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Environmental Knowledge Spillovers and Productivity: A Patent Analysis for Large International Firms in the Energy, Water and Land Resources Fields

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Abstract: Ensuring sustainable transition from more to less polluting technologies has become an area of increasing interest to academics and policymakers alike over the recent years. Environmental innovations play a key role in this transition. Still, to date relatively little empirical research has been undertaken on the topic. This applies particularly to the potential impact of knowledge spillovers stemming from environmental innovation, termed here as environmental knowledge spillovers (ES), on firms' productivity; a research gap explored in this paper. The focus is laid on three economic areas (Europe, Japan and USA), over the period 2002–2017. Additionally, firms' technological diversity, institutional quality, corporate taxes and the stringency of environmental policy are taken into account to estimate their role in facilitating firms' technical efficiency. The findings indicate that ES affect firms' productivity significantly and positively in all the investigated economic areas, whereas technological diversity increases technical efficiency for Japanese and European, but decreases it for American firms. The findings also show how the stringency of environmental policy (positively), institutional quality (positively) and corporate taxes (negatively) affect firms' technical efficiency.

Keywords: Environmental innovation; Knowledge spillovers; Technical efficiency; Technological diversity; Institutional quality; Environmental policy; Corporate taxes.

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1. Introduction

Environmental innovations[1] produce important knowledge spillovers[2] that can benefit others pursuing similar interests. That is, knowledge spillovers stemming from environmental innovation, termed here as environmental knowledge spillovers (ES), have been proven to assist the introduction of subsequent environmental innovations (Awan & Sroufe, 2020; Antonioli et al., 2016; Anser et al., 2020; Aldieri et al., 2019a; 2019b). This underlines the need for in-depth understanding – with both practical and policy implications – of the mechanisms on how ES facilitate innovativeness as well as of appropriate policy design to support the greening of resource use (Awan, 2020; Nassani et al., 2019; Sinha & Sengupta, 2019; Cao et al., 2020; Dogan et al., 2020). Moreover, there is still a lack of empirical studies investigating the impacts of ES on firms' productivity and efficiency (Awan, 2019; Hoppmann, 2018; Aldieri & Vinci, 2018; Tiba, 2019; Khan et al., 2020). That is, the contemporary academic literature is indecisive concerning whether ES facilitate or hinder firms' productivity (for a recent literature review, see Aldieri et al, 2019a), particularly, in relation to technological diversity and varying institutional contexts. This is an important caveat considering the statements made in favor of more stringent environmental regulations for promoting sustainable development. While it is known that ES do induce environmental innovation and, overall, have positive impacts on the environment (Makkonen & Repka, 2016), there is no consensus whether they actually lead to a "win-win" situation as hypothesized by Porter and van der Linde (1995). That is, do ES facilitate better firm performance, not just in terms of environmental impact but also, in terms of productivity and technical efficiency?

Therefore, this paper makes an original contribution to the existing literature by exploring the role of ES, technological diversity and institutional contexts in enhancing firms' productivity and technical efficiency. The empirical analysis is based on large international firms' patent data, over the period 2002–2017, related to environmental innovation in the energy, water and land resources

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[1] Commonly defined as innovations that have been introduced based on environmental goals and motivations, such as facilitating sustainable development, and/or have a positive effect on the environment via, for example, improved environmental efficiency or decreased environmental impact. For a literature review on the varying definitions of environmental innovation, see Díaz-García et al. (2015).

[2] Empirical literature distinguishes between knowledge and rent spillovers, which are pecuniary externalities that travel along the supply chain (Griliches, 1979); i.e. spillovers that are transmitted through traded goods. We use the measure of environmental knowledge spillovers (ES) as a proxy of (pure) 'knowledge' spillovers. While authors define knowledge spillovers in various ways (i.e. there is no wide consensus on their "exact" definition), they relate to the capture, integration and utilization of knowledge generated elsewhere into firms' (or nations', regions', industries', etc.) own innovation processes: "one firm's innovative activity leads to new ideas and enhances innovative activity in a second firm without the second firm having to compensate the first" (Barry et al., 2003: p. 590).

fields (land use and waste recycling, water pollution abatement and solar wind and renewable energy) in three different economic areas (Europe[3], Japan and USA).

The remainder of the paper is organized as follows: First, a literature review summarizing the most relevant literature on the concepts and topics discussed in this paper, leading to the research questions, is presented. This is followed by, second, a discussion on the data sources and calculations behind the chosen variables and, third, a description of the chosen empirical framework. Fourth, the most relevant results of the paper are presented. Finally, the concluding chapters discuss the main implications of the results and shortcomings of the chosen approach that lead to suggestions for further research.

2. Literature

While it has been established that, generally, knowledge spillovers affect firms' productivity positively (see e.g. Audretsch & Belitski, 2020), in the case of environmental innovation the literature on the topic is quite scarce (cf. Barbieri et al., 2016). What is known is that ES induce further innovation (Antonioli et al., 2016; Aldieri et al., 2019a; 2019b), drive environmental efficiency (Constantini et al., 2013) and that total industry investments in environmental practices are positively related to an individual firm's performance (Awam & Sroufe, 2020; Galdeano-Gómez et al, 2008) hinting at positive productivity effects from ES. Therefore, intuitively, it would seem plausible that ES will have a positive impact on firms' productivity. However, a recent study has actually pointed towards negative impacts of ES on firms' energy production efficiency: by utilizing a spatial Durbin model and patent data covering large R&D-intensive firms in USA, Japan and Europe Aldieri and Vinci (2018) have found a statistically negative impact of spatially distributed ES on firms' productivity. This simple controversy (or, rather, the lack of earlier empirical studies on the topic) leads us to our first research question tested empirically in the subsequent sections:

(i) Is the impact of ES on firms' productivity in the energy, water and land resources fields positive or negative?

Moreover, there is still a lively debate in the economics literature on spillovers and firms' productivity with regard to technological diversity. That is, whether intra-sectoral spillovers (termed as Marshall externalities) or inter-sectoral spillovers (termed as Jacobs externalities) matter more for firm productivity and regional growth (see e.g. Cooke, 2012). While the most recent literature on the topic suggests that both types of spillovers are needed as they reinforce each other (Mitze & Makkonen,

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[3] The following European countries are considered in our sample: Belgium, Denmark, Finland, France, Germany, Italy, Sweden, the Netherlands and the UK.

2019), it is fair to say that the contemporary literature is yet to reach a consensus on the matter. With regard to the topic at hand, a recent literature review (Aldieri et al., 2019a) on ES suggested that there is more empirical evidence supporting the view that intra-sectoral, rather than inter-sectoral, spillovers produce salient positive effects on the productivity of firms pursuing clean technologies. Particularly, the results by Braun et al. (2010) on solar and wind technologies and the results by Aldieri and Vinci (2017) on water pollution abatement technologies support the view that intra-sectoral spillovers seem to matter more for firms' productivity in the case of technologies related to the energy, water and land resources fields. Aldieri and Vinci (2017) even show negative productivity effects from ES originating from unrelated sectors. That is, by using a one-stage generalized method of moments estimator and a dataset composed of worldwide R&D-intensive firms Aldieri and Vinci (2017) show that Marshall externalities (i.e. spillovers related to specialized environmental patent portfolios) have a positive, while Jacobian externalities (i.e. spillovers related to diversified environmental patent portfolios) have a negative impact on firms' productivity.

Contrarily to the studies above, technological (inter-sectoral) diversity has, however, also been highlighted as a key feature of sustainable transitions towards less polluting technologies in a range of studies (e.g. Oltra & Saint Jean, 2009; Frenken et al., 2012; van Rijnsoever et al., 2015). For example, Cooke (2008), by inspecting the cluster histories of various green technologies in USA and Europe, has highlighted how many of the contemporary renewable energy innovations in use today (such as wind energy) are amalgamations of knowledge and technological expertise stemming from several different sectors. These studies underline the importance of taking technological diversity into account when analyzing the productivity of firms.

The discussion on ES and technological diversity is linked to technical efficiency (Farrell, 1957). In short, firms can increase their productivity through heightening their efficiency in turning inputs into outputs; that is through an increase in their technical efficiency (Kourtit & Nijkamp, 2012). Differences in the technological diversity of firms within an industry are expected to explain, at least part of the, variance in their productivity, indicating the presence of inefficiency (Patibandla & Chandra, 1998), whereas clean technologies and adoption of environmental innovations are expected to improve the technical efficiency and, thus, the productivity of firms (del Rio Gonzalez, 2004).

This discussion on technological diversity leads us to a discussion on its measurement. The entropy index is one of the most frequently utilized measures for technological diversity of countries, regions, industries and firms in the literature on economics and economic geography (e.g. Fu & Revilla Diez, 2010; Kalapouti & Varsakelis, 2015; Kalapouti et al., 2017; Colombelli & Quatraro, 2019). Basically, when exploring the impacts of knowledge spillovers the entropy index is commonly used to measure innovation specialization and variety of the given research object (be it a city, a firm, etc.) based on its patent portfolio (Ó Huallacháin & Lee, 2011). In other words, it indicates whether (in our case) the firm in question is specialized within similar technologies or diversified across different technologies. Therefore, we also utilize the entropy index to disentangle the following research question:

(ii) Is the impact of technological diversity (measured with the entropy index) on firms' technical efficiency in the energy, water and land resources fields positive or negative?

Recent literature on the innovation inducement effects of environmental policy – discussing and testing the so-called "Porter hypothesis" formulated by Porter and van der Linde (1995) – has established that an increase in the stringency of regulations for meeting environmental targets will give rise to environmental innovations (e.g. Triebswetter & Wackerbauer, 2008; Makkonen & Repka, 2016; Makkonen & Inkinen, 2018) with knowledge spillovers diffusing across borders and inducing innovations even in foreign countries (Herman & Xiang, 2019; 2020). Still, it is commonly perceived that for most firms, stringent environmental policy induces costs and, thus, they lower firms' productivity. That is, while there is plenty of evidence supporting that stringent environmental policy has a positive impact on the output of innovation activity, firms' productivity appears to be either negatively impacted or unaffected by the degree of stringency of environmental policy. For example, by focusing on the manufacturing sectors of 17 European countries between 1997 and 2009 and by adopting an instrumental variable estimation approach Rubashkina et al. (2015) found evidence of a positive impact of environmental regulation on patenting (as a a proxy for innovation) but no evidence that environmental regulations would enhance productivity.

However, the results vary between more and less polluting industries. More polluting industries see long-run declines in productivity after an increase in the stringency of environmental policy (due to the required heavy "unproductive" investments, such as end-of-pipe equipment, often needed to meet the regulations). Contrarily, while environmental innovations generally exhibit lower productivity returns compared to other innovations in the short run (Marin & Lotti, 2017), in less polluting industries the long-run impact of increased stringency of environmental policy on productivity is less detrimental or even positive due to the productivity growth induced by environmental innovations (Lanoie et al., 2008). The same applies on firm level. That is, an increase in the stringency of environmental policy may force heavily polluting firms to shut down but is likely to bear only small negative impacts on surviving firms' productivity (Wang et al., 2018). Further, studies specifically focusing on environmental policy and technical efficiency have noted that firms respond to increased regulatory stringency by finding technical efficiency enhancements: with data from the electric power industry and regression analysis Galloway and Johnson (2016) found these efficiency gains to be caused by the development of efficiency-enhancing process innovations. This earlier empirical evidence leads us to test the following research question:

(iii) Is the impact of stringent environmental policy on firm's technical efficiency in the energy, water and land resources fields positive or negative?

Moreover, since there is an abundant amount of literature corroborating that institutional quality, or good governance, has a significant and positive impact on technical (for example, energy) efficiency at the national, regional, industry and firm level – better governance is associated with greater efficiency and improvements in the quality of institutions reduce firms' inefficiency (e.g. Méon & Weill, 2005; Castiglione et al., 2018; Sun et al., 2019; Zalle, 2019; Aldieri et al., 2020a) – we propose the following research questions (and expect the answer to be positive):

(iv) Is the impact of institutional quality on firms' technical efficiency in the energy, water and land resources fields positive or negative?

Finally, from earlier literature we know that the correlation between taxation and productivity assumes an important role for the development of public policy (Lee & Gordon, 2005; Arnold, 2008; Myles, 2009; Romer & Romer, 2010). The impact of higher corporate taxes on firms' productivity can depend on different channels such as reduced incentives for innovations and risk taking, since corporate tax schemes are characterized by an asymmetric treatment of losses and profits in most countries (Zilcha & Eldor, 2004; Zwick & Mahon, 2017; Cai et al., 2018). Empirical research on the link between corporate taxes and productivity and/or technical efficiency point towards a negative association. As stated by Gemmell et al. (2018) higher corporate tax rates lower the after-tax returns to productivity enhancing investments and, thus, reduce the speed in which firms converge to the productivity frontier. That is, "investment and productivity are shown to respond negatively to an increase in the corporate tax rate" (Galindo & Pombo, 2011: p. 158). Hence, we propose our final research question (and expect the result to be negative):

(v) Is the impact of corporate taxes on firms' technical efficiency in the energy, water and land resources fields positive or negative?

3. Data

The data utilized in this paper is based on a dataset that combines firm-level data on inputs and outputs with data on the patents registered by each firm in the data (Aldieri & Vinci, 2016). Firm-level data were sourced from the JRC-IPTS EU R&D investment scoreboards (European Commission, 2017) released each year from 2002 to 2017. The dataset covers European countries as well as Japan and

USA. The scoreboards report data on net sales (S), output, annual R&D expenditure (R), number of employees (L) and annual capital expenditure (C), inputs. The data is classified according to the reported industrial sector of the firms (measured at two-digit level) based on the Industrial Classification Benchmark (ICB)[4].

Monetary values in the scoreboards are expressed in Euros. However, the exchange rate used to convert national currencies into Euros varies each year. Therefore, we reconverted the monetary values from the scoreboards into their original currency and then convert them into Euros using the exchange rate from 2007 (our reference year). We used data on *R* and *C* to construct a measure of R&D stock *(K)* and physical capital stock *(PC)* using the perpetual inventory method (see e.g. Dey-Chowdhury, 2008). We applied a depreciation rate of 0.15 in line with earlier studies (Hall & Mairesse, 1995; Aldieri, 2011). Finally, we applied the same cleaning procedure as in Aldieri et al. (2018) by removing the observations with missing values and outliers (that is, R&D intensity below 0.1% or above 100%) from the data (Aldieri et al., 2018). As a result, our data consists of an unbalanced panel of 825 firms, observed over the period 2002–2017, that have introduced at least one patent in the environmental fields under investigation here. This data on patents registered by the firms in our panel were sourced from the OECD (2017) REGPAT database[5]. REGPAT records the technological class of the patent and whether the patent holder is an individual or a company. This last field allowed us to match the firms in our dataset (derived from the scoreboards) with the patent data from REGPAT (Aldieri & Vinci, 2016). In Table 1, we report the environmental patent codes used by Marin and Lotti (2017) and in this paper. In particular, we distinguish three environmental fields: land use and waste recycling, water pollution abatement and solar, wind and renewable energy.

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[4] Firms are grouped into the following industries: Automobiles, Basic resources, Chemicals, Construction, Financial services, Food and beverage, Health care, Industrial goods, Media, Oil and gas, Household goods, Retail, Technology, Telecommunications, Travel and leisure, Utilities.

[5] See Maraut et al. (2008) for a description of REGPAT.

Table 1. Environmental patent classes

Field	IPC (International Patent classification) codes
Land use and waste recycling	A23K, A43B, B03B, B22F, B29B, B30B, B62D, B65H, B65D, B65F, C03B, C03C, C04B, C08J, C09K, C10M, C22B, D01G, D21B, D21C, D21H, E01H, H01B, H01J, H01M, C10G, F09B, A61L, F03G, A62D, B09B
Water pollution abatement	C09K, C02F, E02B, E03F, E03C, E03B, C05F, B63J
Solar, wind and renewable energy	F02B, F02M, F01N, F02D, G01M, F02P, F01M, F01N, F02B, F02D, F02M, G01M, B01D, B01J, B60, B62D, B60K, B60L, B60R, B60S, B60W, F24D, F03D, F24J, F21L, F21S, F22B, F25B, F03G, B62D, B60C, B60T, B60G, B60K, B60W, F04B, E06B, H01J, H05B, F24D, H01L, H01G, F03D, H02K, B63B, E04H, B60K, B60L, B63H

Source: http://www.wipo.int/classifications/ipc/en/.

For measuring the environmental quality of countries, we use CO_2 emissions data obtained from World Development Indicators[6].

Knowledge spillovers are typically measured as the stock of R&D conducted outside the focal firm and weighted by some measure of closeness between the source and the recipient of the spillovers (Griliches, 1992). We use the Jaffe (1986) measure as a proxy of 'knowledge' spillovers (eq. 1–2). The measure computes the uncentered correlation coefficient between the corresponding technology vectors based on the environmental patents' distribution. It is expressed as:

$$J_{ij} = \frac{\sum_{k=1}^{K} V_{ik} V_{jk}}{\sqrt{\sum_{k=1}^{K} T_{ik}^{2} \sum_{k=1}^{K} T_{jk}^{2}}} \qquad (1)$$

where V_i is the technological vector of the firm i and J_{ij} is the technological proximity between firm i and j. The spillovers weighted stock is expressed as follows:

$$ES_i = \sum_{i \neq j} J_{ij} K_j \qquad (2)$$

with K_j being the R&D capital stock relative to company j (Aldieri & Cincera, 2009; Aldieri et al., 2018).

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[6] Data available from: https://data.worldbank.org/indicator/EN.ATM.CO2E.EG.ZS?end=2014&start=2002&view=chart

The entropy index measures the degree of randomness of the firm's knowledge base. It is based on the probability of co-occurrence of the technological classes of patents within the patent portfolio of the firm (Attaran & Zwick, 1987). Given the probability of co-occurrence p_{jm} of technological classes j and m within the same patent document, the entropy measure (E) is defined as:

$$E = \Sigma\Sigma p_{jm} \log_2 (1/p_{jm}) \qquad (3)$$

This index measures the heterogeneity of the environmental patent classes (reported in Table 1): the higher the index, the higher is the technological diversity in a given firm. Thus, the index is utilized here to test whether technological diversity matters for firms' technical efficiency.

We employ the Environmental Policy Stringency Index (EPSI) as a proxy for the stringency of environmental policy. The index is a country-specific and internationally comparable measure of the stringency of environmental policy. In particular, stringency is defined as the degree of explicit or implicit price laid on polluting or environmentally harmful behavior. The index ranges from 0 (low/no stringency) to six (high stringency) and is based on the degree of stringency (primarily) related to climate and air pollution[7] (Botta & Kozluk, 2014).

The information concerning institutional quality and corporate taxes are taken from the Quality of Government (QoG) database, which provides information concerning six specific aspects of governance (control of corruption, government effectiveness, political stability, regulatory quality, rule of law and voice and accountability). These data are matched with firm-level information using the country's ISO Code[8]. We measure institutional quality through one variable, namely control of corruption, but the results are robust with the other variables in the database[9].

Table 2 defines the variables used in the estimation process, while Table 3 presents the average values of these variables in our sample. In particular, the variables refer to net sales as our dependent variable, while the regressors are distinguished into two types of determinants:

1. Factors related to productivity (Number of employees, Physical capital stock, R&D capital stock, Knowledge spillovers stemming from ES);
2. Factors related to technical efficiency (Technological diversity, Institutional quality based on

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[7] Data are available from: https://stats.oecd.org/Index.aspx?DataSetCode=EPS.

[8] Data are available from: https://qog.pol.gu.se/data/datadownloads.

[9] Results are robust also with other variables measuring government quality: government effectiveness (GE); political stability (PS); rule of law (RL); regulatory quality (RQ); voice and accountability (VA). The results are available from the authors upon request.

the control of corruption variable as reported in QoG, Stringency of environmental policy based on ESPI, Corporate taxes).

Table 2. Variables definitions

Variable	Definition
Y	Net Sales
L	Number of employees
PC	Physical capital stock
K	R&D capital stock
ES	Environmental spillovers, obtained as the weighted sum of R&D in Energy, Water and Land resources fields
E	Entropy index
CC	Control of corruption index
ESI	Environmental Stringency Policy index
T	Corporate taxes

Table 3. Summary statistics

Variable	Mean[a]	Std. Dev.
Y	8.21	2.491
L	8.87	3.172
PC	6.66	2.591
K	6.32	2.156
ES	4.71	3.22
E	0.47	0.317
CC	1.47	0.248
ESI	1.97	1.018
T	2.61	1.355

Note: a) 3039 observations.

4. Empirical framework

Backgrounds: In order to evidence the empirical and theoretical foundation motivating the impact of ES on firms' productivity, we consider a model in line with the environmental economics approach (Perman et al., 2011), where we assume a production function of country *i*:

$$Y_i = f_i\left(L_i, K_i, W_i([R_i], A[\textstyle\sum_j W_j]\right) \quad (4)$$

where L=labor; K_T=capital; W=waste generated from the use of resources R; A=measures the quality of the environment. We can assume the following properties:

$$\delta Y_i/\delta L_i > 0;\ \ \delta Y_i/\delta K_{Ti} > 0;\ \ \delta Y_i/\delta W_i > 0;\ \ \ \delta W_i/\delta R_i > 0;\ \ \ \delta Y_i/\delta A < 0.$$

When firms grow, they commonly use more resources. This leads to higher waste and other negative environmental outputs not only in the country they are produced but potentially also in other countries. For this reason, the environmental quality derives also from other countries' ($\sum_j W_j$) waste and pollution through negative externalities. As described in the previous section, we use CO_2 emissions as a measure of environmental quality (A).

Capital K_T derives from the private (K) and the public sector, i.e. from the institutional context (Z). Hence, we can substitute $K_T=K+Z$ in the previous equation.

Estimation strategy: In this paper, we are interested in investigating the extent to which ES, technological diversity and institutional contexts can affect the productivity of firms in three environmental fields: energy, water and land resources. From eq. (4), we can derive the following function:

$$Y_{j,t} = f(L_i, K, Z_i) \quad (5)$$

where Z indicates other variables (see Section 3) relative to the institutional contexts of economic areas.

For our empirical analysis we are also interested in technical efficiency and, thus, estimate a production frontier that identifies the maximum level of output firms can produce given their current input usage and the state of technology. Formally, a production frontier is defined as:

$$Y^*_{ijt} = f\left(X_{ijt}; \beta\right) exp\left(v_{ijt}\right) \qquad (6)$$

where j's represent countries, t's time and i's industries observations. X_{ijt} identifies the set of production inputs; β is the set of technology coefficients, whilst v_{ijt} is an i.i.d. disturbance term. This term captures the effects of random shocks and is distributed normally, i.e. N (0, ${\sigma_V}^2$). Firms that are in the frontier are considered to be efficient while firms below the frontier are considered to be inefficient. As such, the distance from the frontier is a measure of the firm-level technical inefficiency. The inefficiency terms are usually assumed to be positive and to be half-normally distributed.

We consider that production depends on capital, R&D stocks and labor. Since industries are heterogenous in terms of, for example, their technological diversity, as evidenced by patent citations (Noailly & Shestalova, 2017), our specification includes a number of intercepts, α_i, that take into account this industry heterogeneity. Specifically, we test whether technological diversity (the Entropy index) and the institutional context (institutional quality, stringency of environmental policy and corporate taxes) affect firms' technical efficiency by assuming that they affect the variance of the inefficiency term distribution (Caudill & Ford, 1993):

$$\log(\sigma^2) = \delta_0 + \delta_1 E_{ijt} + \delta_2 CC_{ijt} + \delta_3 ESI_{ijt} + \delta_2 T_{ijt} \quad (7)$$

5. Results

Table 4 presents the estimates of the production frontier and the inefficiency model for each geographical area: USA (col. 1), Japan (col. 2) and Europe (col. 3). The negative coefficients found for some of the variables of interest on technical inefficiency indicate that the variables reduce the productivity dispersion below the frontier. That is, they improve firms' technical efficiency. The positive ones indicate an increased inefficiency in terms of a growing gap between the maximum achievable and realized productivity. In other words, these variables affect firms' productivity through either improving or impairing their technical efficiency.

Table 4. Results

Production frontier Dep. var.: y	(1) USA		(2) Japan		(3) Europe	
L	0.34***	(0.017)	0.38***	(0.037)	0.62***	(0.045)
PC	0.43***	(0.018)	0.24***	(0.028)	0.14***	(0.022)
K	0.17***	(0.022)	0.16***	(0.039)	0.10***	(0.029)
ES	0.07***	(0.007)	0.04***	(0.012)	0.14***	(0.028)
Inefficiency equation. Dep. var.: ln(σ^2_v)						
E	0.36***	(0.112)	-0.50***	(0.169)	-0.86**	(0.367)
CC	1.02	(1.209)	-0.31**	(0.130)	-0.39***	(0.141)
ESI	-0.53***	(0.047)	-0.76***	(0.073)	0.04	(0.048)
T	-0.75	(0.867)	0.94**	(0.440)	0.54***	(0.108)
Obs	1587		971		481	
Log-Likelihood	-2258.27		-1398.18		-744.03	

Notes: Standard errors in parentheses. ***, ** Coefficients significant at 1%, 5%.

The results are clear with regard to ES and firms' productivity in all the investigated economic areas: ES significantly and positively affects firms' productivity. However, the results related to firms' technical efficiency are more dispersed. First, the stochastic frontier regression estimation shows that technological diversity reduces inefficiency for Japanese and European firms but increases inefficiency for American firms. Second, the results related to the control of corruption and stringency of environmental policy point towards either insignificant results or reduced inefficiency. That is, there is more support for the notion that good institutional quality and stringent environmental policy increase the technical efficiency of firms than that they would hamper it. This picture gets reversed in the case of corporate taxes: there is more support for the notion that corporate taxes decrease the technical efficiency of firms than that it would improve it. Table 5 summarizes the findings in terms of the impact of ES on firms' productivity as well as the impacts of E, CC, ESI and T on technical efficiency providing the answers to our research questions.

Table 5. Summary of results: Impact on productivity (ES) and technical efficiency (E, CC, ESI and T)

Country	USA	JAPAN	EUROPE
Environmental spillovers (ES)	(+)	(+)	(+)
Technological diversity (E)	(-)	(+)	(+)
Control of corruption (CC)	NO	(+)	(+)
Stringency of environmental policy (ESI)	(+)	(+)	NO
Corporate taxes (T)	NO	(-)	(-)

6. Discussion

As explained in O'Connor et al. (2018), there is no consensus about the different sources of agglomeration economies. Beyond the pure information-based sources, other market-based sources can produce pressures for dispersion or agglomeration of economic activity and the empirical outcome varies considerably across locations in terms of both impacts. For this reason, we investigated the relationship between technical efficiency and diversity by employing the JRC-IPTS EU R&D investment scoreboards (European Commission, 2017) released each year from 2002 to 2017 for large international firms. Through these data we were able to distinguish the manufacturing from non-manufacturing sectors and measure technological diversity (proxied by the entropy index) within the industry.

The importance of such an investigation is to uncover patterns of economic resilience to "shocks", like the transition from high to less polluting activities, where industrial structures impact positively on other sectors due to entropy. Our results reveal that diversification has a larger impact on the technical efficiency than specialization in Japan and Europe. This implies that Japanese and European firms are best stimulated within a country by promoting a wide breadth of sectors, while the opposite finding is registered for American firms. In order to "speed up" the transition toward more sustainable economic pathways, public interventions must also consider institutional and fiscal features. Indeed, the findings of the analysis evidence that the stringency of environmental policies and the control of corruption improve the technical efficiency, while (higher) corporate taxes depress it. Thus, an important takeaway from this paper for facilitating sustainable development is that, in line with Galloway and Johnson (2016), an increase in the stringency of environmental policy can, in addition to having positive impacts on the environment, lead to technical efficiency enhancements. Moreover, supporting actions for improving institutional quality and tax reductions, will, at the same time, leverage the economic incentives of firms to pursues environmental goals.

7. Conclusions

This paper set out to explore, the rarely studied topic of, the impact of ES on firms' productivity and the effects of technological diversity of the firms as well as institutional quality, corporate taxes and the stringency of environmental policy on large international firms' technical efficiency. The paper focused on the energy, water and land resources fields in three economic areas (Europe, Japan and USA), over the period 2002–2017, via patents related to natural resources use: land use and waste recycling, water pollution abatement and solar, wind and renewable energy. The results, providing the answers to the posed research question, can be summarized as follows:

1) The impact of ES on firms' productivity in the energy, water and land resources fields is positive.
2) The impact of technological diversity (measured with the entropy index) on firms' technical efficiency in the energy, water and land resources fields is positive for Japanese and European but negative for American firms
3) The impact of stringent environmental policy on firm's technical efficiency in the energy, water and land resources fields is positive.
4) The impact of institutional quality on firms' technical efficiency in the energy, water and land resources fields is positive.
5) The impact of corporate taxes on firms' technical efficiency in the energy, water and land resources fields is negative.

The policy implications of the results can be summarized as follows: First, facilitating ES will lead to improvements in firms' productivity. Second, increasing the stringency of environmental policy (in addition to having a positive impact on meeting sustainable development goals), improving institutional quality and lowering corporate taxes, generally, promote firms' technical efficiency. However, the results related to technological diversity warn us that there are no "one-size-fits-all" policies for enhancing firms' technical efficiency (nor productivity). Interestingly the results (a negative impact of technological diversity on technical efficiency for American but a positive impact for European and Japanese firms) coincide with the findings reported by Aldieri et al. (2020b) stating that, whereas American firms produce more (in relative terms) environmental patents, the majority of patents filed by Japanese and European firms can still be considered as "dirty"; that is, linked to non-environmental innovation activities. Integrating this observation to the results presented in this paper would indicate that facilitating technological diversity works in countries, where the majority of innovation are non-environmental, whereas in countries already heavily engaged in green patenting technological specialization (as opposed to diversification) should be promoted. However, further exploration would be required to substantiate these views. Nonetheless, these contrasting results for different economic areas underline that policies need to be designed bearing in mind the institutional and technological contexts of the firms and the environments they are embedded in.

Finally, there are naturally limitations to the approach chosen in this paper. First, the sample used in the analysis refers to large international firms. Thus, the results cannot be generalized for small- and medium sized firms (SMEs). An empirical investigating testing whether our findings hold also for SMEs would be useful in terms of policy implications to evaluate how they deal with the important transition towards less polluting activities, even when their resources are much more limited than the resources of the firms in our sample. Further, our sample is limited to firms based in developed countries. Since factors such as the openness of the economy and the level of in-house R&D affect firms' technical efficiency (see e.g. Sun et al., 1999; Chudnovsky et al., 2006), the results presented here might not hold for developing countries with lower levels of innovativeness and economic openness, meriting further research with data from the Global South. For example, given the technological progress obtained in the Chinese economy (Cai et al., 2018; Cao et al., 2020), we could expect that also Chinese, as do Japanese and European, firms benefit more from industrial strategies promoting diversification rather than specialization. In order to test this hypothesis, the analysis could be replicated with data gathered from the Chinese Patent Office, i.e. China National Intellectual Property Administration (CNIPA). Second, we constructed our variable measuring ES on the basis of the distribution of patent applicants. The analysis could be developed by taking into account the distribution of patent inventors. This would allow exploring the impact of innovator mobility as a channel of knowledge flows. Finally, our measure for ES is symmetric. However, we can assume that firms' market powers are different, so an asymmetric measure, based, for example, on the number of patent citations could be more opportune for further research on the topic.

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