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Analysis

Economic and Environmental Efficiency, Subsidies and Spatio-Temporal Effects in Agriculture

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ABSTRACT

In this paper, we investigate how farms' environmental and economic efficiency is shaped by Pillar I CAP subsidies over time and by spatial effects originating from subsidies received by neighbours. To reach this goal, we estimate a spatial stochastic frontier model including intra and inter province spatial effects and differentiate among environmental and economic outcomes to evaluate the direct and indirect effects of subsidies on both aspects. The results of the analysis indicate that on one hand, subsidies are helping farmers to achieve environmental sustainability especially after the 2013 reform, on the other, they are leading to increased economic inefficiency levels. Considering spatial effects originating from subsidies, we find positive and significant spillovers occurring among closest neighbours both from the economic and the environmental perspective.

1. Introduction

Despite agriculture constitutes one of the most important sectors for economic development (Magrini, 2021), environmental impacts from agriculture are highly significant due to increased energy consumption, usage of non-renewable products as nitrogen, phosphorus and pesticides causing different environmental issues such as biodiversity loss, land deterioration and pollution (Nemecek et al., 2011). In this context, the term eco-efficiency (economic and environmental efficiency) by Schaltegger and Sturm (1990) and the term sustainable productivity by Lankoski and Thiem (2020) have been proposed to indicate the need for achieving financial and sustainable development in agriculture by creating more economic value with less ecological impact (Kharel and Charmondusit, 2008). For instance, as well underlined by Lankoski and Thiem (2020, p.1) “*a key policy question for governments concerns the design and implementation of policies that could stimulate positive environmental performance while maintaining, or even increasing, productivity growth*“.

Since 1962 the European Union played a key role in supporting agriculture and rural areas through the EU Common Agricultural Policy (CAP). This European policy, accounting for roughly 40% of the EU budget, is considered one of the major drivers of change in the agricultural sector, thanks to its direct effects on income and the orientation of farming activities. Recently, besides fostering agricultural productivity by ensuring technical progress, sustainable development has been recognized as one of the main objectives of the CAP in order to comply with the “Agenda 2000” and the 2030 Sustainable Development Goals. In particular, starting in 2013, the CAP began prioritizing more sustainable management of agricultural resources by promoting best nutrient management practices and by adopting cross-compliance measures and green direct payments.

Several empirical studies have concentrated on assessing the effectiveness of the CAP in supporting farmers' economic performance (Rizov et al., 2013; Skevas et al., 2018; Zhu and Lansink, 2010; Khafagy and Vignani, 2022; Kazukauskas et al., 2014), in reducing the environmental impact of agricultural production (Saman, 2021; Balogh, 2022; Barraquand and Martinet, 2011; Jacquet et al., 2011) and in encouraging ecological protection behaviours among farmers (Koiry and Huang, 2023; Varela-Candamio et al., 2018; Arata and Sckokai, 2016). Only a limited number of papers jointly analysed the impact of subsidies on both farmers' economic and ecological performance. Between those, Eder et al. (2021) found that farmers with higher shares of subsidies are, on average, less technically and soil use efficient, Lankoski and Thiem (2020) showed that agricultural policies supporting production with environmental constraints are important for reaching sustainable productivity, while Sidhoum et al. (2023) found a non-significant impact of agri-environmental schemes on both economic and environmental efficiency proxied by nitrogen pollution. However, to date, there is not a common consensus on whether the economic impact of subsidies is positive or negative and if subsidies play an effective role in mitigating

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environmental degradation mainly due to the incomparable approaches followed by scholars in empirical investigations as the choice of different time periods, countries, and kinds of subsidies considered in empirical analyses.

Besides their direct contribution to agricultural performance and environment, subsidies can also influence farmers' efficiency levels through spillovers from neighbouring producers. Indeed, an individual's working motivation may be affected by one of the surrounding farmers and this can result in shared knowledge, similar investment decisions, and common choices in the adoption of cleaner or dirtier technologies. Thus, farmers working in the same area can emulate each other and a farmer may experience efficiency gains by learning how to use its resources more efficiently from neighbouring farmers, leading to common adoption patterns.

Other than understanding the impact of subsidies on agricultural ecological and economic outcomes, the investigation of both direct and indirect mechanisms resulting from CAP subsidies on farmers' economic performance and environmental sustainability is fundamental for achieving long-run sustainability. Although the spatial dimension related to subsidies is crucial in terms of policy implications, this aspect is relatively unexplored in existing literature. Thus, the main innovative contribution of this study regards the analysis of spatial effects originating from subsidies received by neighbours. In particular, in this paper, we evaluate the effect of Pillar I subsidies (i.e., the main agricultural subsidy both in terms of farms' coverage and amounts granted) on economic and environmental efficiency differentiating among direct effects and spatial spillovers generating by peers. Moreover, we evaluate the time dynamics of economic and environmental efficiency to understand whether CAP subsidies are effectively contributing to the achievement of both economic and sustainable goals in time.

The analysis focuses on Italy in the time period 2008–2018. Italy is one of the main agricultural producers among the EU 24 countries and the agricultural sector is the largest manufacturing sector in Italy. In 2018, total agricultural production reached EUR 55.8 billion while total production value reached 113.7 billion euros (fi-compass, 2020). However, the Italian agricultural sector is characterized by inadequate resources and unqualified personnel, unable to develop new technologies (Cardamone, 2020). Anyway, innovation is essential to be competitive in foreign markets and to produce sustainable, healthy, and good quality products that can meet consumers' needs. To make up for the lack of new technologies and innovations that can lead to more efficient food production (Ciliberti et al., 2016), farms tend to share information, knowledge and best practices (De Martino and Magnotti, 2018). As a consequence, internal R&D investments are replaced by external sources of knowledge and thus, in the Italian agricultural sector, networking and collaboration among farms have become essential practices that can help spread knowledge and foster innovation (Acosta et al., 2015). Hence, in this work, we evaluate subsidies' contribution to shaping farmers' environmental and economic efficiency levels taking into account also spatial effects related to subsidies received by neighbours. In particular, we distinguish among neighbours located in the same province and in surrounding provinces providing relevant insights to policy makers on the spatial scale which mostly favours the occurrence of spatial interactions.

In sum, we investigate subsidies' contribution to farmers' efficiency level concentrating on Pillar I subsidies since they constitute the largest amount of EU direct payments to farmers with the aim to support agricultural production with a specific focus on environmental and climatic matters. In particular, we pose the following research questions:

Q1: how do Pillar I subsidies affect farmers' economic and environmental efficiency?
Q2: does the effect of subsidies spread across space influencing neighbouring producers?
Q3: how are economic and environmental efficiency evolving over time?

To reach these goals we use RICA data at the farm level referring to the Italian agricultural sector in the time period 2008–2018 and we take advantage of a spatial stochastic frontier model inspired by Galli (2023b). Specifically, we distinguish between economic and environmental efficiency by estimating separately two frontier functions with value added and fertilizer intensity as the respective outputs to be maximised/minimized. This approach allows us to assess the effect of Pillar I subsidies differentiating between economic and environmental efficiency in order to clearly evaluate how subsidies contribute to shaping both aspects. Moreover, we enrich the model specification by including time interactions to investigate how the effect of Pillar I subsidies is evolving in time and inter and intra province spillovers in order to disentangle the different kinds of spatial effects related to subsidies. Finally, we compute time-varying firm-specific ecological and economic efficiency scores to investigate the different efficiency dynamics characterising Italian farms. Several additional analyses and robustness checks further support and enrich the main results of the study.

To our knowledge, this is the first paper that evaluates the role of subsidies in influencing farmers' economic and environmental efficiency taking spillover effects into account and analysing their dynamics. Results from this analysis may be of great interest to policy makers in order to fix current policies and plans based on some detailed empirical insights on the diversified impact of subsidies on economic and environmental outcomes. Moreover, identifying the different kinds of spillover effects could be essential to public governments in order to exploit existing spatial interactions in policy interventions aiming at reinforcing agricultural sustainability while supporting economic development.

2. Literature Review

2.1. The Impact of CAP Subsidies on Agricultural Performance

The common agricultural policy (CAP) was first outlined in 1958 and began formally in 1962 to guarantee food security in Europe after the Second World War. Among the original objectives of the CAP, the main ones concerned increasing agricultural productivity through technical progress, ensuring the optimum utilization of the production factors, and guaranteeing a fair standard of living for the agricultural community. Over the years several reforms of the CAP have been made but it was in 2000 that the original objectives were modified in order to encourage market competitiveness, food quality and safety, environmental sustainability, and development of rural areas. In order to achieve these goals two different pillars of the CAP were introduced, the first one funded by the European Agricultural Guarantee Fund receiving the larger share of the total budget (about 75.6% of the overall budget in the period 2014–2020) and the second one based on a combination of funds from the European Agricultural Fund for Rural Development and regional and national stakeholders. The aim of Pillar I is to support farmers' income through direct payments and in return, farmers are asked to reach specific standards of food safety, animal welfare, environmental management, and good maintenance of agricultural land. On the other hand, Pillar II is directed at fostering balanced development of rural areas guaranteeing social inclusion and reducing poverty through the creation and maintenance of working places and sustainable management of natural resources. Thus, subsidies from Pillar II tend to be very context specific and are personalized based on the characteristics and needs of the different rural areas. Environmental requirements have been additionally reinforced by the 2013 reform (adopted in 2014) which introduced the adoption of Green Direct Payments. This policy instrument, incorporated in Pillar I subsidies, aims at rewarding farmers complying with specific sustainable agricultural practices such as permanent grassland, ecological focus area and crop diversification.

Agricultural subsidies influence farmers' economic performance by affecting both their productivity and technical efficiency levels. Considering productivity, subsidies may distort farmers' investment decisions toward relatively less productive activities that are supported by subsidies (Alston and James, 2002) or to overinvest in subsidized inputs (Rizov et al., 2013). Moreover, subsidies may also reduce farmers' willingness to adopt cost-optimizing strategies (Minviel and Latruffe, 2017). Conversely, some studies have underlined that subsidies may play a role in stimulating productivity growth, both when rural market imperfections are present, by boosting a farmer's financial resources and improving access to credit (Ciaian and Swinnen, 2009), or when farms operate in imperfect insurance markets, by mitigating risks and triggering investments in certain types of risky activity (Roche and McQuinn, 2004). Despite several works in agricultural economics literature analysed the effectiveness of agricultural subsidies on farmers' productivity level to give European and national governments consistent policy directions (Mary, 2013; Rizov et al., 2013; Khafagy and Vignani, 2022; Kazukauskas et al., 2014; Mennig and Sauer, 2020), empirical results are mainly mixed and inconclusive.

Regarding efficiency, subsidies can lower farmers' motivation to work efficiently, distort the production structure of farms, and generate soft budget constraints that lead to an inefficient use of resources (Baumol, 1990). On the other hand, they can also act as a source of credit and allow farmers to innovate thanks to increased credit access, reduced risk aversion, and higher productive investments (Blancard et al., 2006). Analysing the link between agricultural subsidies and economic efficiency, empirical evidence mainly highlighted a negative link between CAP subsidies and farms' efficiency levels. For instance, Skevas et al. (2018) showed that farmers receiving agri-environmental and animal welfare payments resulted to be more inefficient than those who did not receive them, while Skevas and Lansink (2020) found that a one-unit (i.e. €10,000) increase in subsidies leads to a 2% decrease in farms' technical inefficiency. Recently, Koiry and Huang (2023) argued that farmers consider subsidies as an extra income, making different production decisions and reducing technical efficiency.

Besides economic outcomes (i.e. productivity and technical efficiency), CAP subsidies also affect farmers' environmental performance. Several criticisms have been directed at the CAP due to its possible negative effects on the environment, landscape, and biodiversity (Saman, 2021). Indeed, the increasing need for food, feed, and bioenergy in the EU has the potential to cause substantial environmental harm, resulting in alterations in land use, loss of biodiversity, and environmental degradation. Empirical evidence on the effect of subsidies on farmers' environmental performance indicates that CAP payments increased the use of renewable energy in some countries but with limited effects (Saman, 2021), helped to cut greenhouse gas (GHG) emissions by increasing the area of organic farming (Balogh, 2022), increased pesticide expenditures through Pillar I while decreased it through Pillar II (Aubert and Enjolras, 2022) and acted as an incentive for farmers' environmental friendly behaviours (Varela-Candamio et al., 2018). For a detailed list of studies investigating the impact of subsidies on different environmental outcomes such as biodiversity, soil quality, water quality, GHG emissions, etc. see Mennig and Sauer (2020).

To address the ecological concerns, the CAP 2014–2020 incorporated tools such as the green payment in Pillar I and agri-environmental measures in Pillar II to balance agricultural production with the protection of the environment and biodiversity. However, agri-environmental measures are typically believed to adversely impact productivity by placing limitations on input utilization such as fertilizers, pesticides, and land. Nevertheless, the empirical evidence regarding the productivity consequences of agri-environmental payments is inconclusive. Some studies report a detrimental impact on productivity (Lakner, 2009), while others observe either no impact or a positive effect (Dudu and Kristkova, 2017; Mary, 2013). As for the impact on efficiency, agri-environmental subsidies are likely to stimulate farmers' ecological innovation and consequently economic efficiency levels by requiring the adoption of specific management practices and environmentally friendly actions that can lead to increased technical efficiency levels (Sidhoum et al., 2023). For a comprehensive review of factors influencing farmers' adoption of environmentally friendly behaviours by participating in agri-environmental schemes see Schaub et al. (2023).

Recently, agricultural economists have shifted their focus from considering economic and environmental objectives separately to viewing the pursuit of both goals as highly interconnected. Indeed, exclusively supporting the sector's productivity may result in negative externalities related to industrialization that threaten sustainability and environmental preservation. In particular, policies that incentivize agricultural production, such as market price supports and coupled payments can lead to increased agricultural land use, greater use of agricultural inputs and consequently, adverse effects on biodiversity, GHG emissions and water quality (Lankoski and Thiem, 2020). Conversely, concentrating solely on environmental concerns may put at risk the economic viability of farmers. Indeed, subsidies aimed at supporting environmental sustainability primarily impact farmers' choices regarding the selection and intensity of inputs, land use and the allocation of land among different crops. This, in turn, may result either in reduced levels of productivity for farmers (DeBoe, 2019) or in increased economic efficiency by stimulating eco-innovation (Sidhoum et al., 2023). Therefore, a key challenge for policy makers is to address the complicated tradeoff between ecological and economic goals by achieving a balance between environmental sustainability and economic performance (Fusco et al., 2023).

To date, only a limited number of studies investigated the impact of subsidies on both economic and environmental efficiency. As for Austrian crop farms, Eder et al. (2021) showed that farmers with higher shares of subsidies are, on average, less technically and soil use efficient. Lankoski and Thiem (2020), by using country-level observational data and Qualitative Comparative Analysis, highlighted that agricultural policies supporting a low level of production or a high share of payments with environmental constraints allow to obtain high levels of sustainable productivity. Concentrating on Bavarian dairy farms between 2013 and 2018, Sidhoum et al. (2023) demonstrated, by using a combination of propensity score matching and difference in difference approach, that agri-environmental schemes do not significantly impact either farms' economic or environmental efficiency.

Despite the acknowledged importance of having clear indications on the impact of agricultural subsidies for policy decisions, there is still not a clear consensus on the effect of subsidies on both economic and environmental outcomes. Moreover, no previous works have analysed whether and how spillover effects originating from CAP subsidies affect farmers' efficiency levels. Therefore, in this paper, we contribute to this stream of research by evaluating the direct and indirect spatial impact of CAP subsidies on agricultural ecological and economic efficiency.

2.2. Spatial Effects in Agriculture

Spatial effects in agriculture can realize through different channels. First, farmers' performance may be closely linked with the one of neighbours due to knowledge transmission, learning from others, exchange of ideas and best practices (Cardamone, 2020), common behaviours such as similar investment decisions (Skevas and Lansink, 2020), and farmers' adoption of new similar technologies to address specific techno-economic challenges faced by farms operating in neighbouring territories (Billé et al., 2018).

Knowledge and information spillovers as well as common technology adoption patterns have been extensively explored in agricultural economics literature. Foster and Rosenzweig (1995) is one of the first contributions investigating the presence of learning spillovers and finding evidence of a significant impact of neighbours' experience on rural Indian households' profitability levels. Later on, Wollni and Andersson (2014) demonstrated that farmers having a larger availability of information in their neighbourhood network and acting in cooperation with their neighbours are more likely to adopt new technologies such as organic agriculture. Similarly, Lapple et al. (2017) revealed that farmers, in the decision to adopt new technologies, are influenced by their peers which in turn affect neighbouring farms, generating a global spatial spillover effect that influences the adoption rates of all neighbours. Likewise, Skevas and Lansink (2020) confirmed the existence of both positive and negative spillover effects across Dutch dairy farms observed over the period 2009–2016. Specifically, the authors found that being surrounded by older farmers negatively influences neighbours while being located close to more intensive producers decreases peers' inefficiency level. Vidoli et al. (2016), concentrating on the Italian wine industry, highlighted that spatial proximity among wine producers can stimulate productivity, and that Italian wine clusters can be considered communitarian networks that continuously share technical advice in a collaborative environment. Considering environmentally friendly practices, several studies (Arora et al., 2021; Dessart et al., 2019; Lapple and Kelley, 2015; Rode et al., 2015) highlighted that peer relationships and interactions among neighbouring farmers are often connected to a higher likelihood of adopting agri-environmental schemes thanks to shared information about practices, culture, descriptive norms, and favorable bio-physical conditions.

Despite scholars largely assessed the importance of emulation behaviours and knowledge spillovers in shaping farmers' environmental and economic performance, spatial effects in agriculture can also arise through various other channels. For instance, they may result from greater availability of inputs such as specific products, suppliers, assets and workers with specific skills in a certain area (Marshall, 1890), from unobserved factors common to neighbouring territories such as soil conditions or climatic, topographic and environmental characteristics (Schmidt et al., 2009) and from policies and institutions operating at the local level (Areal et al., 2012).

Spillovers from subsidies can encompass both spatial dependence in the distribution of subsidies across regions and common behaviours of subsidized farmers in adopting environmental-friendly or economically efficient practices. The first mechanism depends on the fact that the amount of support allocated to a region can be influenced by the support received by neighbouring regions, as neighbouring regions often share similar agricultural, economic, or development challenges (Camaioni et al., 2016). Moreover, policymakers may decide to distribute similar assistance to neighbouring areas to ensure political equity. Regarding the second channel, the receipt of subsidies in a particular area may promote the adoption of new technologies or improved practices both within that area and in neighbouring territories. As suggested by Skevas and Lansink (2020), positive spillovers could generate from subsidized peers if neighbouring farmers share the advantages arising from the uptake of new technologies, which can boost farmers' willingness to innovate and consequently efficiency. Thus, social network connections with subsidy recipients may raise others' adoption of new technologies obtaining societal gains from the subsidy (Foster and Rosenzweig, 1995). On the other side, farmers' perception of subsidies as an additional source of income that can allow them to work less efficiently may be supported by neighbours through reduced motivation spillovers generating negative spatial effects.

Among the various economic mechanisms driving spillovers, in this paper, we concentrate on the spatial effect of subsidies on farmers' environmental and economic performance. Indeed, despite understanding the role of subsidized neighbours on farmers' behaviours is a key issue for policy decisions, to our knowledge, limited attention has been devoted to studying this potential source of spillovers (Skevas and Lansink, 2020). Therefore, in this work, we extend the current literature on spatial effects in the agricultural sector analysing whether being located in an area or close to areas with a large subsidy allocation contributes to favouring farmers' environmentally friendly or economically efficient behaviours. In particular, we concentrate on Italy and we investigate the presence of inter and intra province spillovers related to Pillar I subsidies by estimating a spatial stochastic frontier model. This approach makes it possible to identify which spatial level mostly allows spillovers to materialize providing relevant insights to policy makers on the spatial scale which mostly favour the diffusion of technological advice, best practices and knowledge among peers.

3. Data

In this study, we use firm level data collected through the RICA survey, which is the Italian counterpart of the FADN survey. Overall, we dispose of an unbalanced panel of 119,229 observations in the time period 2008–2018 (the year 2015 covers the smallest sample with 9569 farms surveyed while the highest number of units, 11,398, is available for 2013). To perform our spatial analysis, we use information about the province where farms are located since it is the most detailed geographical information available, for confidentiality reasons.

Since we aim to analyse both economic and environmental outcomes, we adopt the efficiency scheme known as "managerial output disposability" which refers to the capacity of a decision-making unit to simultaneously optimize several outputs (Sueyoshi and Goto, 2011). The idea is that farms may be able to increase or at least maintain desirable outputs such as economic value and minimize undesirable outputs like environmental pressure, based on a vector of production inputs (Exposito and Velasco, 2018). The multiple output approach is not new in the agricultural economics literature, although not yet used in a stochastic frontier framework. Among others, Exposito and Velasco (2020) examined the environmental efficiency of the agricultural sector for a group of European countries by maximising the value of gross agricultural production (desirable output) and minimizing the intensity of use of mineral fertilizers (undesirable output) considering labour, cultivated land and crop capital stock as production inputs. Similarly, in the context of the recycling market, Exposito and Velasco (2018), for analysing the efficiency of Spanish regions, considered the total amount of municipal solid waste and operational revenues as desirable outputs to maximise and the amount of mixed-collected municipal solid waste as the undesirable output to minimize based on a vector of labour and capital inputs.

In this study, we define value added as the economic output to be maximised while fertilizer intensity measured as fertilizer expenditure represents farms' environmental impact to be minimized. Indeed, on one hand, value added is one of the most commonly used measures for economic performance in productivity analyses (Moutinho et al., 2018; Bonjec et al., 2014). On the other, fertilizers constitute one of the main sources of nitrogen and phosphorus in agriculture generating land, water and air pollution (Shah et al., 2019). Following Fusco and Vidoli (2013), we choose labour, capital, land, and water, energy and fuel as inputs respectively defined as the logarithm of total worked hours, fixed capital, utilized agricultural area, and water, energy and fuel expenditure.

Moreover, given our goal of analysing the direct and indirect impact of subsidies on agricultural economic and environmental efficiency, we introduce the level of Pillar I subsidies as an inefficiency determinant together with subsidies perceived by neighbours in the same province and in surrounding provinces. In the inefficiency model, we also consider additional characteristics of the farm such as farm dimension, gender and age of the farmer, whether the farm is biological or not, altimetric area and if the farmer receives additional subsidies through Pillar II incentives. Table 1 describes all the variables considered in the analysis, i.e. outputs, inputs, and determinants of farms' efficiency.

Some insights on the spatial distribution of Pillar I subsidies are shown in Fig. 1 aggregating the data at the NUTS-3 level since the province is the finest geographical detail at our disposal. The figure depicts strong similarities in the level of subsidies among neighbouring

Table 1
Descriptive statistics.

Variables	Description	Min	Mean	Max	SD	*n*
Output						
VA	ln(Value added)	1.38	10.46	16.51	1.29	118,126
FI	ln(Fertilizer)	0	4.91	12.78	1.34	103,443
Inputs						
L	ln(Total working hours)	2.99	8.06	12.44	0.70	119,196
AA	ln(Agricultural area)	0.01	2.76	8.14	1.24	119,197
K	ln(Fixed assets)	2.77	12.07	20.03	1.59	118,677
WEF	ln(Water, energy and fuel)	0.69	6.99	13.78	1.55	103,745
t	1 for 2008, …, 11 for 2018	1	5.88	11	3.16	119,229
Inefficiency Det.						
Sub	ln(Pillar I subsidies)	0	7.00	14.65	3.56	119,229
PillarII	1 if Pillar II subsidies >0	0	0.33	1	0.47	119,229
$Sub1_{Coupled}$	ln(coupled Pillar I subsidies)	0	1.14	13.54	2.62	119,229
$Sub1_{Decoupled}$	ln(decoupled Pillar I subsidies)	0	6.97	14.65	3.54	119,229
$Sub2_{Env}$	ln(agri-environmental Pillar II subsidies)	0	1.58	13.57	3.30	119,229
$Sub2_{Other}$	ln(other Pillar II subsidies)	0	1.38	13.13	3.09	119,229
Male	1 if Male	0	0.79	1	0.41	119,229
Age	ln(Famers' age)	2.48	4.11	4.80	0.25	119,229
Small	1 if annual gross income<€25,000	0	0.23	1	0.42	119,229
Medium	1 if annual gross income>€25,000 and < €100,000	0	0.43	1	0.50	119,229
Bio	1 if Biological	0	0.11	1	0.31	119,229
Lowland	1 if Lowland	0	0.32	1	0.47	119,229
Valley	1 if Valley	0	0.45	1	0.50	119,229

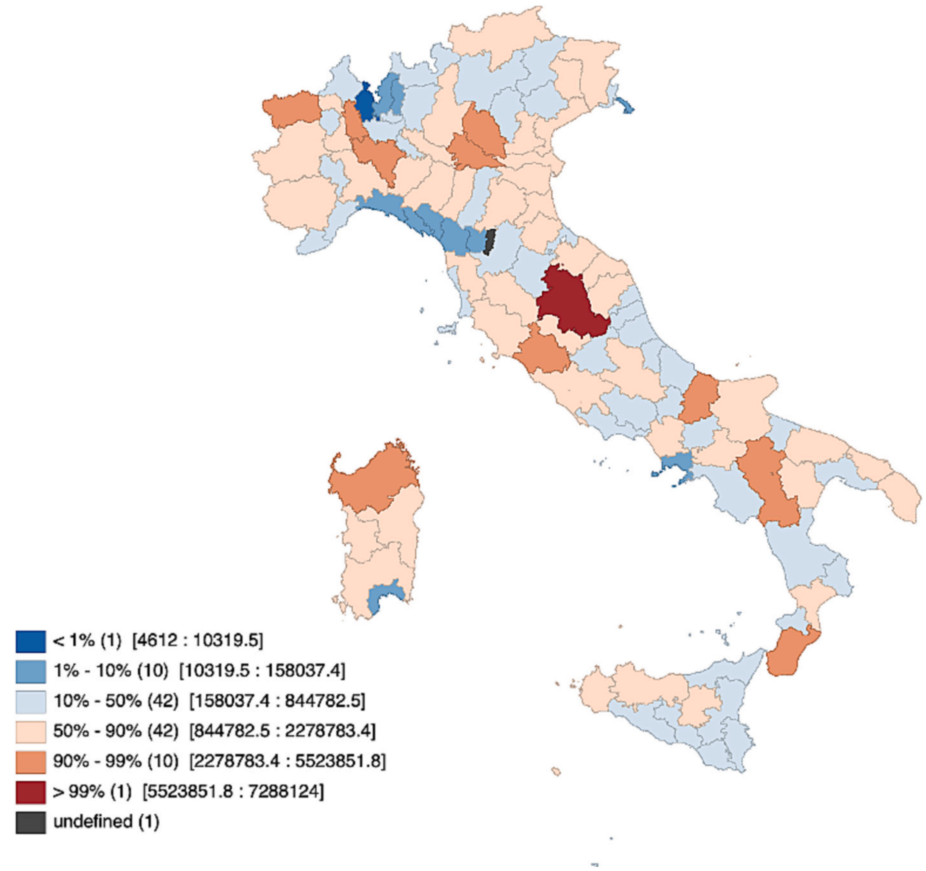

Fig. 1. Pillar I subsidies by province (year 2018).
Note: provinces are classified based on the percentiles of Pillar I subsidies. The number of provinces in each category is reported in round parentheses while the range of total subsidies received by provinces in each category is described in square parentheses.

provinces. This evidence is confirmed by the global Moran's I statistics which reaching a value of 0.09 indicates the presence of positive global spatial dependence in 2018.[1] However, aggregating the data by province may hide relevant insights on the spatial effects occurring among individual farmers. Thus, in our empirical analysis, we use firm-level data, and we consider both intra and inter province spillovers.

4. Modelling Strategy

Previous works mainly used data envelopment approaches (DEA) to analyse agricultural eco-efficiency (for a review see Song and Chen, 2019). DEA techniques allow to non-parametrically optimizing a production function based on different input and output variables. In particular, the multiple optimization problem handling both desirable and undesirable outputs is achieved by means of innovation into the way that inputs are used to obtain outputs, thereby allowing undesirable outputs to be lowered while still increasing (or at least maintaining) desirable outputs (Sueyoshi and Goto, 2011). The use of stochastic frontier models to assess agricultural eco-efficiency is still very limited since differently from non-parametric DEA techniques, stochastic frontier models allow to consider one single output at a time raising some difficulties in maximising both economic and environmental outcomes given a certain set of inputs. However, considering environmental and economic outcomes separately may provide meaningful insights to policy makers on the specific achievement of the two goals as well as on the kind of association and time dynamics characterising them. Moreover, from a modelling perspective, a parametric SF approach leads to several advantages compared to non-parametric DEA techniques. First of all, estimating a SF model allows separating inefficiency from random shocks, while using DEA analysis random disturbances are absorbed in the inefficiency component. As recommended by Coelli (1995), measurement errors and missing variables are highly relevant in the agricultural sector and thus, it is fundamental to separate random shocks from inefficiency. Second, in a stochastic frontier approach it is possible to evaluate the effect of some inefficiency determinants using a one-stage procedure which guarantees unbiased and more robust estimates than two stage approaches (Wang and Schmidt, 2002). Lastly, SF model can be easily extended to a spatial setting.

Therefore, in this paper, we use a spatial stochastic frontier approach to analyse the direct and indirect role of CAP subsidies on ecological and economic efficiency. In particular, we differentiate between economic and environmental outcomes by considering separately the role of inputs in maximising value added and in minimizing fertilizer intensity estimating two distinct frontier functions. Transposing the approach proposed by Sueyoshi and Goto (2011) for modelling desirable and undesirable outputs to a SF setting, in this study, when considering value added, economic inefficiency is defined as the decrease in the maximum level of desirable output given a certain set of inputs due to technical frictions while for fertilizers, inefficiency is defined as the increase in the minimum level of undesirable output due inefficient environmental practices. By using a stochastic frontier approach and defining CAP subsidies as inefficiency determinants, it is also possible to simultaneously evaluate the effect of Pillar I subsidies on farms' inefficiency level while estimating the frontier. Moreover, following Galli (2023b), we include the spatial lag of subsidies in the inefficiency model in order to evaluate inter and intra province spillover effects related to subsidies received by neighbouring producers. This modelling strategy allows us to measure the direct and indirect effect of Pillar I subsidies on agricultural performance precisely identifying subsidies' contribution to economic and environmental efficiency.

The model specification is shown in Eqs. ((1)–(2)) for $i = 1, \dots, N$ and $t = 1, \dots, T$. In particular, for the frontier function we adopt a Cobb-Douglas specification since it involves the estimation of fewer parameters compared to a Translog functional form facilitating the interpretation of the results and due to its ability to provide more efficient estimates (Yao and Liu, 1998).

$$Y_{it} = L_{it}\beta_1 + AA_{it}\beta_2 + K_{it}\beta_3 + WEF_{it}\beta_4 + t\beta_5 + v_{it} - cu_{it} \tag{1}$$

$$\mu_{it} = Sub_{it}\phi_1 + W_{intra}Sub_{it}\phi_2 + W_{inter}Sub_{it}\phi_3 + \mathbf{Z\delta} \tag{2}$$

As introduced in the previous section, Y_{it} represents the economic or environmental outcome of firm i at time t, L_{it}, AA_{it}, K_{it}, and WEF_{it} are the four production inputs and t captures the deterministic time trend. As usual in SF analysis, the error term is split into two independent components v_{it} and u_{it} that respectively represent the normally distributed random error and the inefficiency error term. Since inefficiency can only take positive or at least zero values, the inefficiency component is commonly assumed to be distributed as a truncated normal with mean μ_{it} and variance σ_u^2. In this framework, u_{it} is subtracted to the frontier function when inefficiency represents a decrease in firms' production level due to technical or economic issues and thus $c = 1$, while u_{it} is added to the frontier equation and $c = -1$ if inefficiency represents an output increase. Therefore, in this analysis, we set $c = 1$ to investigate economic efficiency since we aim to maximise value added (i.e. the desirable output) while we fix $c = -1$ to evaluate environmental efficiency since we need to minimize fertilizer intensity (i.e. the undesirable output).

Following Battese and Coelli (1995) and Galli (2023b), we model the mean of the inefficiency error term as function of some inefficiency determinants in Eq. (2). Specifically, we introduce subsidies (*Sub*) and the level of subsidies perceived by neighbours differentiating among inter and intra province spatial effects. To reach this goal, the spatial weights of the intra spatial weight matrix (W_{intra}) take values of one for farmers located in the same province and zero otherwise while for the inter spatial weight matrix (W_{inter}) we define farmers living in neighbouring provinces as peers. Both spatial weight matrices are row standardized and time varying since we have unbalanced panel data and the structure of the network changes every year. Therefore, ϕ_1 measures the direct contribution of Pillar I subsidies to economic/environmental inefficiency while ϕ_2 and ϕ_3 respectively represent subsidies' indirect effects generating from neighbours located in the same area and in surrounding provinces. Moreover, we also estimate the model by including the interaction between time and subsidies in the inefficiency model to investigate how the direct effect of Pillar I subsidies varies in time. As additional controls in the inefficiency model, we introduce a dummy variable to control for farms subsidized by Pillar II incentives (*PillarII*), a dummy variable for gender (*Male*), the logarithm of farmers' age (*Age*), two dummy variables (*Small* and *Medium*) to control for the farm's dimension with *Big* as the reference category, a dummy variable for biological farming (*Bio*) and a set of dummies (*Lowland* and *Valley*) for the altimetric area with *Mountain* as reference.

The model specified in Eqs. ((1)–(2)) can be estimated by maximum likelihood techniques. In particular, incorporating in the model the spatial lags of the subsidy variable corresponds to expanding the set of the inefficiency determinants in the inefficiency model since they capture local spillovers (i.e. spatial effects do not exhibit endogenous feedback effects and thus, they only affect the neighbouring observations as defined by the spatial weight matrix). Similarly to using a SLX specification, this approach leads to several advantages. First, the model can be estimated by standard approaches without handling the endogeneity resulting from considering global spatial dependence. Second, the estimated coefficients of the inputs and the subsidy variable can be

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[1] Positive and significant spatial dependence is detected for all the years under consideration. Detailed information on the Moran's I statistics for years 2008–2017 is available in Table A1 of Appendix A.

meaningfully interpreted as elasticities while the coefficients related to the spatial lags of subsidies can be straightforwardly interpreted as indirect effects since they reflect the average spillover effects to neighbouring units.

Starting from the parameter estimates from Eqs. ((1)–(2)), the efficiency scores for each unit i at time t can be computed following Kumbhakar and Kumbhakar and Lovell (2000) as $TE_{it} = exp(-u_{it}|\varepsilon_{it})$ with $\varepsilon_{it} = v_{it} - cu_{it}$. Our modelling approach allows computing time-varying farms' efficiency scores differentiating among environmental and economic aspects in order to separately investigate their time dynamics. In particular, efficiency scores range between zero and one equalling zero for fully inefficient farms and one for completely efficient farms.

5. Results

5.1. Estimation Results

Table 2 shows the estimation results of the model presented in Eqs. ((1)–(2)).

As expected, all the input variables have positive and significant coefficients. Concentrating on the variables of interest to answer to the first research question (Q1), we find that Pillar I subsidies contribute to significantly decreasing the level of inefficiency of farmers both from an economic and an environmental perspective with a similar and very small intensity (−0.01).

First, Pillar I subsidies can contribute to decreasing farmers' economic inefficiency by providing a stable source of income. This stability helps in lowering financial risks, promoting investments in innovative technologies and practices, encouraging farmers to adopt methods that enhance long-term productivity, and reducing the environmental and economic costs of unsustainable practices. Second, the positive effects of subsidies on environmental efficiency may depend on the fact that part of Pillar I subsidies, the so-called greening component, is directed toward farmers who voluntarily adopt environmentally friendly practices. As expected, incentives and rewards for farmer complying with specific ecological practices effectively incentivize them to adopt sustainable methods that reduce the environmental impact of their operations, leading to increased environmental efficiency levels. This result aligns with the finding of Biffi et al. (2021) on the success of European agri-environmental subsidies in targeting areas of high GHGs, achieving the program's goals regarding agricultural emissions reduction and carbon sequestration.

Investigating the time dynamics of the coefficient related to subsidies, on the economic side we find that the effect of CAP subsidies on inefficiency is negative, significant and constant between 2010 and 2016, but it is not significantly different from zero in the last two years of analysis. From the environmental side, our results indicate that while the impact of subsidies is not stable in more distant years showing positive, negative and non-significant values, it reaches increasing negative magnitudes starting from 2014. Therefore, consistent with the empirical literature reviewed by DeBoe (2019) and in line with the results of Lankoski and Thiem (2020), we find that the achievement of environmental goals is strongly supported by the introduction of cross-compliance measures and green direct payments. In sum, the 2013 CAP reform significantly contributed to increasing farmers' efficiency levels from an environmental perspective despite a more nuanced impact from an economic point of view.

Focusing on the indirect effects generating from subsidies addressed in the second research question (Q2), we find that subsidies generate

Table 2
Estimation results.

Input	Value Added				Fertilizer			
	Coeff.	SD	Coeff.	SD	Coeff.	SD	Coeff.	SD
L	0.66***	0.01	0.66***	0.01	0.34***	0.01	0.33***	0.01
AA	0.09***	0.01	0.09***	0.01	0.40***	0.01	0.41***	0.01
K	0.08***	0.01	0.08***	0.01	0.04***	0.01	0.04***	0.01
WEF	0.17***	0.01	0.17***	0.01	0.14***	0.01	0.13***	0.01
t	0.02***	0.01	0.02***	0.01	0.04***	0.01	0.08***	0.01
Constant	3.37***	0.05	3.47***	0.05	1.48***	0.06	1.18***	0.07
Inefficiency Det.								
Sub	−0.01***	0.01	–	-	−0.01***	0.01	–	-
Sub_{2008}	–	–	−0.00	0.01	–	–	0.01***	0.01
Sub_{2009}	–	–	−0.00	0.01	–	–	0.00	0.01
Sub_{2010}	–	–	−0.01***	0.01	–	–	−0.01***	0.01
Sub_{2011}	–	–	−0.01***	0.01	–	–	0.01***	0.01
Sub_{2012}	–	–	−0.01***	0.01	–	–	0.00*	0.01
Sub_{2013}	–	–	−0.01***	0.01	–	–	−0.01**	0.01
Sub_{2014}	–	–	−0.01***	0.01	–	–	−0.01***	0.01
Sub_{2015}	–	–	−0.01***	0.01	–	–	−0.02***	0.01
Sub_{2016}	–	–	−0.01***	0.01	–	–	−0.03***	0.01
Sub_{2017}	–	–	−0.00	0.01	–	–	−0.04***	0.01
Sub_{2018}	–	–	−0.00	0.01	–	–	−0.05***	0.01
$W_{intra}Sub$	−0.03***	0.01	−0.02***	0.01	−0.12***	0.01	−0.13***	0.01
$W_{inter}Sub$	0.08***	0.01	0.08***	0.01	−0.02***	0.01	−0.02***	0.01
PillarII	0.10***	0.01	0.10***	0.01	−0.24***	0.01	−0.23***	0.01
Male	−0.06***	0.01	−0.06***	0.01	0.03***	0.01	0.02**	0.01
Age	0.23***	0.01	0.23***	0.01	−0.03*	0.02	−0.03	0.01
Small	0.87***	0.01	0.88***	0.01	−0.38***	0.02	−0.40***	0.02
Medium	0.49***	0.01	0.50***	0.01	−0.16***	0.01	−0.16***	0.01
Bio	−0.05***	0.01	−0.05***	0.01	−0.13***	0.02	−0.14***	0.02
Lowland	−0.06***	0.06	−0.06***	0.07	0.86***	0.01	0.86***	0.01
Valley	0.00	0.01	0.00	0.01	0.54***	0.01	0.54***	0.01
Constant	−1.00***	0.06	−0.94***	0.07	1.76***	0.08	2.00***	0.08
Number of obs.	103,745		103,745		103,443		103,443	

***: p-value≤0.01; **:p-value≤0.05;*:p-value≤0.10.

positive and significant spillovers between farmers belonging to the same province with a larger negative effect on inefficiency for fertilizers (−0.13) than for value added (−0.02). On the other hand, we detect an increase in farmers' economic inefficiency resulting from inter-province spillovers (0.08) and a decrease in environmental inefficiency (−0.02). Therefore, knowledge spillovers among farmers located in the same province allow neighbours to share technical advice, best practices and new technologies resulting in increased efficiency levels considering both economic and environmental outcomes. Considering farmers located in neighbouring provinces, learning spillovers are preserved, with a reduced intensity, for environmental sustainability while competition effects arise from the economic side. The existence of negative spillover effects among farmers located in neighbouring provinces in terms of economic efficiency may depend on competitive pressures stemming from an unequal distribution of subsidies across different provinces. Specifically, subsidies can drive overproduction in widely subsidized territories, resulting in market price distortions and trade imbalances (for a comprehensive review of possible cross-border distortive effects of subsidies, see OECD (2022)). Windfall effects, as explained by Chabé-Ferret and Subervie (2013) can represent a further motivation since subsidies may be used to sustain practices that would be adopted anyway.

Further insights from our analysis indicate that farmers subsidized by Pillar II incentives tend to be more economically inefficient (0.10) and less environmentally inefficient (−0.23) compared to non-recipients.[2] Pillar II measures are generally assumed to have a negative effect on economic efficiency because they impose constraints on input usage, such as fertilizers, pesticides, and land (Garrone et al., 2019). Conversely, these types of payments may ensure that agricultural land remains cultivated in areas with less favorable natural agricultural conditions, thus promoting environmental efficiency (Knific and Bojnec, 2010; Latruffe and Desjeux, 2016). Moreover, while small and medium sized farms report higher levels of economic inefficiency compared to bigger farms, they turn out to pursue more sustainable practices. Concerning biological farming, we find that it contributes the boosting both economic and environmental efficiency. Finally, farmers' age is positively related to economic inefficiency and negatively associated with environmental inefficiency.

5.2. Additional Analysis

In the main body of the paper, we concentrate on the total amount of Pillar I subsidies received by farmers, as it constitutes the largest share disbursed by the EU per hectare through direct payments. However, as additional analysis, we differentiate among different types of subsidies because the impact of the CAP can vary depending on the specific scheme adopted (Kazukauskas et al., 2014). Therefore, we distinguish between coupled and decoupled Pillar I subsidies and between Pillar II subsidies directed to the adoption of agri-environmental practices and other types of Pillar II subsidies. In our dataset, 81.73% of farmers receive Pillar I subsidies in general, with 81.66% receiving decoupled Pillar I subsidies and 16.54% receiving coupled Pillar I subsidies. As for Pillar II, 19.10% of farms in our data receive Pillar II agri-environmental subsidies and 17.34% other Pillar II subsidies. Therefore, the results of this additional analysis apply to a relatively small number of Italian farmers who meet specific criteria, such as being located in rural or forestry areas or operating in sectors facing particular challenges. To examine the differential impact of these different schemes on environmental and economic inefficiency, we include in the model specification the logarithm of the different payments ($Sub1_{Coupled}, Sub1_{Decoupled}, Sub2_{Env}, Sub2_{Other}$). Moreover, we introduce the spatial lag of the overall amount of subsidies received by neighbours under the hypothesis that farmers may only perceive the overall level of neighbours' subsidies without having information or being able to distinguish between the different typologies of payments. The results presented in Table A2 of Appendix A indicate that while coupled and decoupled Pillar I subsidies contribute to reducing the inefficiency level of farmers both from the environmental and the economic perspective, Pillar II subsidies have a diverse impact depending on the outcome considered. Indeed, on one hand, environmental and other Pillar II subsidies positively affect farmers' environmental efficiency, but on the other hand, they negatively impact farmers' economic efficiency levels. These findings are consistent with previous results obtained by including in the model the *PillarII* dummy variable, which showed a positive sign for value added and a negative sign for fertilizers. Therefore, these additional results reinforce the idea that, while agri-environmental schemes and other Pillar II subsidies effectively promote farmers' environmentally friendly practices, they may lead to increased economic efficiency levels. Regarding the first Pillar, differentiating between coupled and decoupled Pillar I subsidies does not significantly improve the analysis, as their impact appears to be similar in terms of magnitude, significance and sign.

Finally, additional results by macro-area (North, Centre, South-Islands) and main settlement typology (Purchase, Rent, Inheritance) are provided in Table A3 and A4 of Appendix A, respectively. Considering the different macro-areas, the main insight concerns the direct effect of Pillar I subsidies on economic inefficiency. Indeed, while it is negative in the South-Islands area, it turns out to be positive and significant in the North and the Centre of Italy. On the other hand, differentiating the analysis by settlement typology, we find that subsidies contribute to significantly decreasing the level of environmental inefficiency in purchased and rented farms while for inherited farms the effect is non-significant. Moreover, inter-provincial environmental spillovers are highly positive and significant only for rented farms. These results may indicate a lower propensity to actively engage in environmental sustainability for farmers who inherited their business compared to farmers who actively invested in it.

5.3. Robustness Check

As the first robustness check, we estimate the model using alternative dependent variables. Specifically, we consider standard production value and net income as further economic outcomes to be maximised while, from the environmental side, following Exposito and Velasco (2020) we introduce the ratio between fertilizers and land and the ratio between fertilizers and value added as other possible dependent variables to be minimized. The estimates shown in Table B1 of Appendix B confirm the robustness of our results concerning spatial effects and direct effects related to environmental outcomes while, from the economic point of view, they provide additional interesting insights. Indeed, the direct effect of subsidies on economic inefficiency results to be positive and significant starting from 2013 using standard production value as a dependent variable and for 2018 with net income as a response. These results further corroborate the idea that, while the positive impact of CAP subsidies on environmental efficiency is increasing over time, subsidies are contributing to economic inefficiency in the last few years. Thus, if on one hand, subsidies are helping farmers to achieve environmental sustainability, on the other, they are leading to increased economic inefficiency.

As the second robustness check, we use alternative measures for subsidies such as a dummy variable equalling one if the farm received Pillar I subsidies, the logarithm of the ratio between Pillar I subsidies

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[2] As shown in the robustness check in Table A3, when we specify Pillar I subsidies by using a dummy variable as we do for Pillar II, the effect of Pillar I subsidies is higher in magnitude compared to the one of Pillar II.

and total area since the largest share of Pillar I subsidies is disbursed by hectare, and the logarithm of the total amount of subsidies defined as the sum of Pillar I and Pillar II subsidies in order to verify whether the amount of incentives for rural development received by farmers significantly impacts our results. The estimates shown in Table B2 of Appendix B are in line with previous results further corroborating our findings. Moreover, alongside the logarithm of the amount of payments received by farmers, we also include in the model specification the share of Pillar I subsidies as a percentage of the farm's gross value added. While most studies rely on the nominal amount of subsidy payments (see Minviel and Latruffe, 2017), considering the share of subsidies relative to value added can provide valuable insights on how the impact of subsidies varies based on farms' output (Khafagy and Vignani, 2022; Garrone et al., 2019). The estimation results presented in Table B3 of Appendix B reveal that the share of Pillar I subsidies as a percentage of farmers' gross value added negatively affects farmers' efficiency level, both in terms of environmental and economic efficiency. Thus, as the share of subsidies rises for increasing levels of subsidies with equal value added or for equal levels of subsidies with decreasing value added, this negative effect may be attributed to the fact that farms unable to transform the additional amount of subsidies in technological improvements needed to increase their production tend to be, as expected, more economically and environmentally inefficient than others.

Third, while in our baseline model, following the literature on multi-output optimization, we define the same set of inputs (i.e. labour, capital, land, and water, energy and fuel) for both outcome variables (i.e. fertilizers and value added), as a robustness check we also consider additional intermediary inputs in the production function of value added. Therefore, we include extra inputs such as pesticides and weed killers, fodder and manure, and fertilizers together with water, energy and fuel in order to encompass a broader set of intermediary inputs. The estimation results contained in Table B4 of Appendix B indicate that considering additional intermediary inputs results in a higher output elasticity to intermediary inputs (0.25) compared to the previous model only including water, energy and fuel (0.17). This change is accompanied by a slight decrease in output elasticities to labour, capital and land. However, the parameter estimates of the inefficiency models concerning the impact of subsidies on inefficiency (both overall and over time) and on spatial effects remain consistent, confirming the robustness of our findings to alternative specifications of the production function.

Fourth, as spillover effects of farming practices may play a relevant role in determining farmers' environmental and economic performance, we estimate the model specification in Eqs. ((1)–(2)) incorporating in the frontier function the mean level of output (i.e. fertilizer or value added) in the province (each time excluding the *i*-th observation) as well as the mean level of output in neighbouring provinces in order to account for potential inter and intra province spatial effects related to the dependent variable. The estimation results shown in Table B5 of Appendix B reveal positive and significant spatial effects associated with value added and fertilizers, occurring both within the province and between neighbouring provinces. Therefore, we confirm that farmers' productivity level and their decisions regarding the adoption of cleaner production techniques are influenced by their neighbours. However, besides corroborating the importance of common technology adoption patterns between neighbouring producers, these additional estimates confirm the validity of our findings as the estimated parameters for subsidies and their spatial lags appear to be robust to the inclusion of the spatial lag of the dependent variable.

5.4. *Technical Efficiency Scores*

Average technical efficiency scores equal 0.57 and 0.49 for economic and environmental efficiency, respectively. Thus, overall, Italian farms result to be more efficient on the economic side rather than on the environmental one. This result is in line with Eder et al. (2021) which found higher technical efficiency levels for Austrian crop farms compared to environmental ones, although measured based on soil erosion.

However, looking at the time trend shown in Fig. 2 in order to answer the third research question (Q3), we find a decreasing trend for economic efficiency ranging from 0.64 to 0.52 between 2008 and 2018 and an increasing trend for environmental efficiency passing from 0.35 to 0.65. Thus, the efficiency pattern reversed in time with 2015 as the year of the switch. These results indicate that Italian farms are achieving higher and higher efficiency degrees from an environmental perspective at the expense of lowered economic efficiency levels. The negative

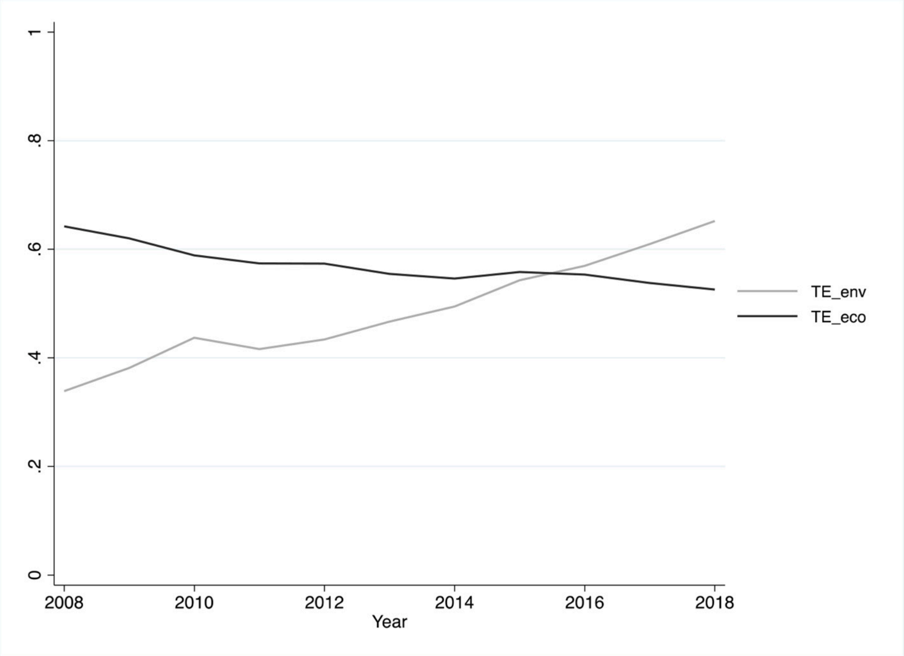

Fig. 2. TE scores in time.

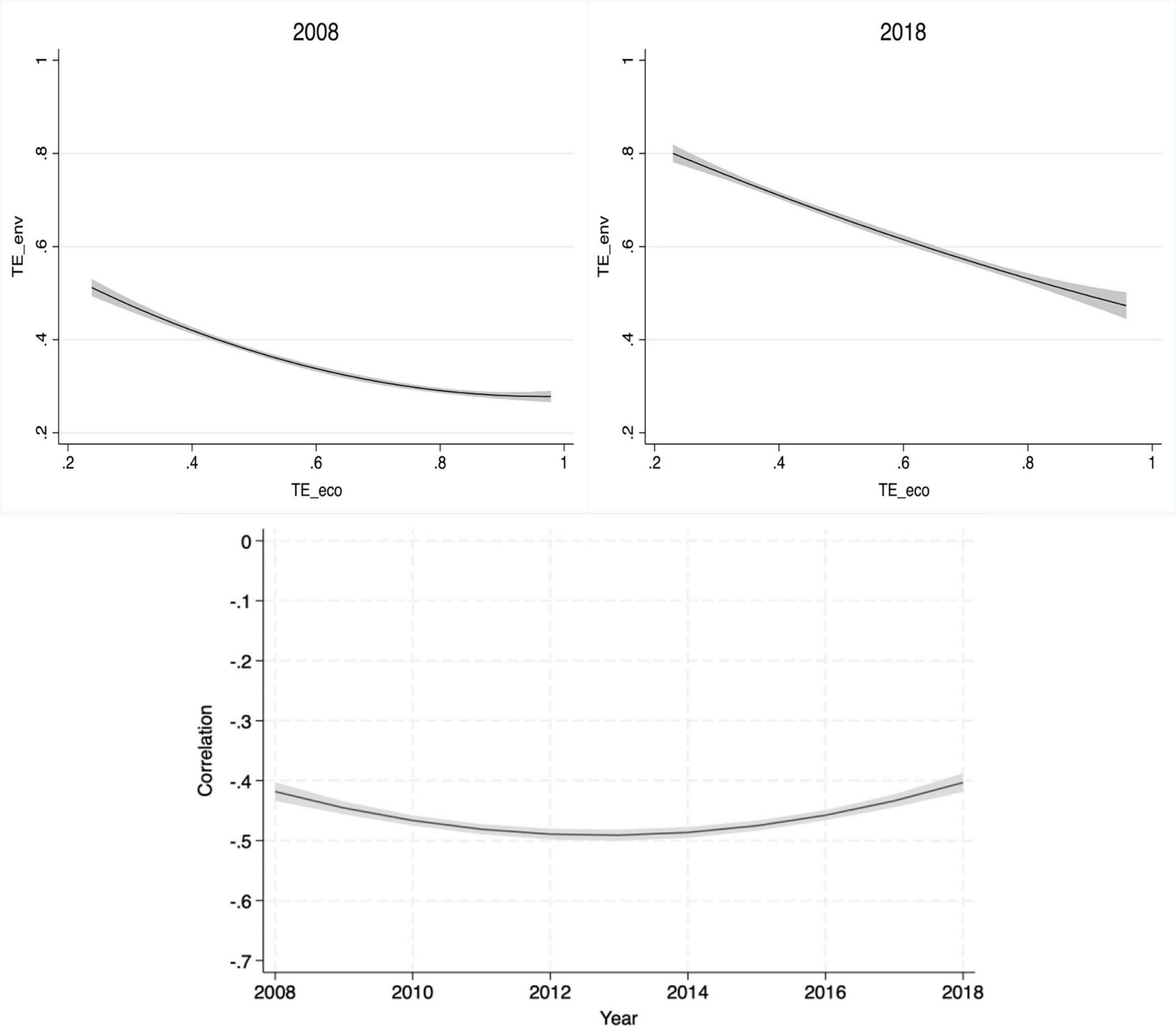

Fig. 3. Association between economic and environmental efficiency.

association between economic and environmental efficiency is confirmed by the plots in the upper panel of Fig. 3 which show that more environmentally efficient farms tend to achieve lower economic efficiency levels and vice versa. Moreover, the correlation coefficients between environmental and economic efficiency over time showed in the lower panel of Fig. 3 indicate that the negative relationship intensified in magnitude between 2008 and 2014 and then it slightly decreased (detailed yearly plots can be found in Fig. C1 of Appendix C). The results of the tests presented in Table C1 of Appendix C confirm the significant fluctuations in the correlation coefficients over time. Therefore, despite the association between economic and environmental efficiency remaining highly negative in all the time period considered, encouraging signs emerge from the last years of the analysis.

When differentiating by macro-area,[3] Fig. C2 of Appendix C shows that while at the beginning of the period the negative relationship between environmental and economic efficiency was less marked in Northern Italy compared to Central and Southern Italy, in 2018 a still negative but milder association characterizes the Southern regions. Thus, the prioritization of sustainable goals differently affected the association between economic and environmental efficiency in Italian macro-areas, favouring the gap in the North and smoothly lowering it in the South. Considering settlement typology, in line with Eder et al. (2021), we find that tenants reach, on average, higher efficiency levels than landowners both from the economic and the environmental side. On the other hand, heir farmers are those achieving higher technical efficiency scores and lower ecological efficiency levels. However, for all settlement typologies, the negative association among economic and environmental efficiency is similarly strengthening over time as shown in Fig. C3 of Appendix C.

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[3] Further insights on average economic and environmental efficiency scores by province are presented in Figure C4 of Appendix C.

6. Conclusion

In this paper, we investigate the direct and indirect role of Pillar I subsidies on economic and environmental efficiency. To reach this goal we use RICA data for Italy in the time period 2008–2018 and differentiating among environmental and economic outcomes, we estimate a spatial stochastic frontier model including intra and inter province spatial effects. This modelling approach allows us to (i) evaluate the direct and indirect effects of Pillar I subsidies on economic and environmental inefficiency and (ii) compute time-varying firm-specific efficiency scores differentiating among ecological and economic aspects.

Findings from our analysis indicate that Pillar I subsidies are positively affecting environmental efficiency with an increasing magnitude starting from 2014 (Q1). However, from an economic point of view, while they effectively contributed to raising farms' efficiency in the past, in the last few years their impact is turning to non-significant and negative values. Considering spatial effects originating from subsidies, we find that farmers' efficiency level is positively affected by knowledge spillovers occurring inside the province both from the economic and the environmental side (Q2). Therefore, farmers' willingness to innovate and adopt new technologies that can lead to increased economic and environmental efficiency is boosted by collaboration and exchange of ideas with closest neighbours. This positive effect is reduced considering farmers located in neighbouring provinces for the environmental side while inter-provinces competition effects arise in terms of value added.

Overall, in the time period 2008–2018, the economic efficiency of Italian farms declined while environmental efficiency grew steadily doubling its values between the first and the last year of the analysis (Q3). These results confirm the effectiveness of CAP subsidies in boosting farms' environmental sustainability in Italy at the expense of economic inefficiency.

Findings from this study may be of great interest to policy makers in order to evaluate the achievement of environmental and economic goals related to Pillar I subsidies in Italy. Indeed, Italian farmers are actively contributing to the sustainability goals targeted by European institutions. However, the urgent need to pursue environmental sustainability is harming Italian farmers' economic efficiency. Therefore, other than concentrating on environmental goals, future incentives should also ensure economic support to farmers in order to achieve both environmental and economic goals which together can lead to long-lasting growth of the sector. Moreover, future policy decisions may be devoted to reinforcing farmers' networking and collaboration practices based on insights on the existence of positive spillovers among closest neighbours which can favour farmers' environmental sustainability and economic efficiency. Indeed, by exploiting existing learning and knowledge spillovers, farmers may speed up the uptake of environmentally sustainable practices and the adoption of new technologies. As underlined by Jacquet et al. (2011, p.1646), and confirmed by our results, CAP policies "*should be gradual and long-term, since the changes in technical systems will be the more thorough if they can benefit from dynamic effects*."

Since, to our knowledge, this is the first attempt to evaluate spatial effects arising from CAP subsidies, in future empirical applications it would be interesting to repeat the analysis considering other European countries and different environmental outcomes based on data availability such as GHG and renewable energy use. Further methodological extensions may consider differentiating between transient and persistent inefficiency taking advantage of recent advances in stochastic frontier analysis. Moreover, based on recent advancements in spatial stochastic frontier models literature (e.g. Galli, 2023a), the econometric model could be further extended in order to consider additional sources of spillovers such as spatial effects related to the frontier function due to spatial diffusion of farming practices and spatial dependence in the error term arising from unobserved but spatially correlated variables such as soil conditions, and environmental, climatic or topographic characteristics.

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CRediT authorship contribution statement

Cristina Bernini: Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing. **Federica Galli:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108120.

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