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Technical change and the Common Agricultural Policy

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ABSTRACT

This paper adopts an alternative method for the analysis of the CAP's impact on farms' productivity based on a system of equations derived from a non-nested three-factors CES production function. With this method, we estimate the elasticity of substitution between labour, capital, and land in the EU agricultural sector, the magnitude and direction of technical change, and the impact of the CAP subsidies. The system of equations is estimated using the GMM estimator on a farm-level panel dataset covering 117,179 farms from all EU MS for the period from 2004 to 2015. Our results suggest that land, labour, and capital in EU farms are complementary production factors characterised by a slow decline or stagnation in the land-, labour-, and capital-augmented technical change. Higher levels of Pillar I and Pillar II CAP payments as percentage of total agricultural income have negative or no impact on farms' technical change, but higher nominal amounts of Pillar I decoupled subsidies, Pillar II investment and LFA subsidies have a positive impact. Moreover, the larger the share of subsidies in total agricultural income the stronger is the negative impact of the CAP on agricultural technical change.

1. Introduction

The Common Agricultural Policy (CAP) of the European Union (EU), which has been in existence since the early 1960s, continues to evolve. Improving agricultural productivity is one of the core founding principles of the CAP. The Article 39 of the Treaty on the Functioning of the European Union (TFEU), or Treaty of Rome, states that "the objectives of the common agricultural policy shall be […] to increase agricultural productivity by promoting technical progress and by ensuring the rational development of agricultural production and the optimum utilisation of the factors of production, in particular labour" (EU, 2008). Agricultural productivity is the relationship, measured in physical quantities, between outputs produced and inputs required in the production process. Successive CAP reforms aimed to improve agricultural productivity, while responding to environmental and social challenges. Environmental challenges impose additional constraints on agricultural production, pressuring the sector to adopt more sustainable practices (EC, 2018). Moreover, the EU enlargement brought fresh challenges and a wider set of geographical, environmental and socio-economic conditions that needed to be considered, along with revised policy goals, and the need to react to external drivers of change, such as the integration of global supply chains and climate change.

The current concern is the new CAP agreement that will be implemented from 2023 and the need to adapt the CAP to smart growth and enhanced productivity while at the same time maintaining viable rural populations and adapt agricultural activities to climate change and global market conditions. All of this relies on the development of effective policies and programmes with capacity to be applied flexibly across the EU-27. Good policy design requires a credible evidence base, but a major issue facing EU policy makers is the lack of clarity regarding the impact of the CAP support on agricultural productivity, as demonstrated by recent literature surveys (e.g. Minviel and Latruffe, 2017). There is a need for improved capacity of models to provide quality data that can underpin policy decisions that must be made in the face of potential budget cuts, the reduction in direct subsidies, and the continuing shift of emphasis from Pillar I to Pillar II support. Without high quality and reliable data, policy makers are at a disadvantage in determining the future direction of CAP policies and programmes (Dudu and Ferrari, 2018).

There are two broad modelling approaches that are frequently used to estimate the impact of agricultural subsidies on farm productivity. These two approaches are identified as the 'growth accounting' and the 'frontier approaches' (McCloud and Kumbhakar, 2008; Kumbhakar and Lien, 2010; Bokusheva et al., 2012; Dudu and Kristkova, 2017). Growth accounting approaches employ regression analysis to estimate the growth in productivity (e.g. Zhengfei and Lansink 2006). These

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Table 1
Empirical literature on the impact of CAP on farm productivity.

Authors	Year	Period	Sector	Type of productivity	Data level	Panel data	Method/model	Net effect
Arata & Sckokai	2016	2003–2006	All	Output value	Farm level	✓	PSM DID	+/−
Arovuori & Yrjola	2015	1980–2010	All	Value added per worker	Country level	✓	RE	+/−
Ayouba et al.	2017	2005–2008	Crop	TE	Farm level	✓	DEA	−
Bakucs et al.	2010	2001–2005	All	TE	Farm level	✓	SFA	−
Banga	2014	1995–2007	All	TFP and TE	Country level	✓	DEA	+
Bojnec & Latruffe	2013	2004–2006	All	TE	Farm level	✓	DEA	+/−
Boussemart et al.	2019	1992–2012	All	TE and technical catching-up	Farm level	✓	DEA	−
Brummer & Loy	2000	1987–1994	Dairy	TE	Farm level	✓	SFA	−
Cillero et al.	2018	2000–2013	Beef	TE	Farm level	✓	SFA	+
Coelli et al.	2006	1987–2002	Crop	TFP	Farm level	✓	DEA	−
Dudu & Kristkova	2017	2007–2013	All	TFP	NUTS 2	✓	GMM	+/−
Emvalomatis et al.	2008	1996–2000	Crop	TE	Farm level	✓	SFA	−
Ferjani	2008	1990–2001	All	TE	Farm level	✓	Tobit model	−
Fogarasi and Latruffe	2009	2001–2004	Crop and dairy	TFP and TE	Farm level	✓	DEA	+/−
Garrone et al.	2019	2004–2014	All	Labour productivity	Nuts 2	✓	CCG	+/−
Gohin	2006	1995–2008	Crop and beef	Output value	Aggregate Europe level		CGE and simulation	−
Guyomard et al.	2006	1995–2002	All	TFP and TE	Farm level	✓	DEA	+/−
Henningsen et al.	2009	1991–2006	Crop	TFP	Farm level	✓	FE	+/−
Kazukauskas et al.	2014	2001–2007	All	TFP	Farm level	✓	RE probit model	+
Kleinhanß et al.	2007	1999–2000	Livestock	TE	Farm level		DEA	+/−
Kumbhakar & Lien	2010	1991–2006	Crop	TFP and TE	Farm level	✓	RE and SFA	+/−
Lambarraa & Kallas	2009	2000–2004	Crop	TE	Farm level	✓	SFA and RE Tobit model	−
Lambarraa et al.	2009	1995–2003	Crop	TE	Farm level	✓	SFA	+/−
Latruffe & Desjeux	2016	1990–2006	All	TE	Farm level	✓	DEA	+/−
Latruffe et al.	2011	1990–2007	Dairy	TE	Farm level	✓	SFA	+/−
Latruffe et al.	2017	1990–2007	Dairy	TE	Farm level	✓	SFA	+/−
Latruffe et al.	2016	2014–15	All	TE	Farm level	✓	DEA	+/−
Mary	2013	1996–2003	Crop	TFP	Farm level	✓	GMM	−
Marzec & Pisulewski	2017	2004–2011	Dairy	TE	Farm level	✓	SFA and Bayesian approach	−
McCloud & Kumbhakar	2008	1997–2003	Dairy	TE	Farm level	✓	Bayesian approach	+
Mennig and Sauer	2019	2007–2011	Dairy and Crop	TFP and TEs	Farm level	✓	DID	+
Minviel & De Witte	2017	2006–2011	All	TE	Farm level	✓	Conditional efficiency model	−
Nilsson	2017	2007–2013	All	TFP	Farm level	✓	FE and CEM	+/−
Nowak & Kijek	2015	2010	All	TE	Country level		DEA and Tobit	+/−
Pechrova	2015	2005–2012	All	TE	Farm level	✓	SFA and FE	+/−
Quiroga et al.	2017	1996–2009	All	TFP and TE	NUTS 2	✓	SFA	+/−
Rizov et al.	2013	1990–2008	All	TFP	Farm level	✓	OLS and Spearman correlation	+/−
Zbranek	2014	2012	Crop and Livestock	TE	Farm level		DEA and Tobit model	−
Zhengfei & Lansink	2006	1990–1999	Crop	TFP	Farm level	✓	Malmquist index and GMM	−
Zhu & Lansink	2010	1995–2004	Crop	TE	Farm level	✓	SFA	+/−
Zhu & Demeter	2012	1995–2004	Dairy	TE	Farm level	✓	SFA	−

Notes: DEA: Data envelopment analysis; SFA: Stochastic frontier analysis; FE: Fixed effects; RE: Random effects; GMM: Generalized method of moments; OLS: Ordinary least squares; PSM: Propensity score matching; DID: Difference in Differences; CGE: Computable General Equilibrium; CEM: coarsened exact matching method; CCG: conditional convergence growth model. TE: Technical efficiency; TFP: Total factor productivity. +/−: mixed results; +: positive effect; −: negative effect.

approaches treat subsidies in the production function as traditional inputs, generating inconsistent measurement of productivity as subsidies by themselves cannot produce output unlike the traditional factors of production (McCloud and Kumbhakar, 2008). Frontier approaches can be either parametric (e.g. Stochastic Frontier Analysis (SFA)) or nonparametric (e.g. Data Envelopment Analysis (DEA)). They estimate a stochastic production function and examine the effects of subsidies on technical inefficiency in a two-step procedure. As pointed out by Bokusheva et al. (2012) and Mary (2013), a major drawback of frontier approaches used so far is that they do not account for regional heterogeneity and endogeneity problems. Other methods that do not strictly fall under these two categories are also used and they will be discussed in the next section.

Despite such variety in methods, a common feature is that they describe the production technology using Cobb-Douglas production functions. For instance, McCloud and Kumbhakar (2008) estimated a Bayesian hierarchical model fitted with a Cobb-Douglas production function to measure if subsidies can be treated as traditional or facilitating inputs. They found that subsidies can increase farms' output by increasing the contribution of capital and materials to production but decreasing the productivity of labour and of other inputs. However, their estimations do not control for endogeneity, and their assumption that subsidies have complementarity or substitutability relationships with traditional production factors has no strong theoretical support (Latruffe et al., 2017). Mary (2013) estimated a Cobb-Douglas production function using a system Generalized Method of Moments (GMM) econometric model, incorporating traditional inputs, in addition to time and farm-specific effects to link subsidies to total factor productivity. Similarly, Rizov et al. (2013) assumed a Cobb-Douglas production function and employed a structural semi-parametric estimation based on Olley and Pakes (1996). They used a model of unobserved productivity with Ordinary Least Squares (OLS) that included subsidies as an additional control factor. Their model allowed CAP subsidies to be linked directly to farm decisions, factor markets, and demand conditions. Both studies, Mary (2013) and Rizov et al. (2013), have controlled for the endogeneity problem of subsidies, however, a major limitation of using the Cobb–Douglas production function is the restrictive assumption that elasticity of substitution between inputs is equal to one. In addition, there had been an increasing body of literature that proved that Cobb-Douglas production functions perfectly fit a wide range of data even when its fundamental assumptions are violated (Shaikh, 1974; Miller, 2008; Gechert et al., 2019).

In alternative to Cobb-Douglas production functions, Constant Elasticity of Substitution (CES) production functions are increasingly popular in micro- and macroeconomic policy research, especially with computable general equilibrium (CGE) models as it provides flexibility in the modelling of input (or commodity) substitution options. CES models allow to relax the Cobb-Douglas assumption of unitary elasticity of substitution between inputs, which has very limited empirical support, and make it possible to estimate the elasticity of substitution between production factors, while still giving the opportunity for testing whether the production technology follows a Cobb–Douglas functional form – i.e. testing if the elasticity of substitution is equal to one.

In this paper, we expand on Dudu and Kristkova (2017) work, linking CAP subsidies to factor-augmenting technical change in a CES production function with constant returns to scale (CRS). We derive a system of equations from the first-order condition of a non-nested production function which combines three factors (land, capital and labour) to create value added. We then used the GMM estimator to control for endogeneity problems. This method has been widely applied in environmental and R&D policy modelling (Van der Werf, 2008; Carraro and De Cian, 2013; Kristkova et al., 2017).

With this study we aim to provide three main contributions to the literature. Firstly, we estimate the elasticity of substitution between land, labour and capital in the whole EU agricultural sector, testing also the validity of a CES against a Cobb-Douglas elasticity of substitution. Secondly, we estimate the factor-augmented technical change of EU farms testing for the potential presence of Hick-neutral technical change. Finally, we estimate both the exogenous and endogenous factor-augmented technical change modelling the impact of CAP subsidies on farms' productivity. We use a large farm-level panel dataset from the Farm Accountancy Data Network (FADN) covering 117,179 farms from all EU Member States (MS) for the period 2004–2015. Overall, we find that land, labour and capital in EU farms are complements with below one or negative elasticity of substitution. There has been a slow decline or stagnation in the land-, labour-, and capital-augmented technical change during the examined period, with both Pillar I and Pillar II CAP payments having negative or no effects on farms' technical change, with the exception of nominal amount of Pillar I decoupled subsidies and Pillar II investment and LFA subsidies which have a positive effect on the productivity. Finally, we find that the larger the share of subsidies in total agricultural income the stronger is the negative impact of the CAP on agricultural technical change.

The reminder of the paper is structured as follows. Section 2 provides a review of the studies on the CAP and productivity. Section 3 discusses the data and the model used for this paper's analyses. Results are presented in Section 4 and discussed in Section 5. Section 5 concludes highlighting policy implications.

2. Literature review

The impact of the CAP on farm productivity has been extensively studied over the past decades finding opposite positive and negative impacts. These effects operate through four main channels: 1) changing relative input and output prices and, consequently, the allocation of inputs; 2) changing investment decisions and on-farm labour supply; 3) changing farmers' risk behaviour by acting as an insurance instrument or substitute to credit; and, 4) changing farmers' growth and exit decisions (Zhu and Lansink, 2010).

The empirical evidence is divided among the effects of CAP subsidies on productivity, although a majority of the studies report on negative impacts as shown in Table 1. Zhu and Lansink (2010) explain that negative effects can be due to the fact that subsidies may demotivate farmers to expend the required efforts to improve the farm's productivity, or to seek economically and environmentally efficient farming techniques. This negative effect is further explained by Rizov et al. (2013) through three channels. First, subsidies may distort the structure of production and factor use as farms may invest in less productive activities if these will qualify them for subsidies, or invest in subsidised inputs leading to allocative inefficiency. Second, the extra income from subsidies may reduce budget constraints providing low incentives for farmers to manage the farm's accountancy more efficiently. In other words, farmers may not seek cost efficient methods if they perceive subsidies as part of the profit, rather than as a form of financial aid. Within this line of reasoning, Kornai (1986) argued that subsidies can lead to an inefficient use of resources, because additional costs are paid by another agent and not incurred by the farm itself. Therefore, subsidies act as a form of insurance potentially increasing moral hazard problems - i.e. the farmer takes unusual risks relying on the fact that he/she will not incur in the additional costs, which are shifted to the subsidy provider. On the contrary, if the farm is strongly constrained by a fixed budget, it will continuously seek to adopt more cost-efficient methods to meet any fluctuations in external conditions. Third, given that subsidies can target the less competitive or the more naturally-constrained farms to keep them in the sector, subsidies may shift capital to less productive farms based on political rather than economic considerations, reducing the average productivity of the sector. This argument is derived from Olson's (1982) explanation of how subsidies may distort the reallocation of resources across firms and sectors in response to changing market conditions or new technologies.

There negative effects are supported by a number of relevant empirical studies. For example, Brümmer and Loy (2000), found a slight decrease in the technical efficiency of farmers participating in Farm Credit Programmes in Northern Germany between 1987 and 1994. Similarly, Zhengfei and Lansink (2006) found significant negative correlation between total subsidies and productivity growth for Dutch farms during the 1990 to 1999 period. Zhu and Lansink (2010) found negative impact of total subsidies to revenues on technical efficiency in crop farms in Germany, the Netherlands and Sweden in 1995–2004. Mary (2013) suggested that farmers perceive CAP subsidies under two categories: *"automatic"* or *"selective"* payments. *Automatic* payments are mainly subsidies that are paid per hectare, per output or per head (i.e. set-aside premiums, and livestock subsidies). Whereas *selective* payments are typically payments under Pillar II (rural development policy) that are conditional on the approval of LEADER Action Groups (e.g. investment and agri-environmental subsidies). According to Mary's (2013), *automatic* payments have negative impact on productivity while *selective* subsidies have a null impact. Bojnec and Latruffe (2013) found negative correlation between technical efficiency and total subsidies to total output ratio in Slovenia during 2004–2006. Looking at Table 1, it is interesting to note that all the above-mentioned studies have analysed the period before 2005, when subsidies where still largely coupled to production volumes. However, negative effects where found also in the period after 2005, when decoupling was implemented. For example, Minviel and De Witte (2017) found negative impact of subsidies on a small sample of French farms' technical efficiency during 2006–2011. Garrone et al. (2019) estimated the impact of CAP subsidies on agricultural labour productivity growth using a conditional convergence growth model. The authors find that, on average, CAP subsidies increase agricultural labour productivity growth, but highlight an important heterogeneity among different types of subsidies.

Regarding positive productivity impacts, agricultural subsidies may improve technical efficiency by giving farmers the financial means to invest in new technologies or improved inputs (Zhu and Lansink, 2010). This is related to "investment-induced productivity gains" (Rizov et al., 2013). These gains result from easing farmers' access to credit, and changing their risk behaviours, which can increase productive investments and reduce risk averse decisions. Subsidies may also allow credit rationed farmers to invest in improved inputs or new technologies either directly by providing them with the sufficient financial resources, or indirectly by improving their accessibility to formal credit. Moreover, subsidies can improve farmers' wealth and change their risk attitudes, enabling them to undertake higher risk actions that are necessary to respond to market uncertainties.

The heterogeneous results in the above described literature are not surprising, given that these studies focus on different policies, time and geographic coverages with different resource endowments, as well as other factors. The heterogeneity of the results in the empirical literature suggests that there will be no one-size fits all policy. It seems that the effectiveness of the CAP subsidies will have to be measured frequently, and policies will have to be revised and adjusted according to different agricultural systems.

In the following sub-sections, we discuss the methodologies used to estimate the impact of CAP support on farms' productivity; and previous findings on the impact of Pillar I subsidies (coupled and decoupled payments), and Pillar II subsidies (subsidies on investments, agri-environment measures, and less favoured areas scheme).

2.1. Estimating the impact of CAP on agricultural productivity

Technical efficiency and Total Factor Productivity (TFP) are two commonly used measures of productivity to estimate the impact of CAP subsidies (see Table 1). The two methods are related indicators of farms' performance but measured in different ways. Technical efficiency is the maximum output a farm can obtain from a given set of inputs and a given technical level. Inefficiency is a measure of the difference between a farm's actual output and the maximum output obtainable from the given set of inputs. The technical inefficiency of farms using different inputs or operating at different technical levels are not directly comparable. On the contrary, TFP is the portion of output not explained by the amount of inputs used in production. It can be represented as a residual (Solow, 1957) or as the ratio of total output to total inputs and it is determined by technical efficiency which is one component of TFP. These differences are, as one would expect, translated in different empirical models. Generally, it is difficult to draw a clear trend from the literature review that correlates the impact of CAP subsidies to a specific methodology. This is in line with the meta-analysis conducted by Minviel and Latruffe (2017) which did not find a significant correlation between methodological approaches and the subsidy–efficiency impact.

2.2. Impact of Pilar I subsidies on agricultural productivity

The larger part of Pillar I subsidies consists of direct area and livestock payments. Such payments can be "coupled" or "decoupled" to the farm production. Coupled subsidies are more likely to negatively affect productivity, because by being tied to the level of certain outputs they can disrupt the efficient allocation of inputs and land (Garrone et al., 2019). The decoupling of CAP subsidies started with the 2003 CAP reform that was implemented from 2005 under the Single Farm Payment (SFP). Decoupled payments are expected to support farms' productivity by increasing farms' capital, their ability to borrow from credit markets, and by changing farmers' preferences towards productive investments (Kazukauskas et al, 2014).

Guyomard et al. (2006) found that the CAP direct payments had a negative effect on technical efficiency; however, direct payments also had positive impacts on the productivity growth rate of French crop, beef, and dairy farms during 1995–2002. Ferjani (2008) examined Swiss farms during the 1990 to 2001 period and found that farms that received more direct payments were less efficient. Mary (2013) examined the effect of CAP subsidies on the TFP of French crop farms between 1996 and 2003. He found that livestock subsidies and set-aside premiums had negative effects on TFP. Rizov et al. (2013) estimated the impact of the CAP subsidies on TFP in 15 EU countries using FADN data for the 1990 – 2008 period. They found that subsidies had a negative impact on TFP before the decoupling reform was applied. Outcomes from the decoupling reform were having mixed effects on productivity but with some positive impacts for most countries. Latruffe and Desjeux (2016) found negative effects of production subsidies on technical efficiency of French farms during the period 1990–2006. On the other hand, Kazukauskas et al. (2014) also found a positive impact of decoupling subsidies on the TFP for beef farms in Ireland, and dairy farms in Denmark, during 2001–2007. But interestingly, in the same study, he also found no statistically significant correlation between subsidies and productivity for Irish dairy and crop farms, Danish crop farms, and Dutch beef, and dairy farms. Cillero et al. (2018) found that coupled and decoupled payments had a positive impact on the technical efficiency of beef farms in Ireland using data covering the period between the years 2000 and 2013. Garrone et al. (2019) also found a positive effect on labour productivity growth from decoupled payments but a slowdown in labour productivity growth from coupled subsidies.

Generally, coupled subsidies are expected to have a negative impact on total factor productivity as they might induce production distortions incentivizing the cultivation of certain products over others, therefore potentially disrupting the efficient allocation of inputs. On the contrary, one of the main objectives of decoupling was to mitigate such negative effects by increasing farms' financial resources for new productive investments. Almost all the studies mentioned above confirm the expected negative impact of coupled subsidies on productivity. However, the impact of decoupled payments is not straightforward as several studies found positive impacts on productivity but other studies found a null impact.

2.3. Impact of Pilar II subsidies on agricultural productivity

The rural development policy was introduced under the 'Agenda 2000′ reform as the second pillar of the CAP. This includes subsidies on investments, agri-environmental measures, LFA schemes, as well as wider rural development payments. Subsidies on investments may have a positive effect on productivity and cost reduction, as it can improve knowledge transfer and encourage farms to adopt efficient farming practices. Latruffe and Desjeux (2016) found negative effect of investment on technical efficiency for crop, dairy and beef French farms, with no effect of rural development subsidies on efficiency. Nilsson (2017) found that increasing the total investment subsidies to total income had significantly negative effect on total factor productivity of Swedish farms during 2007–2012. Garrone et al. (2019) found a positive impact on labour productivity from total pillar II payments which is mainly driven by the positive impact of subsidies on investments in physical capital. However, they found that LFA and agri-environmental measures have statistically insignificant impact in productivity.

Agri-environmental measures are often associated to negative impacts on productivity as they restrict the use of agricultural inputs, such as fertilizers and pesticides (Garrone et al., 2019). However, results from a study conducted by Sauer and Park (2009) showed a positive impact of organic subsidies on TFP change for Danish organic dairy farms during the 2002–2004 period. Lakner (2009) found significantly negative impact on technical efficiency from agri-environmental payments and investment programmes in German organic dairy farms, however, the parameters reported are close to zero.

The impact of LFA schemes on productivity is not straightforward, because it either keep inefficient farms in the sector, or improve the efficiency of lands with poor natural endowments (Latruffe and Desjeux, 2016). Mary (2013) found that less favoured area payments had negative effects on TFP, whereas Agenda 2000 reform had a positive impact on TFP, while investment and agri-environmental payments had no significant influence on TFP.

These three main categories of Pillar II subsidies are used also in the econometric analysis below.

Table 2
Data description.

Variable	Description
Quantities and prices	
Labour quantity	Total labour input expressed in time worked in hours.
Capital quantity	Average farm capital in Euro. It includes value of livestock, permanent crops, land improvements, buildings, machinery and equipment, and circulating capital. It is only calculated if the value of buildings is recorded separately from the value of land capital.
Land quantity	Total utilised agricultural area in hectares. It includes land in owner occupation and rented land.
Net value added	Calculated as: farm net value added – balance current subsidies.
Labour price	Calculated as: wages paid / paid labour input (missing values with unpaid labour inputs were replaced with the FADN region and economic size's yearly average price of labour).
Land price	Calculated as: rent paid / rented utilised agriculture area (missing values without rented land were replaced with the FADN region and economic size's yearly average price of land).
Capital price	Calculated as the net return on invested capital after paying labour and land costs, such that: capital price = (net value added – rent paid – wages paid) / capital quantity. Rent and wages paid are calculated using land and labour prices multiplied by total utilised agricultural area and total labour input, to account for unrented land and unpaid labour.
CAP subsidies (values are in Euro)	
Coupled subsidies	Calculated as: total subsidies on crops + total subsidies on livestock + subsidies on intermediate consumption + subsidies on external factors + other subsidies.
Decoupled subsidies	Decoupled payments.
Subsidies on investments	Subsidies on investments.
Agri-environment measures	Environmental subsidies.
Less favoured areas scheme	LFA subsidies.
Data clustering	
Northern region	If the farm is in Denmark, Ireland, United Kingdom, Finland, or Sweden.
Southern region	If the farm is in Italy, Greece, Spain, Portugal, Cyprus, Malta, or France.
Central and Eastern region	If the farm is in Czech Republic, Hungary, Poland, Slovakia, Slovenia, Croatia, Estonia, Latvia, Lithuania, Bulgaria, or Romania.
Western region	If the farm is in Germany, Austria, Belgium, Luxembourg, or the Netherlands,.

3. Data and method

3.1. Data

We use farm-level FADN data for all EU MS covering the period from 2004 to 2015. The FADN data sufficiently covers detailed information on quantities and values of agricultural inputs and outputs.

During the period considered, the composition of the EU MS passed from EU25 in 2004–06 to EU27 in 2007–13 (with the addition of Bulgaria and Romania) and EU28 in 2014–15 (with the addition of Croatia). During the same period there have been three reforms of the CAP, in 2003, 2008 and 2013. It should be noted that the starting dates for the reforms differ by countries subject to outlines issued by the EU. For example, in the UK the 2003 CAP reform started in 2005 and the 2013 CAP reform started in 2015. For what concerns direct payments (Pillar I), the period 2004–08 was characterized by the Single Payment Scheme (SPS) decoupled from production but with obligations to manage farms in sustainable ways (cross-compliance). The main focus of the 2008′s 'Health check' was the creation of dairy payments and moving funding from Pillar I to Pillar II (modulation). Coupled payments were removed, but some production-linked (coupled) payments were allowed to avoid the abandonment of key crops and are still available until this moment in the EU. In 2014–15, direct payments become linked to specific objectives (targeting) and composed of different strata of compulsory (Basic payment scheme (BPS)/Single area payment scheme (SAPS); greening payment for environmental public goods; young farmers payment) and voluntary payments (payment for areas with natural constraints (ANCs/LFAs); coupled payments; small farmers scheme). Rural development policies (Pillar II) remained more consistent from 2004 to 2015. Measures and instruments changed, but the focus remained broadly the same: the competitiveness of the rural economy; the respect of the environment and the countryside; improving the quality of life in rural areas. As mentioned earlier, CAP payments can distort the allocation of inputs where farmers may choose to prefer specific inputs in order to be eligible for the subsidies (e.g. coupled and agri-environmental subsidies), or it can improve productivity through increasing farms' investments in physical capital, labour, or agricultural inputs (e.g. decoupled, investment, and LFA subsidies). In addition, several other factors can affect the farms' productivity, such as weather conditions and soil quality. A large number of control variables was considered and tested but it did not allow the model to converge as we are using a complex simultaneous estimation of several equations with a large dataset.

In addition to providing an unbalanced panel, another limitation of the FADN data is that they do not register heterogeneity in production technology and differences in subsidies between one reform to the other. For example, FADN data do not allow to distinguish between the coupled payments to avoid production abandonment in 2004–2008 from the voluntary coupled payments in 2014–15; nor to distinguish between payments from different rural development measures.

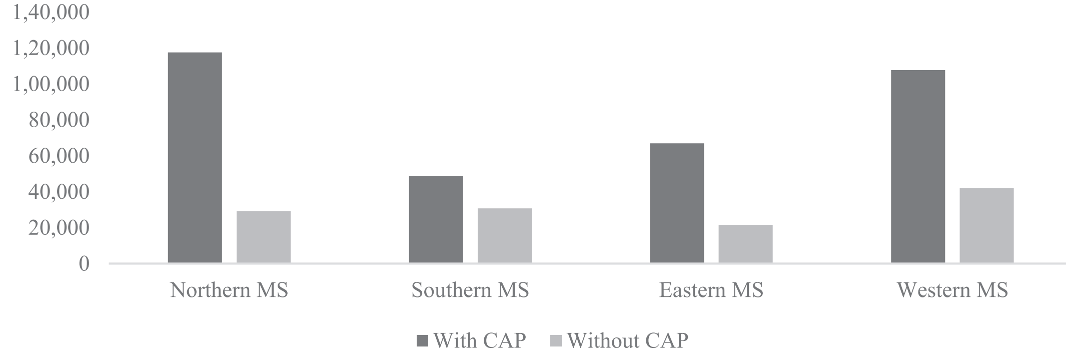

Fig. 1. Average Net Value Added in 2004–2015 with and without CAP (in Euros).

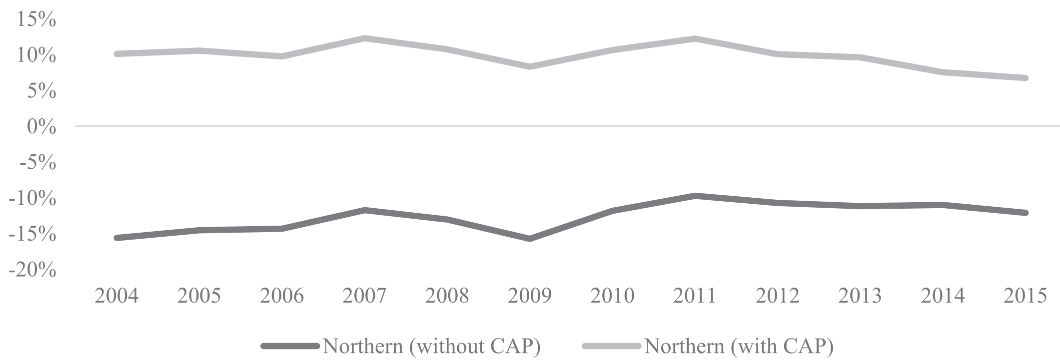

Fig. 2. Average return on capital (price of capital) with and without CAP (Northern MS).

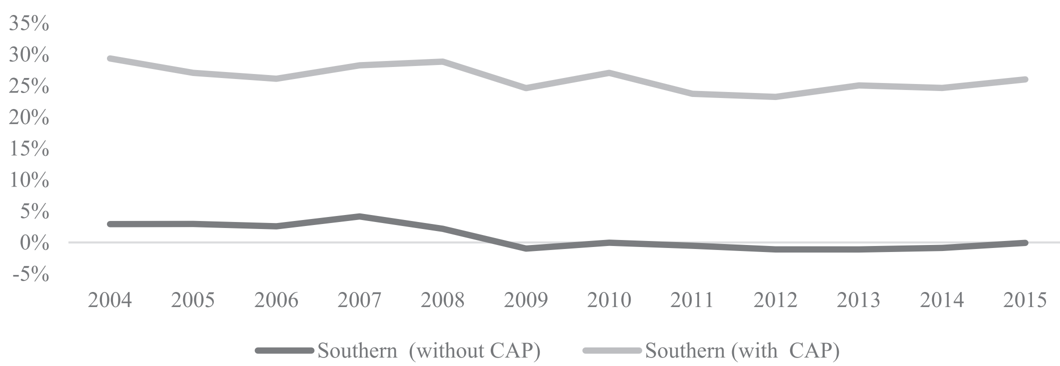

Fig. 3. Average return on capital (price of capital) with and without CAP (Southern MS).

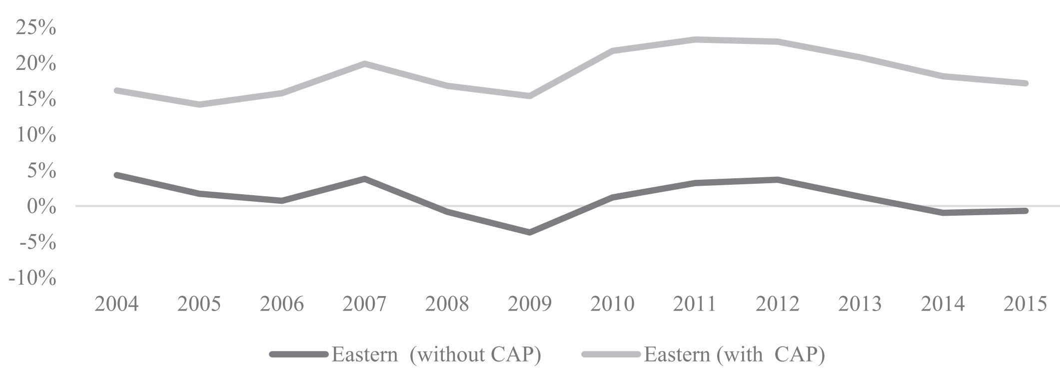

Fig. 4. Average return on capital (price of capital) with and without CAP (Eastern MS).

However, the FADN provide a consistent way to measure amounts of different type of payments across the whole period, distinguishing between coupled/decouple direct payments and between macro-categories of rural development payments – i.e. subsidies for investments, for agri-environmental schemes and for less developed areas (see Table 2). Moreover, a further limitation of the FADN data is that they do not directly report information on prices and quantity of outputs (or value added). However, we can estimate the price of value added and subsequently the quantity of value added using the available data on net value added, and the calculated variables for price and quantities of inputs as shown in Eq. (5).

In order to account for the heterogeneity across different agricultural sectors and the variability of the agricultural systems across MS, the analyses were conducted for all EU27 MS, and for four EU macro-regions, which are: Northern; Western; Southern; and Central and Eastern Europe. Table 2 provides details on the data.

Figs. 1–4 show the relative significance of the CAP subsidies to farms' income for the sample of FADN farms. From the figures, the CAP payments represent a significant portion of the income of EU farms. This is apparent because the average net value added substantially increases with the CAP payments and the net returns on capital (after wages and rent) would be nearly zero or negative without the subsidies. This suggests that the CAP payments allow farmers to maintain sufficient levels of profitability ensuring the continuation of the farming business. In the absence of the subsidies, sufficient profits to remain in the sector could be achieved only with higher output prices. In other words, CAP payments keep farms from requiring higher output prices by supplementing profits, maintaining the farming businesses. Moreover, two main observations standout from the figures below. First, the average net value added with the CAP is significantly higher in Northern and Western farms compared to Southern and Eastern/Central farms (Fig. 1). This might be because the agricultural systems in Northern and Western MS is composed by many dairy farms that traditionally have been highly supported by the CAP and suffered high price volatility, especially since 2007 onwards. Second, the average return on capital without the CAP payments is positive or nearly zero in Southern and Eastern/Central

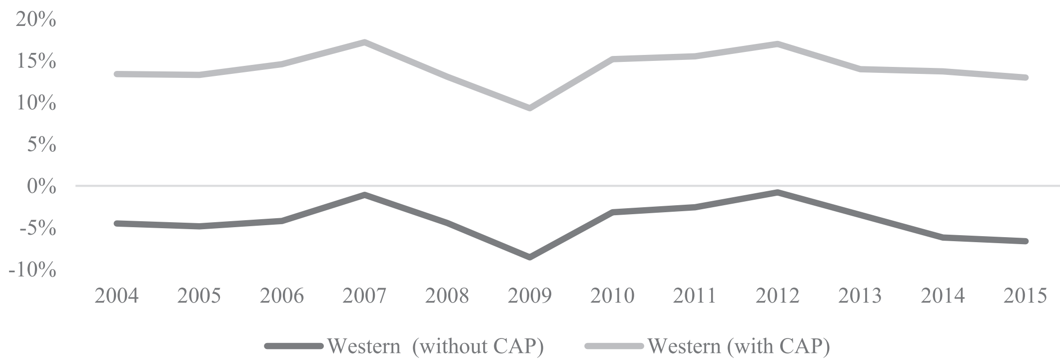

Fig. 5. Average return on capital (price of capital) with and without CAP (Western MS).

farms (Figs. 3 and 4), while average net value added without the CAP in Northern and Western farms has been significantly negative during the period 2004–2015 (Figs. 1 and 5). This may indicate that Northern and Western farms are more dependent on the CAP payments compared to farms in Southern and Eastern/Central regions.

3.2. Model

In order to study the technical change of EU farms we estimate: i) the elasticity of substitution between land, labour, and capital; ii) the exogenous factor-augmented technical change; iii) the impact of the CAP subsidies on endogenous factor-augmented technical change. For robustness checks we test for the presence of Hick-neutral technical change and Cobb-Douglas production technology.

In this study, we employ a three-inputs non-nested CES production function. Previous studies using CES production functions in the context of the agricultural sector adopted different nesting structures for different countries (Hemilä, 1982; Kaneda, 1982; Ruttan and Hayami, 1988; Mupondwa, 2005; Dudu and Kristkova, 2017). Van der Werf (2008) tested all possible nesting structures of ten different policy assessment models using industry-level data from 12 OECD countries. He showed that the most appropriate nesting structure depends on balancing theoretical and empirical factors, and it is likely to be country-specific. More specifically, the nesting combinations that best fitted the data were varying significantly across countries, while non-nested production function could not be rejected for most countries. On top of that, Okagawa and Ban (2008) used the same method and data as van der Werf (2008), but obtained different results when considering the individual effects for each country. Given that we are performing a cross-country estimation, it is unlikely that a given nesting structure can fit all data. For this reason, we decided to adopt the simplest CES structure that has an empirical foundation in Carraro and De Cian (2013), and Dudu and Kristkova (2017). Moreover, Carraro and De Cian (2013) demonstrates that a non-nested structure is the most appropriate when the objective is to identify the endogenous determinants of factor-augmenting technical change.

We define the production technology of a representative farm by a non-nested three-inputs CES production function with factor-specific technology parameters and CRS (Van der Werf, 2008; De Cian, 2009; Carraro and De Cian, 2013; Kristkova et al., 2017; Dudu and Kristkova, 2017). The CES production function has the following form:

$$Y_{it} = \left[\alpha_L(A_L L_{it})^{\frac{\sigma-1}{\sigma}} + \alpha_K(A_K K_{it})^{\frac{\sigma-1}{\sigma}} + \alpha_D(A_D D_{it})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{1}$$

Where Y, L, K, and D denotes net value added, labour, capital, and land, respectively, for the (i) th farm at the year (t). α_L, α_K, and α_D are distribution parameters of labour, capital, and land, A_L, A_K and A_D are factor-augmenting technology parameters that describe the productivity of the production factors, and σ is the elasticity of substitution between the two factors ($\sigma = 1$ is a Cobb-Douglas production function, $\sigma > 1$ means factors are gross substitutes, and $\sigma < 1$ means gross complements).

Through A_L, A_K, and A_D it is possible to estimate the factor-augmenting technical change, defined as the growth from one year to the other in factor productivity that can occur either exogenously or endogenously (De Cian, 2009). Exogenous factors are those beyond farms control, such as prices and weather conditions. Endogenous factors are born within the farm, such as the decision-making process of the farmer that can affect the allocation of resources across the factors of production and the production practices. For example, a farmer may decide to adopt sustainable practices such as organic farming in order to receive agro-environmental subsidies.

We start from the following cost minimization problem:

$$\min C_{it} = PL_{it}L_{it} + PK_{it}K_{it} + PD_{it}D_{it} \tag{2}$$

Where PL, PK, and PD are prices of labour, capital, and land. After solving the cost minimization problem, we can express the first order conditions (FOCs) for the three factors of production:

$$\begin{aligned}
\ln\frac{L_{it}}{Y_{it}} &= \sigma.\ln\alpha_L + (\sigma-1).\ln A_L + \sigma.\ln\frac{PL_{it}}{PY_{it}} \\
\ln\frac{K_{it}}{Y_{it}} &= \sigma.\ln\alpha_K + (\sigma-1).\ln A_K + \sigma.\ln\frac{PK_{it}}{PY_{it}} \\
\ln\frac{D_{it}}{Y_{it}} &= \sigma.\ln\alpha_D + (\sigma-1).\ln A_D + \sigma.\ln\frac{PD_{it}}{PY_{it}}
\end{aligned} \tag{3}$$

One of the main limitations of CES functions is that it is difficult to obtain estimates for all the parameters without imposing additional restrictions or assumptions, because the estimated equations will be under-identified, as we only have variables for prices and quantities and three unknown parameters to be estimated. If we estimated Eq. (3), we will not be able to separate between the distribution parameters α and the productivity parameter A (first two terms on the right-hand side), as both will be calculated within the constant coefficient (van der Werf, 2008). To avoid that, and following van der Werf (2008), we take the first differences of the system of Eq. (3) to estimate the percentage changes in the factor-specific technology parameter. Since the distribution parameter is constant, taking the first differences drops it from the system of equations. Furthermore, by log-transforming the conditional factor demand Eq. (3), we obtain the corresponding linear relationships expressed in the following system of equations:

$$\begin{aligned}
(l_{it} - y_{it}) &= (\sigma-1)\delta_L + \sigma(py_{it} - pl_{it}) \\
(k_{it} - y_{it}) &= (\sigma-1)\delta_K + \sigma(py_{it} - pk_{it}) \\
(d_{it} - y_{it}) &= (\sigma-1)\delta_D + \sigma(py_{it} - pd_{it})
\end{aligned} \tag{4}$$

The left-hand sides of (4) denote the annual growth rates in the quantity of factors l, k, and d minus the change in the net value added,

Table 3
Summary statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
l - y	718,096	0.042	2.409	−15.364	14.377
k - y	718,096	0.078	2.408	−17.768	18.509
d - y	718,096	0.059	2.416	−16.419	15.160
py - pl	718,119	−0.020	3.859	−22.918	22.596
py - pk	718,119	−0.016	5.139	−25.822	26.488
py - pd	718,119	−0.025	3.822	−22.702	21.941
Change in the amount of subsidies					
Pillar I coupled payments	718,119	−0.264	2.703	−15.401	15.401
Pillar I decoupled payments	718,119	0.553	2.129	−12.896	14.292
Pillar II subsidies on investments	718,119	0.065	2.465	−14.515	15.076
Pillar II agri-environment measures	718,119	0.004	2.425	−15.407	15.407
Pillar II less favoured areas scheme	718,119	0.073	1.846	−13.561	15.144
Change in subsidy rate					
Pillar I coupled payments/total output	718,119	−0.032	1.768	−15.187	14.849
Pillar I decoupled payments/total output	718,119	−0.092	1.396	−13.149	13.149
Pillar II subsidies on investments/total output	718,119	−0.039	0.974	−14.548	14.548
Pillar II agri-environment measures/total output	718,119	0.004	1.204	−14.006	14.985
Pillar II less favoured areas scheme/total output	718,119	−0.036	1.007	−12.719	13.052

Source: Farm Accountancy Data Network (FADN). All variables are log-transformed.

which depends on: i) the elasticity of substitution σ; ii) the factor-augmenting technology parameters δ_L, δ_K and δ_D; iii) the difference in the price of the net value added py ; and iv) the prices of the input factors pl, pk, and pd. Small letters y, l, k, d, py, pl, pk, and pd are the difference of the log-transformed variables for quantities and prices of factors and value added, and are calculated as $x_{i,t} = \ln(X_{i,t}) - \ln(X_{i,t-1})$; where X is Y, L, K, D, PY, PL, PK, and PD.

Since net value added is.

$$VA_{it} = PY_{it}.Y_{it} = PL_{it}.L_{it} + PK_{it}.K_{it} + PD_{it}.D_{it},$$

where VA_{it} is the total amount of value added expressed in euros and already available in the data. The share of inputs in the total value added is then.

$$\gamma_{L_{it}} = \frac{PL_{it}.L_{it}}{VA_{it}}$$

$$\gamma_{K_{it}} = \frac{PK_{it}.K_{it}}{VA_{it}}$$

$$\gamma_{D_{it}} = \frac{PD_{it}.D_{it}}{VA_{it}}$$

Accordingly, the unit price of the value added PY_{it} and the quantity of value added produced Y_{it} can be calculated as.

$$PY_{it} = PL_{it}\cdot\gamma_{L_{it}} + PK_{it}\cdot\gamma_{K_{it}} + PD_{it}\cdot\gamma_{D_{it}}, \tag{5}$$

and

$$Y_{it} = \frac{VA_{it}}{PY_{it}} \tag{6}$$

Moreover, according to its definition, technical change is specified as an endogenous function of other variables, plus an exogenous component that captures its autonomous evolution over time (De Cian, 2009). Therefore, the factor-augmenting technology parameters δ_L, δ_K, and δ_D are assumed to contain two components: an exogenous ($\theta_{D},$) and an endogenous one (θ_{ENDO}). The exogenous component denotes unobservable factors that have impact on the factor-augmenting technical change but that cannot be measured and, therefore, cannot be included in the model. The endogenous parameter can be further breakdown in a number of endogenous components reflecting the impact of one or more technology drivers on the three factors productivity (Carraro and De Cian, 2013; Smeets Kristkova et al., 2017; De Cian, 2009; Dudu and Kristkova, 2017). Here we assume that the endogenous technology drivers are the CAP subsidies (θ_S). Such that:

$$\delta_L = \theta_L + \theta_S.\boldsymbol{s}$$
$$\delta_K = \theta_K + \theta_S.\boldsymbol{s} \tag{7}$$
$$\delta_D = \theta_D + \theta_S.\boldsymbol{s}$$

Where $\boldsymbol{s}$ is a vector of CAP subsidies, distinguishing between Pillar I coupled (*cp*) and decoupled (*dc*) subsidies and Pillar II subsidies on investments (*inv*), agri-environmental (*env*) and least favoured areas (*lfa*) payments, such that $s = (cp, dc, inv, env, lfa)$. For comparison purposes, the subsidies in $\boldsymbol{s}$ are calculated in two ways: first as the first differences in the nominal amount of the subsidy payments so that $s_1 = \ln(S_{it}) - \ln(S_{it-1})$; and second as the first differences in the share of subsidies in the farm's gross value added, so that $s_2 = \ln\left(\frac{S_{it}}{y_{it}}\right) - \ln\left(\frac{S_{it-1}}{y_{it-1}}\right)$. In other words, subsidies are measured both as total and relative (to the value of output) change, respectively.

While most studies in the literature use the nominal amount of subsidy payments (see Minviel and Latruffe, 2017), a growing number of studies have measured the productivity impact of subsidies using the subsidy rate (Fogarasi and Latruffe, 2009; Bakucs et al., 2010; Dudu and Kristkova, 2017; Garrone et al., 2019). In our analysis, using both measurements have an interesting implication: with constant level of subsidies, the direction of subsidies change depends on farms' output. This becomes apparent with a numerical example. Imagine that in both years T and T-1 subsidies are constant and of 1€, so that $s_1 = S_{it} - S_{it-1} = 0$; and that gross VA in year T-1 is $y_{it-1} = 4$€. In good years $y_{it} = 5$€, so that $y_{it} > y_{it-1}$ and $s_2 = \ln\frac{S_{it}}{y_{it}} - \ln\frac{S_{it-1}}{y_{it-1}} = -0.05$. In bad years $y_{it} = 2.5$€, so that $y_{i\,t} < y_{it-1}$ and $s_2 = \ln\frac{S_{it}}{y_{it}} - \ln\frac{S_{it-1}}{y_{it-1}} = 0.15$. In good years, the change is negative (the importance of subsidies on output decreases) in bad years the change is positive (the importance of subsidies increases).

By substituting equations (7) in the system of factor demand in equations (4) we obtain the system of equations (8) which will be estimated:

$$(l_{it} - y_{it}) = \sigma(py_{it} - pl_{it}) + (\sigma - 1).(\theta_L + \theta_S.\boldsymbol{s})$$
$$(k_{it} - y_{it}) = \sigma(py_{it} - pk_{it}) + (\sigma - 1).(\theta_K + \theta_S.\boldsymbol{s}) \tag{8}$$
$$(d_{it} - y_{it}) = \sigma(py_{it} - pd_{it}) + (\sigma - 1).(\theta_D + \theta_S.\boldsymbol{s})$$

The estimation of Eq. (8) will generate the elasticity of substitution (σ) between land, labour, and capital; the endogenous $(\theta_{L,K,D})$ and

Table 4
CAP payments and technical change estimation by EU27 macro-regions with subsidies measured as change in nominal amount (s_1).

	EU27 (1)	Northern (2)	Southern (3)	Eastern and Central (4)	Western (5)
σ (elasticity of substitution)	**0.240****	**0.183*****	**−0.097*****	**−0.248*****	**−0.083*****
	(0.095)	(0.058)	(0.003)	(0.058)	(0.003)
θ labour	**−0.073*****	**0.018****	**−0.017*****	**−0.149*****	**−0.027*****
(exogenous TC)	(0.012)	(0.009)	(0.006)	(0.012)	(0.004)
θ capital	**−0.105*****	**−0.031*****	**−0.048*****	**−0.164*****	**−0.041*****
(exogenous TC)	(0.014)	(0.009)	(0.005)	(0.013)	(0.003)
θ land	**−0.094*****	−0.001	**−0.036*****	**−0.151*****	**−0.032*****
(exogenous TC)	(0.015)	(0.009)	(0.006)	(0.014)	(0.004)
Pillar I					
θ Coupled subsidies	**−0.016****	**−0.045*****	−0.004	−0.0875	**−0.036*****
	(0.007)	(0.009)	(0.006)	(0.060)	(0.005)
θ Decoupled subsidies	**0.030****	**−0.097***	−0.012	**0.203*****	**0.056*****
	(0.015)	(0.054)	(0.009)	(0.034)	(0.011)
Pillar II					
θ Subsidies on Investment	**0.030*****	0.008	0.003	−0.019	0.003
	(0.008)	(0.010)	(0.006)	(0.018)	(0.003)
θ Environmental subsidies	**−0.024*****	−0.009	**−0.015****	**−0.039*****	**−0.013*****
	(0.006)	(0.013)	(0.006)	(0.012)	(0.005)
θ LFA subsidies	**0.030****	−0.101	−0.008	0.365	−0.016
	(0.014)	(0.078)	(0.007)	(0.397)	(0.021)
No. of obs.	517,157	47,171	157,679	126,558	147,859
No. of farms	117,179	11,556	38,849	28,662	29,524
Instrumental variables for prices	*L.py - pl*	*L.py - pl*	*L.py - pl*	*L2.py - pl*	*L.py - pl*
	L.py - pk	*L.py - pk*	*L.py - pk*	*L2.py - pk*	*L.py - pk*
	L.py - pd	*L.py - pd*	*L.py - pd*	*L2.py - pd*	*L.py - pd*
Hansen's J test (χ2)	0.79	2.11	1.62	7.24	1.91
Hansen's J test (p-value)	0.85	0.72	0.81	0.06	0.59
Test of C–D (χ^2)	64	200	18	471	130,000
Test of C–D (p-value)	0.00	0.00	0.00	0.00	0.00
Test of neutral TC (χ^2)	168.07	310.02	148.43	151.20	506.87
Test of neutral TC (p-value)	0.00	0.00	0.00	0.00	0.00

Newey–West HAC standard errors in parentheses; *p <.1 **p <.05 *** p < 0.01.

exogenous factor-augmenting parameters (θ_s).

Using the estimated elasticity of substitution and the exogenous factor-augmenting parameters we are able to test for the presence of Hick-neutral technical change from Eq. (8), by testing if $\theta_L = \theta_K = \theta_D$, and for the presence of Cobb-Douglas production by testing if $\sigma = 1$.

Table 3 shows main statistical description for the variables used in our estimations.

Finally, we control for several external factors by running the system of equations (8) for different EU regions to account for unobservable region-specific characteristics (e.g. inputs markets or organization of the farming systems)[1].

3.3. Estimation strategy

A commonly used way to estimate CES production functions is the Kmenta approximation. Kmenta (1967) derived a linearized form of the classical two-input CES function, using a Taylor approximation around the elasticity of substitution equal to unity, and proposed a restricted form of the general translog function which could be estimated using ordinary least-squares techniques. However, the linearization is only an approximation of the CES and is strictly applicable for elasticities of substitutions around unity, in addition, the Kmenta approximation can produce considerable biased estimates (Hoff, 2004; Henningsen and Henningsen, 2011).

In order to overcome the above-mentioned drawbacks of the Kmenta approximation, we rely on the estimations of the system of equations (8) which are directly derived from the CES production function with three inputs. Systems of equations can be estimated using different models and estimators, the most common being system ordinary least squares (SOLS) and system generalized least squares (SGLS). Both these two estimators require the explanatory variables to be strictly exogenous for the estimations to be robust. Strict exogeneity condition indicates that the explanatory variables are uncorrelated with the disturbance term (unobservable factors or errors) in the same time period in all equations. This is referred to as explanatory variables orthogonal to the errors. The exogeneity condition is often violated and for that, instrumental variables models provide more valid approaches.

In our estimations, some of the covariates might violate the strict exogeneity condition and be correlated with the error term. Specifically, differences in prices of value added, labour, land, and capital might be endogenous because of the relationship between price levels and inputs and output quantities. In addition, changes in subsidies could also be correlated with changes in land size, or inputs and output quantities as well. This might generate simultaneity bias. Moreover, potential unobservable measurement errors in the variables used to calculate prices may also lead to potential endogeneity.

The modern approach to system instrumental variables estimation is based on the principle of GMM, which uses fewer distributional assumptions than the alternative three-stage least squares (3SLS) approach. The GMM estimator is more efficient to estimate models with potential endogeneity problems by using internal instruments, such as lagged values of the explanatory variables. Therefore, in order to take into account for the potential endogeneity of the variables contained in $\boldsymbol{s}$, the system of Eq. (8) is estimated in STATA using the GMM system estimator. Specifically, we use the two-steps GMM estimator: in the first step the parameters are estimated using an initial weight matrix; in the second step the obtained parameters are used to compute a new weight

[1] We tested the possibility of using control variables directly in the system of equations (8), adding the MS's GDP per capita, domestic credit to GDP, and population density, the farms' economic size and type of farm, in addition to countries and regions dummy variables. However, because of the complexity of the system of equations, the addition of further parameters makes the convergence of the model computationally unsolvable.

Table 5
CAP payments and technical change estimation by EU27 macro-regions with subsidies measured as shares of farm's gross VA (s_2).

	EU27	Northern	Southern	Eastern and Central	Western
σ (elasticity of substitution)	**0.039****	**0.130****	**0.314****	**0.101*****	**−0.077*****
	(0.016)	(0.053)	(0.160)	(0.021)	(0.009)
θ labour	**−0.030*****	**0.022*****	0.020	**−0.198*****	−0.001
(exogenous TC)	(0.003)	(0.008)	(0.017)	(0.018)	(0.003)
θ capital	**−0.058*****	**−0.026*****	−0.008	**−0.232*****	**−0.015*****
(exogenous TC)	(0.003)	(0.008)	(0.019)	(0.018)	(0.003)
θ land	**−0.045*****	0.003	0.001	**−0.222*****	**−0.006****
(exogenous TC)	(0.003)	(0.008)	(0.017)	(0.018)	(0.003)
Pillar I					
θ Coupled subsidies	**−0.086*****	**0.042*****	**−0.178*****	**−0.605*****	**−0.048*****
	(0.005)	(0.008)	(0.067)	(0.093)	(0.005)
θ Decoupled subsidies	**−0.213*****	**−0.155*****	**−0.367****	0.0316	**−0.057*****
	(0.013)	(0.055)	(0.154)	(0.101)	(0.007)
Pillar II					
θ Subsidies on Investment	**−0.091*****	0.012	**−0.098***	**−0.160****	**−0.024*****
	(0.010)	(0.025)	(0.057)	(0.074)	(0.007)
θ Environmental subsidies	**−0.017****	−0.007	**−0.071****	−0.019	**−0.035*****
	(0.0081)	(0.021)	(0.033)	(0.039)	(0.007)
θ LFA subsidies	**−0.109*****	**0.236*****	**−0.085****	**−1.290*****	**−0.061*****
	(0.012)	(0.067)	(0.0422)	(0.256)	(0.020)
No. of obs.	517,157	47,171	157,668	126,556	147,853
No. of farms	117,179	11,556	38,848	28,661	29,523
Instrumental variables for prices	*L.py - pl*	*L.py - pl*	*L.py - pl*	*L2.py - pl*	*L.py - pl*
	L.py - pk	*L.py - pk*	*L.py - pk*	*L2.py - pk*	*L.py - pk*
	L.py - pd	*L.py - pd*	*L.py - pd*	*L2.py - pd*	*L.py - pd*
Hansen's J test ($\chi 2$)	0.72	1.92	7.96	6.79	4.68
Hansen's J test (p-value)	0.87	0.75	0.09	0.24	0.46
Test of C–D (χ^2)	3351	266	110,000	1892	13,945
Test of C–D (p-value)	0.00	0.00	0.00	0.00	0.00
Test of neutral TC (χ^2)	2326.98	416.89	724.89	414.12	537.75
Test of neutral TC (p-value)	0.00	0.00	0.00	0.00	0.00

Newey–West HAC standard errors in parentheses; *p <.1 **p <.05 ***p < 0.01.

matrix which serves to re-estimate adjusted parameters. This is opposed to the one-step GMM estimator where the parameters estimated are just the ones in the first step obtained with the initial weight matrix.

We use several combinations of internal instrumental variables and tested the validity of the instruments using the Hansen's J Chi Square for testing the over-identifying restrictions. As instruments, we used the first three lags of price ratio of value-added and input factors (value-added price divided by input factors' prices) in each equation to instrument for the corresponding explanatory variables, and we used first and second lags of the normalised CAP subsidies as instruments for CAP variables in each equation.

Because we are dealing with an unbalanced panel dataset consisting of a large number of farms for twelve years, it is fair to assume that the residuals may exhibit clustering. In order to exploit the panel structure of the dataset, we specified a weight matrix that accounts for arbitrary correlation among observations within the same farm, and that assumes independent moment equations. In this way, the GMM command in STATA computes a weight matrix that does not assume that errors are independent within each farms' observations (clusters), and we kept the default weight matrix (unadjusted) which assumes that the weight matrix has independent and identically distributed moment equations. We applied our estimations using the Newey and West algorithm to obtain consistent standard errors in the presence of heteroscedasticity and autocorrelation in the data.

Moreover, we examine the presence of a Cobb–Douglas production technology by Wald test to see if the elasticity of substitution is equal to one, as in Carraro and De Cian (2013) and Kristkova et al. (2017). Rejecting the null hypothesis does not support the existence of a Cobb-Douglas technology and confirms the assumption of a CES technology.

Finally, the CES allows also to relax and test for the assumption of Hick-neutral technical change. According to Hicks, neutrality is "an invention which raises the marginal productivity of labour and capital in same proportion". In other words, Hick-neutral technical change assumes that when changes in the production factors occur and the total output increases or decreases, the marginal rates of substitution of labour and capital do not change (Solow, 1957). However, empirical evidence shows that innovation is not neutral and can affect the marginal productivity of production factors differently, shifting the relative importance (and demand) for one factor of production while reducing the demand and the compensation of other factors (Acemoglu, 2003). This suggests that technical change does not only capture Hicks-neutral technical changes but also the effects of technical changes on the marginal rate of substitution. The system of equations derived from the FOC allows to estimate the total magnitude and direction of factor-augmented technical change and to test for the presence of Hick-neutral technical change by testing if labour- and capital-augmented technical changes are equal. We therefore test whether $\theta_L = \theta_K = \theta_D$.

4. Results

Tables 4 and 5 present the results for different EU macro-regions using the change in the nominal amount of subsidies and the change of the share of subsidies on farms' gross value added, respectively. For all the reported estimations, the Hansen's J test shows that the instruments used for correcting for potential endogeneity are valid, as they all pass the overidentifying restrictions test, suggesting that we cannot reject the null hypothesis that the overidentifying restrictions are valid (p-value of the χ^2 is >0.05). Regarding the choice of production function, the parameters of the elasticity of substitution (sigma) and the Wald tests reject the null hypothesis that the technology specification in our data is a Cobb-Douglas technology and supports the presence of a CES technology specification. This suggests that, with the data at hand, the impact of endogenous factors such as CAP subsidies on agricultural technical change are more appropriately captured using CES rather than Cobb-Douglas functional forms. Moreover, the Wald tests also reject the null hypothesis of the presence of Hick-neutral technical change and support the assumption of factor-augmented technical change, confirming different levels of marginal productivity between labour, capital, and land.

The elasticity of substitution between production factors (σ) is statistically significant at 1% or 5% probability levels for all the estimations reported in Tables 4 and 5. The coefficients of sigma are all below one or negative. The coefficient of sigma measures the relative extent to which one factor will be replaced by another because of a change in their relative prices. It can be also interpreted as a measure of the similarity of the technical level of factors. In this context, negative and below one elasticity of substitution indicates that factors are complements and that they can be hardly substituted one for the other, indicating that land, capital, and labour have complementarity instead of substitution relationship in EU agriculture during the examined period. This indicates that the process of capital substitution for labour, such as agricultural mechanisation, have declined during the period, suggesting that even if the relative prices of factors would change, the input mix would nearly remain the same. In alternative, a close to zero elasticity of substitution might indicate that substitution is possible but only in the longer period (Debertin, 2012). In other words, a farmer cannot drastically change the approach to the production from one year to the other, but he/she has the possibility to change production methods over several years. The negative sign can be due to negative net value added and price of capital in some farms (Hicks, 1970; Sato and Koizumi, 1973; Stern, 2011). Although these results may seem counterintuitive with respect the general trends of labour-capital substitution in the EU during the past decades[2], it should be noted that our results indicate that the labour-capital substitution was less intense in the agricultural sector in the most recent years, especially in new Member States. Moreover, our estimates considered the substitution between the three factors of production, including land, and not only labour and capital. In addition, our estimates considered a shorter and more recent period of time in which labour-capital substitution already occurred while currently there is a need for skilled labour (Correa et al., 2019; Marinoudi et al., 2019).

The exogenous theta represents the contribution to productivity of exogenous unobservable factors, which are factor-specific and that impact technical change. These exogenous unobservable factors can be outside the farmers' control, or can be decisions regarding the production process, as well as conditions related to the environmental, market or socio-economic context in which the farms operate, or related to the labour, capital and land markets. Generally speaking, the overall direction of the coefficients of the three exogenous θ in Tables 4 and 5 indicate that there has been a very slow decline (or no change at all) in the labour-, capital-, and land-augmented technical change during the examined period. More specifically, the exogenous technical change of the three factors of production is either negative or statistically insignificant at the EU27 level (columns 1 of Tables 4 and 5), but vary across regions. This suggests that unobservable factors which are labour-, capital- and land-specific have different productivity effects across EU regions. For example, the exogenous technical change is negative and statistically significant in the Eastern and Central region, while exogenous factors have positive and statistically significant effects on the productivity of labour in the Northern region. This is not surprising since the overall productivity of labour, capital and land in our sample has been nearly stagnated during the period 2004–2015 (see Appendices A1-A3), and the yearly changes in productivity have been generally negative or nearly zero for the three factors of production (Appendices A4-A6). Since from equations (8), the exogenous technical change is determined by the changes in the productivity of factors of production (e.g. changes in quantity of labour divided changes in quantity of value added) and changes in their prices; therefore, the negative yearly changes in the productivity of the factors of production (A4-A6) can explain our findings of negative exogenous technical changes.

While the EC (2016) findings suggest that TFP growth in the agricultural sector in the EU has slowed from 1% annually between 1995 and 2005 to 0.8% between 2005 and 15, our results focus only on the growth of technical change, which is one component of TFP. Thus, the growth in TFP during this period might be driven by improved technical efficiencies but not due to technological progress (O'Donnell, 2010; O'Donnell, 2012a). In addition, there are significant contradictions in different estimations of TFP growth, due to theoretical and methodological differences in measuring TFP (O'Donnell, 2012b, O'Donnell (2012); Baráth and Fertő, 2017). For instance, while the European Commission uses the Fischer index to measure TFP (European Commission, 2016); Baráth and Fertő (2017) used the Färe-Primont index to measure TFP, and found a declining trend in agricultural TFP in the EU between 2004 and 2013. Baráth and Fertő (2017) argued that, unlike the Fischer index, the Färe-Primont index is statistically better for cross-country and multi-temporal comparisons.

Comparing the coefficients, one can see that the magnitude of the effects of factor-specific exogenous technical change (θ exogenous) are larger when subsidies are measured in nominal amounts (**s1**). This applies to nearly all the estimates in the both tables.

Looking to the results of our variables of interests, both Pillar I and Pillar II subsidies in Tables 4 and 5 have statistically significant impact on farms' technical change. As mentioned earlier, despite in theory decoupled subsidies should not directly affect production decisions, they indirectly affect productivity via changing farmers risk attitudes and expectations (Banga, 2014). Our results suggest that Pillar I decoupled subsidies have a positive impact on technical change at EU27 level, Western, and Eastern and Central regions, and a negative impact in the Northern region. Whereas decoupled subsidies have a negative statistically significant impact on technical change at EU27 level, Northern, and Western regions when subsidies are measured in nominal amounts (**s1**) (columns 1, 4 and 5 of Table 4). Kazukauskas et al. (2014) found that decoupled payments have positive impact on the productivity of Irish cattle farms and Danish dairy farms, when measuring decoupled payments as a share of total payments. However, they found no statistically significant impact on the productivity of Irish dairy and crop farms, Danish crop farms, and Dutch cattle, and dairy farms. Their results show that in some cases the decoupling of agricultural subsidies could lead to improvements in productivity. Similarly, Latruffe and Desjeux (2016) found production subsidies to have negative impact on the technical efficiency of French farms. Our results are also in line with Garrone et al. (2019) who found that decoupled payments have positive impact on labour productivity while coupled payments have the opposite impact. We believe our estimates provide a more detailed explanation that complement Dudu and Kristkova (2017), Garrone et al. (2019), and previous empirical studies, as we use farm-level data clustered into different groups, while Dudu and Kristkova (2017) and Garrone et al. (2019) used NUTS2 regional-level data clustered into old and new Member States. In addition, unlike previous studies except Dudu and Kristkova (2017), we measured the impact of subsidies on endogenous factor-augmented technical change, without restricting the elasticity of substitution between inputs to unity or imposing Hick-neutral assumption on technical change.

In addition, Pillar II subsidies on investments and LFA subsidies have positive impacts on technical change at EU27 level, although both subsidies are not significant on regional estimates when measured in nominal amounts (**s1**). Moreover, agri-environmental subsidies have negative impact on technical change at the EU level, Southern, Western, and Eastern and Central regions. Contrary to Dudu and Kristkova (2017), we found negative impacts of agri-environmental subsidies in almost all our estimates, whereas Garrone et al. (2019) found no statistically significant impact on labour productivity from LFA and agri-environmental subsidies. Despite most of our results differ from the ones obtained by Dudu and Kristkova (2017), the positive impacts of subsidies on investments on technical change when measured in

[2] Benchmark trends for the period under study are available on the EU Agricultural Markets Brief No 10 of December 2016 at this address (accessed 28 October 2021): https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/trade/documents/agri-market-brief-10_en.pdf.

nominal amounts (**s1**) is in line with Dudu and Kristkova (2017), who found positive impact on productivity from subsidies on human and physical capital.

Most of the statistically significant results in Table 5 show that most types of payments have negative effects on technical change, except for coupled and LFA subsidies in the Northern region which have a positive and statistically significant impact. By comparing Tables 4 and 5 it emerges that the magnitude of the coefficients is larger when subsidies are measured as share of gross VA in Table 5. Moreover, decoupled subsidies, subsidies on investments, and LFA turns negative. Pillar I subsidies (coupled and decoupled payments) are having the largest impact in most of the estimations. These subsidies include single farm payments and single area payment schemes, which are direct income support to farmers and might hinder the motivation of farmers to improve their productivity. In addition, the positive impact of coupled and LFA subsidies on technical change in Northern farms may suggest that subsidies can have a positive impact only on highly capitalised farms when measured as share of gross VA such that additional payments do not discourage farmers to improve their productivity.

These results suggest that the nominal amount of subsidies given to farms, whatever large, has a relatively small impact on productivity, but the more the subsidies contribute to farms' income the slower is the technical change and its contribution to productivity. Note that the share of subsidies is greater when gross VA is small, which occurs during bad years or when farms are inefficient and not competitive. Therefore, on the one hand subsidies act as an income buffer tool to recover from bad years, on the other hand subsidies oppose the technical change of farms for which improvements of productivity are more needed. This sheds additional light to the results of seminal studies such as Mary (2013) and Rizov et al. (2013), both finding negative effects of subsidies on TFP. While these results contradict Dudu and Kristkova (2017) and Garrone et al. (2019), they are in line with Mary (2013), who found that LFA and coupled subsidies have negative impacts on productivity. Similarly, Latruffe and Desjeux (2016) and Nilsson (2017) found investment subsidies to have negative effects on productivity.

5. Discussion

Some studies comparing the productivity effect of coupled and decoupled subsidies suggest a different direction of the effects shown by our results. For example, Rizov et al. (2013) have shown that CAP subsidies negatively affected farms' productivity in the period before the decoupling reform, while after the introduction of decoupling this impact becomes heterogeneous, remaining negative in some EU MS and turning positive in other EU MS. However, Rizov et al. (2013) observe this impact confronting different periods rather than different payments.

Each CAP subsidy is different and has a specific aim, therefore they may have diverse impacts on farms' behaviour and productivity. Generally, the impact of the CAP on productivity is expected to be heterogeneous depending on the scope and design of each type of subsidy, so that the various CAP payments should complement each other. For example, coupled subsidies are likely to disrupt the efficient allocation of inputs and outputs (Garrone et al., 2019), whereas decoupled payments are likely to increase farms' capital and access to credit, encouraging productive investments and therefore boosting productivity (Kazukauskas et al, 2014). However, there are reasons to consider the decoupled Single Farm Payment (SFP) introduced by the 2003 Reform as a form of partial decoupling, because, as pointed out by Boussemart, et al. (2019) "although these payments were supposed to be paid irrespective of production, they were still linked to land. In practice, SFPs were calculated as the mean of the subsidies the farmer received during three base years (2000, 2002 and 2003)". The linking of subsidies with land can benefit landowners but not necessarily the farmers, as subsidies are then capitalised into land rents (O'Neill and Hanrahan, 2016; Varacca et al., 2022). Moreover, reduced budget constraint can reduce farmers' motivation to adopt efficient production methods and reduce the incentive to invest in more productive technologies (Kornai, 1986; Rizov et al. 2013). Therefore, it is not surprising that both coupled and decoupled subsidies have the same negative effect on productivity.

Pillar II payments focusing on rural development are grouped in three macro-categories common across the period 2004–2015, namely subsidies on investments, agri-environmental measures, and LFA. These are the categories used also in the econometric analysis. In theory, investment subsidies should improve productivity by increasing investments in labour and physical capital, while agri-environmental subsidies could reduce farms' yields as they restrict the use of chemical inputs. The impact of LFA subsidies on the other hand is not straightforward (Latruffe and Desjeux, 2016; Garrone et al., 2019). Participation in rural development measures is voluntary, based on applications to grants supporting very specific investments or production practices, increasing the probability of inducing distorting and subsidy-seeking activities and investments. This can ultimately result in over-investments in less productive assets or practices and, at the same time, reducing the farmers' incentives to adopt a more competitive and cost-improving behaviour.

In Table 4, subsidies on investments have a statistically significant positive or no impact on technical change of all estimates using changes in the nominal amount of subsidies. However, except for no statistical significance in the Northern region, all estimates using the changes in subsidy rate indicate a statistically significant and negative impact of investment subsidies on the productivity of farms. These results are consistent with most studies on the impact of investment subsidies on farm productivity (e.g. Lakner, 2009; Latruffe et al., 2016). In particular, Nilsson (2017) points out that subsidies on investments have a positive impact on the productivity of small farms who received the support with respect those who did not received it, but when the amount of support is calculated as a continuous variable (subsidies on investments on farm's turnover) it reveals a negative impact on productivity.

Agri-environmental measures have also a negative and statistically significant impact on factor-augmenting technical change in almost all our estimates. Farmers who are eligible for agri-environment schemes are those adopting production methods preserving the quality of soil, enhancing the landscape, benefiting wildlife and biodiversity, or improving the quality of water and air. As a result, the negative coefficients of agri-environmental measures on productivity can be due to the fact that environment-friendly methods are not necessarily the most productive ones, but they are equally or even more important for the land, the community, and for protecting the environmental assets needed for sustainable agriculture (Vigani et al., 2015). Moreover, Mennig and Sauer (2019), whom find that AES participation reduces dairy farms' productivity, explains that "a farmer's decision to participate will result in future management restrictions and less flexibility for farm development".

Finally, LFA subsidies have negative and statistically significant impact on most of the estimates. LFA subsidies aim to support farmers working in less favoured land that may have limited access to water, have difficult climate conditions, located in mountainous or hilly surface, or other natural constraints. Accordingly, it is reasonable that LFA subsidies are associated with negative impact of factor-augmented technical change, as farms receiving these subsidies may have lower productivity rates than their counterparts due to these natural constraints (Vigani and Dwyer, 2020).

Considering the individual effects of the three types of Pillar II subsidies described above and the findings in the empirical literature, it seems likely that, overall, the type of rural development support in 2004–2015 has not facilitated productivity growth, especially because of yields stagnation. However, the farm-level net effect depends strongly on the relative proportion of subsidies received from the three categories. This because while subsidies on investments have been introduced with the purpose of improving productivity, the target of LFA and agro-environmental schemes are levelling the playing field for farms in disadvantaged area and improving the environmental externalities produced by the agricultural activity, respectively. Therefore, the implications of these subsidies for productivity are more difficult to identify.

6. Conclusion

The literature provides robust empirical evidence on the relationship between CAP subsidies and agricultural productivity using two main measures, namely TFP and technical efficiency. This paper complements such literature by adopting a different approach looking at the relationship between CAP subsidies and technical change. More specifically, we estimated the elasticity of substitution between land, labour, and capital in the EU agricultural sector, the exogenous and endogenous factor-augmented technical change, and the impact of CAP subsidies on the endogenous factor-augmented technical change. We used a large panel dataset covering 117,179 farmers from all EU27 MS for the period from 2004 to 2015.

There are four main conclusions from our study. First, there has been a very slow decline or stagnation in the labour-, capital-, and land-augmented technical change during the examined period across all sectors and EU areas. This is corroborated by observing trends in public agricultural R&D investment in high-income countries that has fallen since 2009 (Heisey and Fuglie, 2018), combined with declining agricultural TFP at the aggregated EU-level since 2004 (Baráth and Fertő, 2017).

Second, the elasticity of substitution between production factors is below one or negative, meaning that factors are complements and they can be hardly substituted one for the other, especially in the short period. This suggests that innovation in physical capital alone is not sufficient to raise productivity, but it needs to be complemented with higher quality labour. For example, innovative digital technologies and precision machineries needs to be accompanied with skilled workers able to operate them (Correa et al., 2019; Marinoudi et al., 2019).

Third, changes in subsidy shares to gross VA explains large part of the negative direction of factor-augmented technical change compared to changes in nominal amount of subsidies. This has significant policy implications. The discussions at the European Parliament concerns cuts to the CAP budget as a mean of fostering the market orientation of the farms. However, as long as subsidies represent a vital share of farms' income it is unlikely that productivity improvements will occur to such levels to stimulate market orientation. This is not to say that subsidies are useless or harmful. On the contrary, this line of reasoning applies to the context of this paper on technical change, which is only one component of TFP along with technical efficiency. Many authors stressed that CAP subsidies have positive impacts on TFP and technical efficiency under certain circumstances (e.g. Kazukauskas et al., 2014; Cillero et al., 2018; Mennig and Sauer, 2019), for example by providing extra liquidity or collaterals for productive investments. Therefore, our results should be interpreted as an additional tool for policymakers to take a more holistic approach to subsidies design than simplistic budget cuts.

Fourth, the majority of the statistically significant results indicate that CAP payments have negative effects on farms' technical change, except for Pillar II subsidies on investments when estimated using the nominal amount of subsidies. These results suggest that CAP payments can induce allocative and technical inefficiencies according to different structural factors. More specifically, Pillar I subsidies that include direct payments like the single farm payment and the single area payment schemes have the largest negative impact. This suggests that direct payments may hinder the motivation of farmers to improve their productivity (Rizov et al., 2013). Similarly, subsidies on investments can induce the selection and over-investments towards less productive assets, reducing the incentives of farmers to invest in more competitive ones. Agri-environmental measures, on the other hand, have negative impact on technical change in most EU MS, but this must be viewed in consideration with the nature of environment-friendly production methods which are not necessarily the most productive technologies (Arata and Sckokai, 2016), but they are extremely significant for protecting the environmental assets needed for sustainable agriculture. Similarly, the negative impact of LFA subsidies is not surprising as these subsidies are paid to farms which have lower productivity rates than their counterparts due to natural constraints.

These results are not only useful as an ex-post assessment of the CAP, but they are significant also for the current and future development of the EU agricultural policies. The current EU policy agenda is developed within the EU Green Deal aiming to boost economic growth through improving the environmental sustainability of all economic sector (including agriculture), while expecting further natural constraints to production due to climate change. This goal can be achieved by increasing the economic and environmental efficiency in using natural resource. Our results suggest that the CAP measures of the last fifteen years, while pursuing environmental and social goals through "cross-compliance", "greening", "targeting", etc., are not suited for achieving the goal of economic efficiency in using natural resources. This is more understandable when thinking of agri-environmental measures that prioritize environmental over economic goals, but it is less intuitive when thinking to the other measures and payments. Part of the explanation can be linked to implementation issues. For example, support to investments through Pillar II is granted to a relatively small number of farms and to the development of investment projects respecting official and bureaucratic criteria that might not be suited for the requesting farm. Moreover, direct payments aim to stabilize incomes. Therefore, their amount is probably enough to top-up the cash-flows to cover farming operations, but they can hardly be in surplus to be used for additional investments.

The new CAP reform will start in 2023, aiming to encourage sustainable and competitive agricultural sector. The new reform is central to the European Green Deal, and will focus on supporting the livelihoods of farmers, ensuring the availability of healthy and sustainable food, and the development of rural areas. Our results suggest that the new reform should aim at dedicating more expenditure to invest in agricultural innovations that aim at improving productivity using environmentally friendly and sustainable agricultural practices.

This debate on how to more efficiently spend the CAP budget and maximize its benefits for farmers and for the society as a whole will fully develop in the next years. For the moment, the current programs have been extended till 2022 and the next CAP reform has been pushed back until 2023 to ensure the continuation of support to farmers affected by the health crisis of the COVID-19. This will also give more time to all the parties involved to achieve an agreement that is proving difficult given that the latest draft CAP budget from the European Council President proposed a €5 billion cut.

CRediT authorship contribution statement

Amr Khafagy: Methodology, Visualization, Writing – original draft. **Mauro Vigani:** Conceptualization, Methodology, Validation, Writing – review & editing.

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.

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Appendix

See Figs. A1–A6.

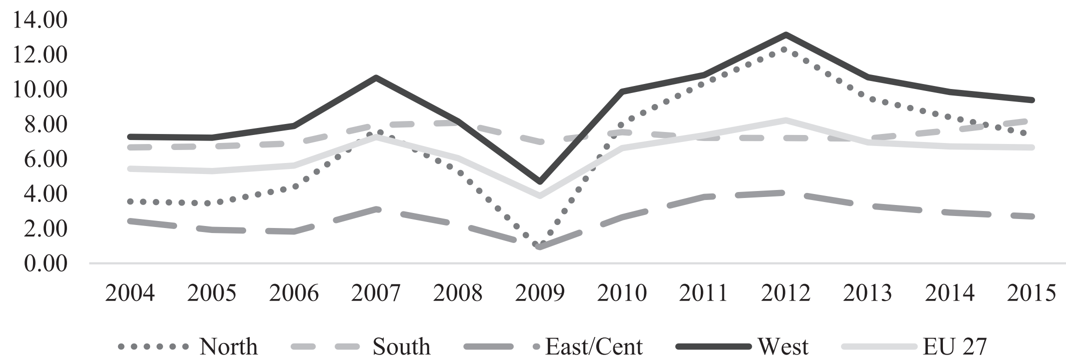

Fig. A1. Average net value added per unit of labour.

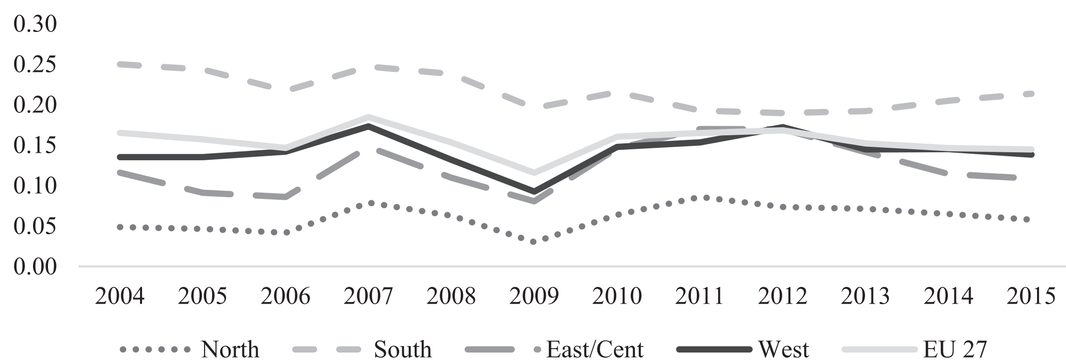

Fig. A2. Average net value added per unit of capital.

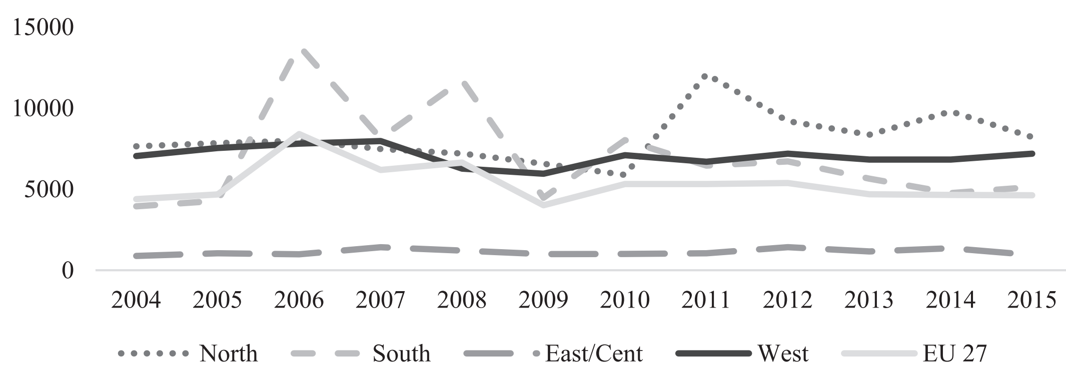

Fig. A3. Average net value added per hectare.

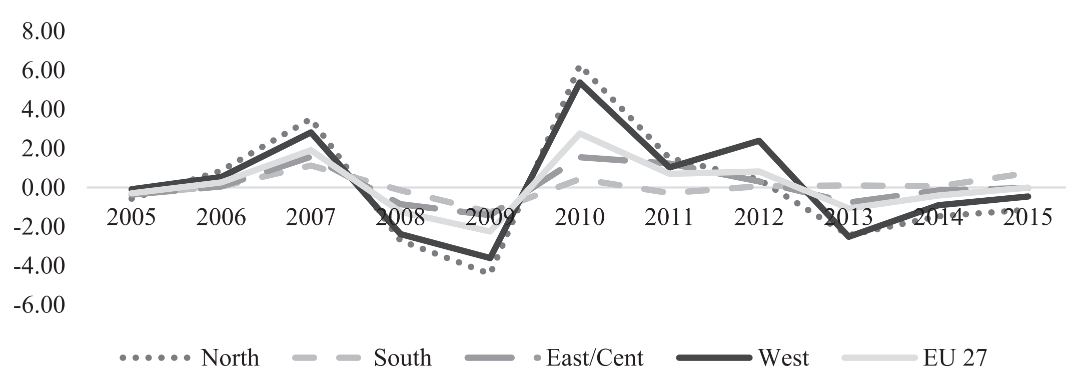

Fig. A4. Average change in net value added per unit of labour.

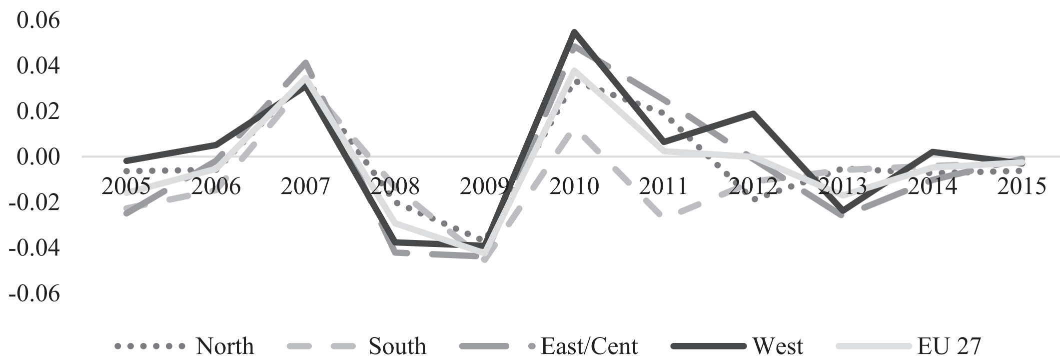

Fig. A5. Average change in net value added per unit of capital.

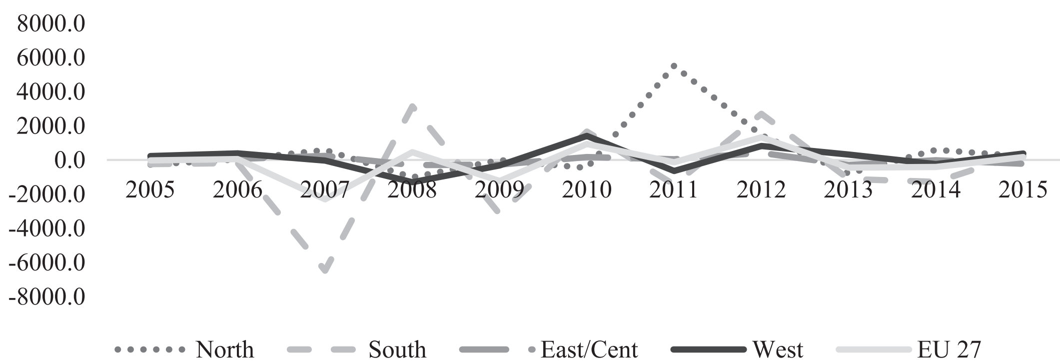

Fig. A6. Average change in net value added per unit hectare.

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