wheat - on an agricultural area of 537 flat land hectares applying a conservative production system (i.e., sod seeding). From 2010 to 2016 the farm has invested in high accuracy PATs for a total cost of about 184.000 € to be used to make decisions with greater precision and to optimize crop yields. The main investments include assisted steering (ISOBUS), service for georeferenced, production and soil mapping system, variable rate fertilizer spreader, machine for weeding and treatment with variable dosage distribution. The description of the phases of the cost-benefits analysis follows:

1) Definition of the time horizon under study:

* 2005-2009 pre-adoption period;
* 2010-2016 period of progressive investment in the PA technological "package";
* 2013-2017 post-adoption (progressive) period of the PA package.

2) Definition of average land productivity (both for durum wheat and soft wheat):

* for pre-adoption period (2005-2009);
* for post-adoption period (2013-2017).

3) Definition of a 10-year amortization schedule (and related constant annual payment) of the PA technology “package”. This phase is aimed at defining the annual capital cost of the investment in PA.

4) Definition of pre-adoption average total cost:

* per hectare (ha);
* per product unit (ton).

5) Estimation of post-adoption monetary saving at a level of average total cost induced by PA adoption:

* per hectare (ha);
* per product unit (ton).

6) Estimation of post-adoption average total cost (ATC):

* per hectare (ha);
* per product unit (ton).

7) Definition of the market price time series (2012-2019) for durum and soft wheat.

8) Estimation of the operating margin generated by the adoption of the PA package:

* per hectare (ha);
* per product unit (ton).

9) Sensitivity analysis on the cost-benefit analysis results in order to evaluate the economic and financial effectiveness of the investment, according to the change in:

* production scale;
* unit product cost;
* land productivity.

**6. RESULTS**

Comparing the pre-adoption and post-adoption period of PATs , the main empirical evidence is relating to two main issues:

* the variation in land productivity;
* the change in cost.

Relating to the first aspect, as shown in table 2, an increase in the average land productivity in the post-adoption period is observed.

Table 2: Variation of crop yields over the entire study period

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Crop** | **Pre-adoption 2005/2009 Average yield (ton/ha)** | **Post-adoption 2013/2017 Average yield (ton/ha)** | **Increase (ton/ha)** | **Increase (%)** |
| Durum W. | 5 | 5.71 | 0.71 | 14.2 |
| Soft W. | 5.93 | 7.31 | 1.38 | 23.3 |

In particular, the post-adoption land productivity enhancement is considerably greater in the case of soft wheat (+23.3%) with respect to the durum wheat (+14.2%). As a consequence, we decided to asses separately – both for durum and for soft wheat – the supposed effect of PA in terms of economic effectiveness.

Analyzing the crop yield trends, it is not possible to say with certainty whether this productivity enhancement is really due to the technological change. We are aware that crop productivity is influenced by a complex set of factors, such as climatic conditions or the type of grain variety, and certainly not only by the possible introduction of a specific technology. However, it has to be noted that the increase in land productivity is referred to a five-year post-adoption period on average, that is, a fairly reliable time period in order to assume the presence of some impact of the technology introduced meantime. Indeed, the improvement of crop yield could be associated with both direct and indirect effects of PATs. The direct effects derive from the optimization of production processes. The indirect effects derive from the greater knowledge on the state of soils and crops. In this way, the farmer can make more timely decisions. In fact, the farmer has declared that the georeferenced mapping of farming lands and of the working time for crops firstly allowed to quantify how much was actually the area worked in addition because of overlapping errors in different cultivation operations. In addition, the mapping of production and the soil analysis allowed to modulate seeds, fertilizers and herbicides according to the real need of the plants and the productivity of the soils.

In order to evaluate the effect on production costs due to the introduction of PATs, the pre-adoption and post-adoption average total costs (ATC) have been firstly estimated and then compared to each other. In summary, table 3 shows a comprehensive picture of the PA cost-benefit analysis results.

Table 3: Cost-benefits analysis results

|  |  |  |
| --- | --- | --- |
| **Cost** | **Soft W.** | **Durum W.** |
| ATC pre-adoption (per hectare) | 768.98 €/ha | 794.56 €/ha |
| Average saving on ATC (per hectare) | - 77.55 €/ha | - 77.55 €/ha |
| Incidence capital cost (per hectare) | 44.08 €/ha | 44.08 €/ha |
| Incidence capital cost (per ton) | 6.0 €/ton | 7.7 €/ton |
| Average saving on ATC due to PA cost efficiency (per hectare) | - 33.47 €/ha | - 33.47 €/ha |
| Average saving on ATC due to PA cost efficiency (per ton) | - 4.6 €/ton | - 5.9 €/ton |
| Total average saving on ATC (per ton): cost efficiency plus productivity effect | - 29.0 €/ton | - 25.5 €/ton |
| **ATC pre-adoption (per ton)** | **129.6 €/ton** | **158.6 €/ton** |
| **ATC post-adoption (per ton)** | **100.7 €/ton** | **133.1 €/ton** |

The pre-adoption ATC resulted to be equivalent to 794.56 €/ha for durum wheat and equivalent to 768,98 €/ha for soft wheat respectively. Besides, the average saving (AS) on ATC in the post-adoption period hypothetically attributable to the cost efficiency of the PATs was found to be equivalent to 77.55 €/ha per hectare namely a cost reduction of 10.08% on average with respect the ATC in the pre-adoption period. In particular, through the use of fertilizer spreaders, machines for weeding, treatments and seeders with variable dosage distribution it was possible to reduce cost of mechanical operations (labor, diesel, lubricants) and technical means (seeds, fertilizers and pesticides). However, in order to evaluate the net savings due to PA adoption, the capital cost (CC) of the technology introduced has to be estimated and then discounted from the average savings on operating production costs previously obtained. Thus, a 10-year amortization schedule at 5% annual interest rate (and related constant annual payment) of the introduced PA technology package has been calculated. As a result, we obtained a CC of the total investment in PA equivalent to 44.08 € per hectare calculated in function of the agricultural area invested in the cereal production by the case study namely 537 ha. It is now possible to calculate the net savings (NS) per hectare on the production cost hypothetically due to the technology package introduced as follows:

AS – CC = NS= 33.47€/ha

This means that, net of the cost of capital, the AS on ATC previously equivalent to 10,08% per hectare now falls to a NS equivalent to 4,3% per hectare and the first interesting notation is that this net effect of PA in terms of cost efficiency is relatively modest and in line with the previous studies examined in the literature review. A possible explanation could be the fact that the case study is a really entrepreneurial farm which was already working, even before PA adoption, with a high level of efficiency with respect to the cost of production per unit of land. Rather, the most significant effect attributable to PA seems to concern productivity. Finally, for measuring the net gains per unit of production obtained in the post-adoption period, the operating margin (OM) per ton of production has been calculated in percent as the difference between the average revenue (AR) – corresponding to the average market price for the period considered – and the ATC as follows:

OM (%) = (AR - ATC)/AR

Table 4 shows the main indicators resulting from the PA cost-benefit analysis.

Table 4: Cost-benefits analysis indicators

|  |  |  |
| --- | --- | --- |
| **Indicators** | **Soft W.** | **Durum W.** |
| Land productivity increase post-adoption | 23.18 % | 14.13 % |
| Average saving on ATC (%) | 10.08% | 10.08 % |
| Average saving on ATC (%) net of the CC | 4.3% | 4.3 % |
| Total average saving on ATC (per ton): cost efficiency plus land productivity effect (%) | - 22 % | - 16 % |
| **OM per ton (%) pre-adoption** | **40.5 %** | **42.9 %** |
| **OM per ton (%) post-adoption** | **50.1 %** | **55.7 %** |
| Net gains in monetary terms pre-adoption | 114.8 €/ton | 98.7 €/ton |
| Net gains in monetary terms post-adoption | 140.3 €/ton | 127.7 €/ton |
| **Net gains in monetary terms due to PA** | **25.49 €/ton** | **28.97 €/ton** |

The operating margin (OM) increases from 40.5% in the pre-adoption period to 50.1% in the post-adoption period for soft wheat while it increases from 42.9% in the pre-adoption period to 55.7% in the post-adoption period for durum wheat. As just stated, this performance is due almost entirely to the increase in land productivity registered for the post-adoption period.

The OM is the summary result of this cost benefit analysis therefore it seems important to make some considerations on the basic meaning of this measurement. Looking at the figure 4, it is possible to visualise in a comparative way the net gains deriving from the production of wheat in the pre-adoption period and the post-adoption period. The first interesting notation is that we are looking to a rarely effective farm in terms of capability to generate income and this is true both for the pre-adoption (thus regardless the PA adoption) and the post-adoption period. The second interesting notation is in the post-adoption period the net gains in monetary terms increases of 9.6% for soft wheat and 12.8% for durum wheat. This means that in absolute terms the net gains in monetary terms is higher in the case of soft wheat (both in the pre-adoption and post-adoption period) while the increase of the operating margin due to PA (in %) results to be higher in the case of durum wheat maybe thanks to a the most favorable average level of the durum wheat market price in the post-adoption period with respect to that of soft wheat.

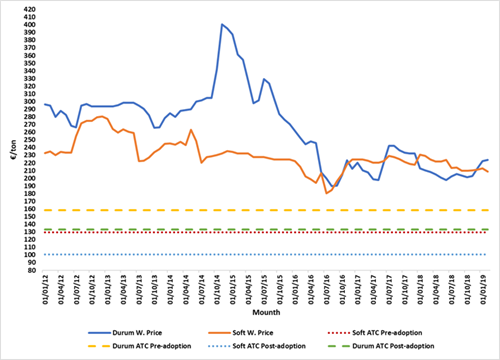


Figure 4: Prices and ATCs for soft and durum wheat

A further consideration which maybe deserves more attention is the following. The present case study is a cooperative farm dedicating more than 500 ha to the production of wheat. This means that the farm we are observing is a “large farm” and that it can be roughly considered a case of minimum efficient scale (MES) with respect to a fixed investment like the one represented by the PA package considered in the present case study. In other words, for this specific case study (therefore not in general) the incidence of capital cost (CC) on the unit of production turns out to be minimized thanks to the optimal farm dimension. However, if the farm size decreases, the incidence of CC on the unit of product will increase accordingly. This is because, as we have verified, the cost of the PA package defined in the present study can be considered, with good approximation, a fixed cost not reducible depending on the reduction of the firm size. Based on this hypothesis, we finally performed a sensitivity analysis to explore the variation of the CC incidence on ATC per unit of production with respect to changes in farm size. The goal of this sensitivity analysis is to identify which is the minimum farm’s size needed to balance the firm budget with respect to the post-adoption market price levels.

Table 5 shows the results of the sensitivity analysis performed on the balanced minimum farm size, assuming as constant all the variables considered in the present case study – i.e., the cost of capital invested in the PA package, the ATC of production per hectare, the average saving on ATC per hectare, the productivity levels – other than production scale. The minimum production scale necessary to balance the firm budget results to be strongly influenced by land productivity. Accordingly, in virtue of a PA post-adoption land productivity of soft wheat 22% greater than durum wheat (7.3 ton vs. 5.7 ton) the “virtual” minimum production scale necessary to balance the firm budget results to be double (60 ha) for durum wheat with respect to soft wheat.

Table 5: Minimum farm size in balance

|  |  |  |
| --- | --- | --- |
| **Indicators** | **Soft**  **scale 30 ha** | **Durum**  **scale 60 ha** |
| Incidence capital cost/ha | 790 €/ha | 395 €/ha |
| Incidence capital cost/ton | 108,1 €/ton | 69.1 €/ton |
| ATC post-adoption (ha) | 1481.4 €/ha | 1112 €/ha |
| ATC post-adoption (ton) | 202.7 €/ton | 194.5 €/ton |

Moreover, very interesting seems to be the fact that the minimum farm size required to balance the budget – in this case regardless of the distinction between soft and durum wheat – is significantly smaller compared to the size of the real study case farm. This means that - keeping as fixed both the cost efficiency and productivity levels expressed by the study case farm – PA technology seems to be financially sustainable even for “medium” production scales.

Finally, as a further point of reference regarding the minimum production scale necessary to hypothetically obtain a positive result by the adoption of PA technology, table 5 illustrates a simulation consisting in the results of a sensitivity analysis aiming to identify the minimum farm’s size needed to balance the firm budget with respect to PA adoption by a cereal farm producing durum wheat in a hilly area. Thus, the fundamental analytical elements which distinguish this “virtual” farm from our real case study are the following:

* Hilly area (v.s. flat land for the case study);
* Minimum tillage (v.s. no tillage for the case study).
* Unit cost of production equal to 170 €/ton (net of savings due to PA adoption);
* Land productivity equal to 5 ton/ha.

It turns out that the minimum farm size necessary to balance the firm budget results to be considerably greater with respect to the farm size caracterizing the case study - i.e. 200 ha in a hilly area against 60 ha in a plane area.

Table 6: Minimum farm size balance in hilly area

|  |  |
| --- | --- |
| **Indicators based on ATC condition of minimum tillage average cost (ha) and hilly area** | **Durum 200 ha** |
| Incidence capital cost/ha | 118.5 €/ha |
| Incidence capital cost/ton. | 23.7 €/ton |
| ATC cost post-adoption (ha) | 968.5 €/ha |
| ATC post-adoption (ton) | 193.7 €/ton |

This result is indicative of how the economic effect of the PA technology changes as the environmental conditions in which the production takes place change. In particular, in this hypothetical scenario characterized by minimum tillage in a hilly area, the unit cost of production is assumed to be 35 percent greater with respect to the production cost characterizing the case study, and the land productivity level is assumed to be 15 percent lower. A concluding consideration which can be made based on these results is that the PA adoption in a hilly area using minimum tillage is convenient only for great farms (larger than 200 ha) or for cooperative systems capable of bringing together many producers in a common management organization.

**7. CONCLUSION**

To date, the knowledge and diffusion of PATs in the agricultural sector are still insufficient especially due to the scarcely aware of the internal and external – with respect to the farm – conditions thanks to which PATs may have a positive role both in economic and environmental terms that this. In this regard, the case study presented in this article contributes to the research on the topic by identifying some important points of reference both in terms of cost-effectiveness and efficiency in the use of production inputs deriving from the adoption of the PA. The case study investigated proves to be a large farm capable to exploit effectively the returns to scale associated with the adopted PATs package, generating income as a consequence. Moreover, precisely with regard to the farm- scale as a crucial condition in function of which evaluate the profitability of PATs, our case study allows to make assumptions on the minimum farm size necessary to balance the budget given the cost of capital associated with technology adoption . As the introduction of regulations, norms, and funding programs could affect the PA innovation field positively and negatively, understanding the circumstances and factors that influence the adoption of PATs is critical for developing targeted policies or initiatives that support the adoption of PA in farming businesses. Insofar as PA technology was capable to reconcile production requirements and environmental protection, questions arise on how best to support PA adoption. However, it is clear that there are still no specific measures for the diffusion of precision agricultural technologies in the sector, but there are generic measures of sector innovation and digitization of the agri-food chain. In addition, while several studies have begun to demonstrate the economic effectiveness of the PATs, the assessment and quantification of environmental benefits are almost totally lacking in the literature. Some farmers do consider these benefits as part of their overall viability decision, based upon their personal values. But apart from general qualitative statements, there is no quantified environmental benefit assessment that can underpin an investment decision: this appears a significant omission that could be addressed by developing a methodology and/or tool to be available for the management decision-making process. Similarly, if policy shifts towards rewarding environmental goods generation (i.e reduction of C02, reduction of agrochemicals), new payment mechanisms could incentivize the use of these technologies.

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