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Eco-innovation, sustainable supply chains and environmental performance in European industries[1]

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ABSTRACT

The introduction and adoption of green technologies are considered the most cost effective way to reduce environmental pressure without compromising economic competitiveness. The scientific literature has emphasized the crucial role played by diffusion pathways of green technologies along the supply value chain, but empirical quantitative findings on the effectiveness of green technologies in improving environmental performance are scarce. The objective of this paper is to highlight the role of inter-sectoral linkages in shaping the influence played by eco-innovations on sectoral environmental performance. Empirical findings show that both the direct and indirect effects of eco-innovations help reducing environmental stress and that the strength of these impacts varies across the value chain depending on the technology adopted and the type of pollutant under scrutiny. The main implications we can deduce are that, first both corporate and policy governance strategies should specifically address the goal of maximizing environmental gains that can be achieved through the development and adoption of clean technologies along the supply chain, and second both strategies should be coordinated in order to minimize the costs for reducing environmental pressures.

1. Introduction

Over the last decade, the policy and scientific communities have devoted increasing attention to the role played by technological innovation in achieving the challenging environmental goals that are currently being debated on the international agenda. The European Union (EU) in particular has been fuelling the debate on green technologies due to continuous improvements in its long term climate and energy strategy. In the specific discussion on mitigation costs in the climate change issue, the development of green technologies has been used as the main argument against the considerable concerns regarding the economic costs of being compliant with stringent regulations. To this end, first, environmental regulation is acknowledged as being capable of stimulating the development and diffusion of new cleaner technologies which represent a major engine for reducing the polluting pressure of human activity. Second, the promotion of eco-innovation (EI) may lead to a win-win situation in which the generation and spread of technologies for improving environmental performance (EP) produce knowledge spillovers that positively affect the international competitiveness of high-tech sectors (EC, 2014; Porter and van der Linde, 1995).

While previous literature closely investigated the inducement effects on EI determined by environmental policies (Cleff and Rennings, 1999; Costantini et al., 2015; Horbach, 2008; Jaffe et al., 2002; among others) and the relevance of regulation-induced EI in driving economic competitiveness (see, for instance, Ambec et al., 2013; Costantini and Crespi, 2008), less attention has been devoted to investigating the actual impact of EI on EP and the mechanisms through which such an effect may take place.

The present paper focuses on the latter issue by arguing that, when studying the environmental impact of the spread of environmental technologies, the role of inter-sectoral linkages in production systems also has to be properly accounted for. On the one hand, inter-sectoral linkages contribute to the process of technology diffusion and foster knowledge spillovers and positive externalities that a firm can gain, for example, due to the innovation

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activities of the supplying industries (Verspagen, 1997; Wolff and Nadiri, 1993). Considering the nature of vertical relationships between firms, the transmission channels through which spillovers can be transferred include all the improvements embodied in the machineries and the inputs purchased from the supplier (Griliches, 1979; Los and Verspagen, 2002) as well as all those related to user-producer interactions (Isaksson et al., 2016). On the other hand, the role of inter-sectoral linkages is not confined to the technological sphere, but can be relevant in enhancing environmental performance as the literature on sustainable supply chains has clearly emphasized. In particular, it has been shown that firms are increasingly trying to incorporate sustainable issues in their corporate strategies (Lozano, 2008; Lozano et al., 2015), with specific attention devoted to the governance choices regarding sustainable supply chains as a crucial factor for achieving environmental goals (Martínez-Jurado and Moyano-Fuentes, 2014; Vezzoli et al., 2015; von Geibler, 2013). Moreover, technological and environmental spillover effects associated with inter-sectoral linkages can be generated both domestically and across countries. In this respect, the growing integration between firms from different countries influences the characteristics and governance of production and distribution systems in such a way that participation in global value chains (GVC) represents not only an opportunity to increase firms' technological and economic performance (Gereffi, 1999; Gereffi and Kaplinsky, 2001; Giuliani et al., 2005; Saliola and Zanfei, 2009), but also a source for enhancing production sustainability by taking advantage of the differentiated and co-evolving environmental constraints and standards across countries, institutions, sectors and agents (Closs et al., 2011; Manning et al., 2012).

Building on this framework of analysis, this paper offers an empirical analysis at the sectoral level based on 27 EU countries in the period 1995–2009 and highlights the role of inter-sectoral linkages in influencing the capacity of eco-innovation to shape sectoral environmental performance, considering both direct and indirect effects. In so doing, we will not only show that at each production stage eco-innovation activities contribute to reducing environmental damage in the sector where it is generated (*direct impact*), but also that they contribute to the improvement of the environmental performance of purchasing sectors via spillover effects activated by inter-sectoral market transactions along the value chain (*indirect impact*). Moreover, both the effects associated with domestic and cross-country inter-sectoral relationships will be considered in the analysis.

The remainder of the paper is organized as follows. Sections 2 and 3 describe, respectively, the background and the methods used for both the construction of the database and the empirical analysis. Section 4 provides a discussion of the empirical results and Section 5 summarizes the main results and discusses their implications in terms of firm level and policy level governance choices regarding sustainable value chains.

2. Background literature and research hypotheses

A large stream of studies analyses the determinants of EI, distinguishing between the influence of public intervention and regulation, market-driven demand and internal strategies driven by environmental management systems (Carrión-Flores et al., 2013; Fischer and Newell, 2008; Kammerer, 2009; Popp, 2006, 2010; Rehfeld et al., 2007; Reinhardt, 1998; Wagner, 2007). On the contrary, the policy and scientific debate has taken almost for granted that the diffusion of eco-innovation is capable of significantly improving environmental performance, whereas less empirical studies have addressed the issue of the effectiveness of eco-innovation in achieving environmental goals. Among them, for example, Lee and Min (2015) examine the impact of green research and development (R&D) investments on environmental and financial performance in Japanese manufacturing firms and show that R&D specifically devoted to supporting EI reduces carbon emissions and increases firms' financial performance. In parallel, Yin et al. (2015) test whether and how institutional and technical factors affect the relationship between economic growth and environmental quality and show that technical progress (measured by R&D expenditures) limits CO2 emission dynamics. Further analyses focusing on the drivers of CO2 emissions account for a number of factors that are likely to determine the emissions level, including innovation. To this end, Cole et al. (2005, 2013) specifically analyse the UK and Japan manufacturing sectors at the firm level and find that environmental innovation, proxied by R&D expenditures, turns out to be a key determinant in the decline of CO2 emissions.

Other contributions focus on the role played by catching up with best available environmental technologies and practices (BAT) in achieving higher EP. Within this line of research, Kortelainen (2008) develops a dynamic framework to analyse eco-efficiency in terms of an environmental performance index (EPI) based on Data Envelopment Analysis (DEA) by applying frontier efficiency techniques. Based on 20 EU countries from 1990 to 2003, an EPI is calculated and the overall changes in EP are further distinguished between changes in the relative eco-efficiency (representing the catching-up effect with BAT) and a shift in the frontier due to environmental technical change, where the latter results to be the main driver of EP improvement. By applying the DEA approach together with directional distance functions,[2] Picazo-Tadeo et al. (2014) confirm that environmental technical change is the most important component in fostering intertemporal EP. Similarly, Beltràn-Esteve and Picazo-Tadeo (2015), when conducting an analysis of the transport industry in 38 countries for the period 1995–2009, draw the same conclusions when considering specific environmental pressures (with some differences between low and high-income countries).

Building on this first set of contributions, we can formulate our first research hypothesis to be tested in the empirical analysis conducted at the sectoral level for EU27 countries.

HP1. *Eco-innovations developed by industrial sectors have a positive direct impact on within sector environmental performance.*

However, the actual strength of new environmental technologies in shaping the reduction of the environmental negative externalities of economic production cannot be fully appreciated without including the role of interconnections between firms, sectors and countries in the analysis. In this respect, the scientific literature is increasingly interested in the acknowledgement of the strategic relevance of the links between sustainability issues and supply chains, leading to the conceptualisation of green supply chains, sustainable value chains and green innovation value chains (Lee and Kim, 2011; Lee et al., 2014; Olson, 2013, 2014; Zhu and Sarkis, 2006). Such analyses show that corporate sustainability strategies go beyond corporate boundaries, by considering the environmental impact of each phase of production from the use of raw materials to manufacturing, distribution, final use and disposal according to a life cycle assessment (LCA) exercise (Kovács, 2008;

[2] The directional distance function, also referred to as *environmental productivity* (Huppes and Ishikawa, 2005), is used to model economic production process with two outputs: the goods or services primarily produced and the associated undesired emissions. It measures the extent to which it is possible to increase the former output (for example, in term of value added) and, at the same time, reduce the polluting emissions while remaining within the feasible combination given the technological possibilities (Picazo-Tadeo et al., 2014).

Mylan et al., 2015), where the production process is addressed from a cradle to the grave approach.

Interactions between suppliers and consumers are also recognized as increasingly affecting environmental, social and economic performance due to their tight connection in sharing responsibility and adopting environmental and social behaviours (Bacallan, 2000; Seuring et al., 2008). Focusing on the supplier side, increasing integration in the supply chain may take the form of a collaborative relation for new product development or technological integration which is also proved to induce a positive improvement in environmental and economic performance (Florida, 1996; Green et al., 2012; Luzzini et al., 2015; Sharfman et al., 2009; Vachon and Klassen, 2006). The inter-sectoral linkages across firms and sectors further contribute to the diffusion of knowledge and technology spillovers in the form of product-embodied knowledge through foreign direct investment but also due to the customer-supplier relationships which foster the adoption and diffusion of environmental technologies and innovation (Hauknes and Knell, 2009; Javorcik, 2004; Florida, 1996; Geffen and Rothenberg, 2000). Another channel through which inter-sectoral linkages help achieve environmental goals is represented by those examples of private global governance, as in global standards and environmental certifications, that are voluntarily adopted by firms to promote sustainability in production processes in firms belonging to different countries and sectors (Cashore et al., 2007; von Geibler et al., 2010; von Geibler, 2013).

With respect to this issues, there are only a few quantitative contributions that address some interesting aspects of EI related to the role played by differently defined linkages among firms, sectors and countries. Among them, Corradini et al. (2014) find that innovation efforts are positively correlated to various spillover effects where R&D innovation expenditures have a positive impact on emissions abatement of other sectors and different reactivity for global and local pollutants. Ghisetti and Quatraro (2014) account for EI in vertical integrated sectors and, by looking at sectoral NAMEA data for the Italian regions, they conclude that EI, measured in terms of patent data in green technologies, as well as spillovers from vertically related sectors, has positive effects on environmental performance. Similarly, Costantini et al. (2013) study the impact of, among others, internal innovation and interregional technological and environmental spillovers in the Italian regions, and find that these latter spillovers effects are more important than sector internal innovation for improving EP. Other contributions highlight the role of international trade flows as a major channel of innovation diffusion in global value chains since trade allows the diffusion of green products and processes in the global market and is also strongly related to the diffusion of EI and its environmental impact along the global value chain (Bi et al., 2015; Costantini and Crespi, 2008; Franco and Marin, 2015; Jiang and Liu, 2015; Tarancón and del Río, 2007).

Following these initial attempts to evaluate the relevance of the mechanisms associated with market transactions across different industries in the supply chain leading to environmental performance improvements, we aim to empirically test the following hypothesis:

HP2. *Eco-innovation activities developed in upstream industries indirectly enhance environmental performance in downstream industries through inter-sectoral market transaction along the supply chain.*

Moreover, by considering the increasing integration of firms along both domestic and global value chains, documented by the flourishing literature that followed the seminal contribution by Gereffi (1994) and the relevance of the co-evolution process of heterogeneous standards adopted by different local and global institutions that is increasingly involving global value chains in converging towards a transnational governance of environmental sustainability (Manning et al., 2012), we also formulate the hypothesis that:

HP3. *Both domestic and foreign inter-sectoral relationships are important channels through which the indirect effects of eco-innovations benefit production sustainability.*

Finally, progress made in the measurement and analysis of eco-innovation clearly shows that this technological domain is characterized by strong within heterogeneity (Kemp and Pearson, 2008; Horbach et al., 2012). On the one hand, while environmental technologies such as end-of-pipe devices are primarily implemented to reduce polluting emissions, it is important to consider all the cleaner production advancements introducing technological, organisational, product and service and green system innovations that increase environmental performance even if initially pursued for economic rationales (Arundel and Kemp, 2009). Thus, the impacts of EI not only include lower energy and material consumption and pollution levels, but also affect the cost of production inputs, the level of production and profits, and the innovation dynamics. Hence, the drivers and potential impact of different types of eco-innovations can significantly differ (Horbach et al., 2012).

On the other hand, relevant specificities also emerge when environmental performance is under scrutiny. As far as an emission-based measure of environmental performance is concerned, this should account for different types of emissions which can be classified according to the natural domain affected by the emissions (e.g., air, water, land and resource use, or environmental functions such as biodiversity, climate stability, etc.) or its scope, given by the local, transnational or global scale of the externalities (Pittel and Rübbelke, 2010). For example, the greenhouse gases (GHG) covered by the Kyoto Protocol include carbon dioxide, methane and nitrous oxide, all of which contribute to the global greenhouse effect, but each one results from different production processes in different economic sectors (burning of fossil fuels, agriculture, industry and transportation). On the contrary, pollutants such as sulphur dioxide (SO2) and nitrous oxides (NOx) are characterized by a localized impact of environmental pollution (Defra, 2006). Therefore, polluting externalities vary both in terms of types of emissions and distribution across sectors, which means that the effect of introducing EI varies according to the local or global dimension of the emissions under scrutiny as well as the sectoral specific characteristics. Accordingly, in the proposed empirical analysis we will account for the role of different types of specific eco-innovations and environmental polluting emissions in shaping the relationships between technological and environmental dynamics.

Summing up, in this contribution we jointly address analysis of the *direct* and *indirect* effects of EI on environmental performance in a systematic way through a large quantitative analysis that considers environmental technologies, different types of environmental pollutants and a wide set of sectors and countries in a relevant time span. In so doing, the analysis proposes a step beyond the state of the art as it tries to integrate different aspects. First, we run a sector-based analysis which allows us to take into account systematic patterns in industries as suggested by the sectoral systems of innovation approach (Malerba, 2002, 2004) in order to consider the performance of industries as a whole and to simultaneously detect inter-sectoral transactions. Second, we distinguish between different environmental technology domains and evaluate their differentiated impact on environmental performance. Third, the proposed analysis considers different types of emissions in order to better grasp the possible differentiated impact of eco-innovation and inter-sectoral linkages on different global or local pollutants associated with different production activities. Finally, we include both domestic and international relationships between sectors in the analysis, allowing us to evaluate the impact of both value chain channels through which eco-innovations may exert their effects on the sustainability of industries.

3. Methods

In order to empirically test the research hypotheses here under scrutiny, some preliminary assumptions need to be described in order to justify the adoption of specific measures on environmental performance and eco-innovation. In particular, three aspects seem to be crucial for the empirical strategy design.

The first aspect to be carefully considered is the coverage in terms of environmental domains selected for the analysis and the analytical form of the performance measure adopted. With respect to the selection and measure of environmental domains, we focus the analysis on environmental negative externalities in the form of polluting emissions associated with supply production activities. This choice allows us to reflect on the role of sustainability management choices in the supply chain that are directly linked to the reduction of negative externalities. On the contrary, by also considering effects related to resource efficiency such as energy or water consumption reduction behaviours, the direct link between innovation and environmental performance may hide supply management decisions required for cost reduction purposes and not only for environmental performance improvement.

With respect to the measurement adopted, it is worth mentioning that by implementing a disaggregated analysis based on manufacturing sectors and distinguished technologies, a suitable match between the environmental performance indicator, the sector under scrutiny and the associated clean technologies must be identified. According to the empirical findings by Beltràn-Esteve and Picazo-Tadeo (2015), when specific sectors are under scrutiny, the adoption of an environmental measure based on specific emission intensity is more suitable for providing robust results. On the contrary, the adoption of a synthetic index as suggested by Kortelainen (2008) with the EPI measure allows overall changes in EP to be detected, losing sectoral details.

Given the HPs under investigation in this paper, it would be inappropriate to adopt an EPI approach in our analysis in which an overall indicator measuring the environmental performance mixes the distinguished dimensions needed for our analysis. The narrower the focus of the analysis is with respect to the anthropic activities under scrutiny, the more specific the environmental measure should be in order to catch the nexus between the activity and the relative environmental pressure produced. Therefore, we provide a detailed representation of environmental pressure by examining several types of polluting emissions related to different environmental pressures and, for each one, we disentangle the effect of specific environmental technological domains.

The second assumption to be adopted refers to the measurement of innovation. Several indicators have been proposed by the economics of innovation literature, including, among others, research and development expenditures and patents (Sirilli, 1999). Given the focus on green technologies and the sector-based environmental performance of this analysis, patent-based innovation measures present greater flexibility and higher availability in terms of sector and country coverage as well as in the final environmental use classification. For our purposes, the use of patent data also appears to be appropriate since they represent a close proxy for (green) product innovations, allowing us to detect their role as strategic inputs from suppliers in enhancing the sustainability of end-use sectors (Archibugi and Pianta, 1996; Crespi and Pianta, 2008; Lee and Kim, 2011).[3]

The EU uses a broad definition of green technologies, based on the OECD classification for environmentally sound technologies (OECD, 2015). This contrasts with an older classification approach, mainly covering traditional end-of-pipe technologies such as water supply and sanitation, waste treatment, air pollution abatement, soil remediation and monitoring techniques. The new approach, now widely accepted, covers cleaner production processes in all industrial sectors, energy-saving techniques and renewable energies, but also new products and services and business methods that have less impact on the environment than their current alternatives. Nonetheless, this new approach also puts the emphasis on a purely defined technological innovation field of analysis since it focuses on improving current technologies and comparing them with existing alternatives. Coherently, in recent years, the EU has adopted a broader concept of eco-innovation in order to cover all forms of innovation, technological and non-technological (i.e. organisational, intangible, or systemic), which aim to reduce the environmental impact of related activities. This evolution in concepts and definitions leads us to consider the classification method adopted for empirical analyses as being of crucial importance. By starting from these different conceptual frameworks, it is first necessary to reflect on what kind of definition is most suitable for the empirical analysis under scrutiny, because a coherent classification of what we would need to include as environmental innovation in the definition adopted must be adopted. Accordingly, besides the general innovation activities, we consider environmental-specific technological innovation, classified according to the OECD indicator of environmental technologies (ENV-Tech indicator) in seven relevant classes:

1. Renewables: Wind energy, solar (thermal and photovoltaic) energy, geothermal energy, marine energy, hydro energy, biofuels, fuel from waste.
2. General Environmental Management: Air pollution abatement, water pollution abatement, waste management, soil remediation, environmental monitoring.
3. Energy Efficiency in Buildings and Lighting: Insulation, heating, lighting.
4. Emission Abatement and Fuel Efficiency in Transportation: Internal combustion engine, electric motor, hybrid propulsion, fuel efficiency-improving vehicle design.
5. Technologies Contributing to Climate Change Mitigation: Capture, storage, sequestration or disposal of GHGs.
6. Technologies with Potential or Indirect Contribution to Emission Mitigation: Energy storage, hydrogen technology, fuel cells.
7. Combustion Technologies with Mitigation Potential: Technologies for improved output efficiency, technologies for improved input efficiency.

Given the alternatives in computing innovation measures based on patent data, we chose to build our indicators by taking patent applications instead of granted patents in order to timely capture the whole innovative effort pursued by production sectors. Indeed, the use of information on patent applications in green technological domains allow the innovative effort to be measured independently of the sole economic market value of the invention activity, thus better shaping the role of sustainable governance of the whole

[3] We acknowledge that there are several limits in the use of patent data that have been extensively discussed in the previous literature (Griliches, 1998; Frietsch and Schmoch, 2006). However, patent data are largely used in innovation studies as a proxy of innovative activities (Johnstone et al., 2010; Popp, 2005) and provide detailed information on technological specialization at the sectoral level.

supply chain in upgrading the innovative content of the production function towards better environmental performance.

The third assumption regards the need to account for the indirect channels that influence environmental performance. For this purpose, we chose to adopt an LCA approach applied to the whole life cycle of the product and the production process adapted to the sectoral dimension available in this analysis. Accordingly, we considered the inter-sectoral upstream and downstream linkages and technological spillovers in an input-output (I-O) approach by selecting the monetary value of the transactions of intermediate inputs across sectors as a measure of these linkages along the value chain. Hence, together with the direct impact of the environmental innovation effort played in each sectoral value chain, we also include the impact on the sectoral environmental performance of the embedded green technological change originated in other sectors in the national and global supply chain (Hekkert et al., 2007).

3.1. The model

By adopting the modelling approach developed by Medlock and Soligo (2001) for the relationship between energy intensity and economic performance as a theoretical starting point, emission intensity may be expressed as a non-constant income elasticity function in its multiplicative form. Additional insights by Cole et al. (2005) suggest that we can express environmental performance as a function not only of the output level, but also of the state of technology and other specific structural fixed effects influencing the statistical unit under investigation. By transforming in logarithm terms the enriched non-constant income elasticity function of environmental intensity, the following linear equation applied to a panel dataset can be econometrically estimated:

$$ln\left(\frac{E_k^c}{L_k^c}\right)_t = a_k + d_c + y_t + \gamma ln\left(\frac{Y_k^c}{L_k^c}\right)_t + \varphi lnTI_{k,t}^c + \psi lnEI_{k,t}^c + \mu lnEIdu_{k,t}^c + \theta lnEIfu_{k,t}^c + \varepsilon_{k,t}^c \quad (1)$$

for each k-*th* sector and c-*th* country at time t. In order to ensure full comparability across sectors, emission (E) and production level (Y) variables are expressed per number of employees (L). In this way, the term $ln\left(\frac{E_k^c}{L_k^c}\right)$ in Eq. (1) represents a measure of the emission intensity that can be interpreted as an inverse measure of environmental performance. As a general remark, the log linearization of the model produces econometrically estimated coefficients that need to be interpreted as elasticities applied to changes in the independent variable under scrutiny in a *ceteris paribus* situation. By taking all the other variables as given, the estimated coefficient of the analysed regressor represents the size of the percentage change in the dependent variable with respect to a one percentage change of the regressor.

There are alternative ways of measuring environmental intensity in an inverse demand function such as Eq. (1). According to Brännlund and Ghalwash (2008), an income-pollution relationship may be investigated by taking an environmental intensity measure based on pollution per unit of consumption in the case of household behaviour. In an analysis of industries, according to Costantini et al. (2013), considering that the production level is a relevant determinant of the emission intensity, by standardizing emissions with the measure of value added the connection with the theoretical inverse demand function provided by the literature would be lost. On the contrary, by adopting a standardization procedure based on the number of employees, according to King and Lenox (2001), the greenness degree of each sector can be represented while explicitly keeping the output variable among the regressors. Moreover, by standardizing emission levels with the employment dimension, the environmental intensity measure can be perfectly compared between different sectors and countries, as clearly suggested by the EPI approach as well.

The term $\ln\left(\frac{Y_k^c}{L_k^c}\right)$ represents the value added per employee, which in turn can be considered as a proxy of the affluence (or labour productivity) at the sectoral level. The terms a_k, d_c and y_t represent sector, country and temporal fixed effects, respectively. Given the research objectives of this paper, technological innovation must be treated according to the different dimensions we are interested in. The influence played by technology on environmental performance is thus specified by distinguishing overall technology ($\ln TI_k^c$) and eco-innovation ($\ln EI_k^c$) as well as domestic ($\ln EIdu_k^c$) and foreign spillovers ($\ln EIfu_k^c$) derived from embedded technology in inputs provided by upstream sectors. In this way, together with the direct effect of global and sector specific technology, we also account for the indirect effect of national and global systems of innovation consistent with a value chain approach. More specifically, in order to analyse the contribution of eco-innovation due to the participation in domestic and global value chains, we include the two terms ($\ln EIdu_k^c$) and ($\ln EIfu_k^c$) interpreted as the green technological content embedded in intermediate inputs used by sector *k-th* deriving from eco-innovations developed by the other *j* sectors (domestically and abroad, respectively).

When domestic upstream innovation is modelled, the green technological content developed by each *j-th* sector influences the environmental performance of the *k-th* sector depending on the share of input *j* on the total amount of intermediate inputs used in the production process of *k*. More formally, we have:

$$EIdu_{k,t}^c = \sum_{j=1}^{J}\left(\frac{I_{j,k,t}^{dom}}{\sum_{j=1}^{J} I_{j,k,t}^{dom+imp}} EI_{j,t}^c\right) \forall j \neq k \quad (2)$$

where the variable $I_{j,k,t}$ represents the amount of input (domestically produced, *dom*, or imported, *imp*) produced in each *j-th* sector that enters in the production process of sector *k* at time *t*. In this way, *ceteris paribus*, the higher the share of the input from sector *j* on the total input mix used by sector *k*, the greater the influence of the embedded green innovation.

When considering foreign upstream spillover effects, we consider the eco-innovation developed in each *j-th* upstream sector in all foreign countries *n*, weighted by the share of inter-sectoral transactions between each pair of sectors (*k*,*j*) wherever the *j-th* sector is geographically located. In formulas:

$$EIfu_{k,t}^c = \sum_{j=1}^{J}\left[\frac{I_{j,k,t}^{imp}}{\sum_{j=1}^{J} I_{j,k,t}^{dom+imp}}\left(\sum_{n=1}^{N} EI_{j,t}^n\right)\right] \forall j \neq k \ \ and \ \ \forall n \neq c \quad (3)$$

It is worth mentioning that in Eq. (3) we lose the bilateral geographical dimension of the inter-sectoral matrix since we are interested in computing the embedded technology from abroad, independently of the origin of the imported input. A further research step for a deeper investigation of international spillovers effects could be to geographically disentangle the origin of foreign upstream eco-innovation, but this is out of the scope of the present analysis.

3.2. The dataset

In order to empirically estimate the model presented in the previous section, different statistical sources have been used.

First, the dependent variable, characterizing environmental performance in terms of emission intensity (tonnes of emissions per employee), has been built using data on different types of polluting emissions from the environmental accounts of the World Input-Output Database (WIOD). WIOD provides a series of socio-economic accounts, environmental accounts and national and world I-O tables, covering 27 EU countries and 13 other major countries in the world for the period from 1995 to 2009 (up to 2011 for socio-economic accounts and world I-O table, not for environmental accounts) at the industry level disaggregated in 35 economic sectors.

Given the focus of our analysis on negative externalities, our panel includes data on four emission types (total GHG, CO2, NOx and SOx) in order to capture different dimensions related to environmental pressures. For this purpose, the computation of the total GHG emission level allows a complex environmental domain to be considered, while single pollutants such as CO2, NOx and SOx may help to better explain sector-specific pressures related to the production chain under scrutiny. It is also worth mentioning that the pollutants considered here may express differences in terms of impact distribution since CO2 emissions are linked to more diffused environmental damage whereas NOx and SOx are more localized.

The countries covered by our panel are the 27 EU member states, while the selected time period is in the range 1995–2007, in order to exclude potential biases deriving from the financial and economic crises. In addition, given the specific focus on the sustainability of value chains with regard to internal environmental performance, we have selected only 14 manufacturing sectors: Food, Beverages and Tobacco; Textiles and Textile Products; Leather, Leather and Footwear; Wood and Products of Wood and Cork; Pulp, Paper, Paper, Printing and Publishing; Coke, Refined Petroleum and Nuclear Fuel; Chemicals and Chemical Products; Rubber and Plastics; Other Non-Metallic Mineral; Basic Metals and Fabricated Metal; Machinery, Nec; Electrical and Optical Equipment; Transport Equipment; Manufacturing, Nec, Recycling. This sector coverage allows us to include major polluting industries on the one hand and also to select those economic branches that are coherent with the patent concordance system needed to assign patents belonging to green technological domains to the relative industry, as explained below.

Accordingly, we have that the manufacturing sectors included in our equations are given by $k \in [1,K]$, with $K = 14$. Considering the cross-country dimension, we have that in our equations $c \in [1,C]$, with $C = 27$. The panel structure is thus given by the three dimensions k, c, t, with a total potential number of observations given by $K \times C \times T = 14 \times 27 \times 13 = 4{,}914$.

As far as the independent variables are considered, we also take value added per employee from the WIOD Socio Economic Accounts, expressed as the ratio between the gross value added at constant prices (in millions USD, base year 1995) and the labour force in terms of number of employees (thousands).

In order to calculate upstream spillovers, from the WIOD Domestic and Import national I-O tables, we also take data on the volume of inter-sectoral monetary transaction (trade flows) in order to build the weights for domestic and foreign upstream innovation, considering that all foreign technologies by sector are weighted equally.

The measurement of the technological dynamics relies on patent application data taken from the OECD REGPAT database that covers all innovation registered to the European Patent Office (EPO). Environmental patents are identified by means of their IPC class, according to the OECD indicator of environmental technologies (ENV-Tech indicator). Considering the increasing complexity of new technologies and the great interaction between different technological areas and different sectors, we choose to use a multiple patent classification. Hence, the eco-innovation technological domains are identified by combining two search strategies and simultaneously following the ENV-Tech IPC-based taxonomy for some technology fields and the CPC Y02 taxonomy (now fully integrated in the OECD ENV-Tech) for climate-related technologies. The ENV-Tech focuses on the definition of environmentally sound technologies (ESTs) which are: "*technologies that have the potential for significantly improved environmental performance relative to other technologies*". Accordingly, the term environmental technology is intended to be a reflection of the public consensus on the usefulness of certain technological innovations in reducing environmental impacts, as compared with available alternatives (it is a dynamic classification that changes over time). On the other hand, the CPC classification (Cooperative Patent classification) is the result of the melting and harmonization process between the European Classification System (ECLA) and the US patent classification (USPC).[4] In particular, the CPC Y02 section "Climate change mitigation technologies" includes technologies related to buildings and appliances; carbon capture and storage; mitigation technologies related to energy production, distribution and transmission; climate change mitigation technologies related to transportation and wastewater treatment or waste management. The environmental patents identified by merging the two search strategies have been divided according to the previously mentioned ENV-Tech Indicator. The seven technological classes, briefly mentioned, are: Renewables, Environmental Management, Energy Efficiency, Transport, Climate Change Mitigation, Emission Mitigation and Combustion Technologies with Mitigation Potential.

Once the patent data have been collected, they have to be assigned to economic activity based on a proper disaggregation level and a concordance system between technology classes and industry classifications. Here, we follow the Schmoch et al. (2003) procedure which, focusing on the manufacturing sector, provides a concordance system between technical (patent classification codes) and industrial fields through a transfer matrix based on the results of an empirical analysis on a large international sample of companies classified by industrial sectors. Accordingly, patents can be assigned to all manufacturing sectors and are allocated to the sector that is more likely to innovate in the specific technology domain of the patent, identified through its IPC class.[5] Patents are subsequently assigned to countries by looking at the nationality of the applicant who will be the actor that is commercially exploiting the invention.[6]

As a final step, for each sector in each country considered, we use the number of patents assigned to calculate the patent stock as a measure of the installed technological capability. Therefore, for the general innovation variable as well as for each eco-innovation domain, we calculate the corresponding patent stock according to the perpetual inventory method with a depreciation rate of 20% (Braun et al., 2010; Coe and Helpman, 1995).[7]

[4] The CPC has been operative at the EPO and United States Patent and Trademark Office (USPTO) offices since 1st January 2013 and replaced ECLA at the EPO as of that date.

[5] For multiple IPC classes for a single patent, the count has been split across different classes.

[6] For patents assigned to multiple applicants from two or more countries, the count has been split according to the share of applicants from a country over the total number of applicants.

[7] See the Appendix for the descriptive statistics of all variables used in the empirical analysis.

3.3. Econometric issues

Our econometric analysis is based on the panel model presented in eq. (1). We test different specifications of the econometric model according to how the technological innovation component is further detailed in terms of general innovative activities or eco-innovation, including or not including upstream spillovers as expressed in eqs. (2)–(3). In all cases, given the richness of the dimensions used, we include industry, country and time fixed effects. These capture unobservable characteristics of countries and sectors and year-specific shocks. Among other things, unobservable characteristics include country-specific regulatory attitudes towards environmental issues, differences across sectors in terms of exposure to regulation, and year-specific shocks that affect all countries and sectors, including EU-wide environmental regulations on selected environmental issues such as climate change policies. All these unobservable features that we partial out were likely to influence both eco-innovation and environmental performance. The inclusion of these fixed effects allows the risk of omitted variables that may bias our estimates to be substantially reduced.

In absence of a proper set of instrumental variables, results should be interpreted as robust conditional correlations rather than causation. In fact, endogeneity issues may arise considering that mitigation policies increasing the stringency of abatement targets also foster innovation efforts that are expected to improve environmental performance (Carrión-Flores and Innes, 2010; Ghisetti and Quatraro, 2014). Hence, when considering the effect of each eco-innovation technology domain, we perform an instrumental variable (IV) estimator, using as instruments the lagged values (in years *t-1* and *t-2*) for each regressor in order to avoid potential endogeneity and other sources of simultaneity bias. The validity of the adopted instrumental variables was tested for all regressions by means of an F-test reported for each estimated model.

4. Empirical results

In order to present interpretable results, we proceed with the econometric estimation by performing a number of steps. We start by considering only the direct effect of environmental innovation (Table 1) accounting for different types of polluting emissions (total GHG, CO2, NOx and SOx) in a very simple econometric framework. In Table 2, we introduce further variables representing the indirect EI effects on the same pollutants, both at the domestic and foreign level. Then, considering CO2 and NOx as examples of diffused and local pollutants, in Tables 3 and 4, we provide a more detailed representation of the direct EI effect disentangling the 7 technological domains classified according to the ENV-Tech Indicator. Finally, in Tables 5 and 6, we also include the indirect effect associated with the aforementioned upstream-embodied technical change.

In Table 1, where we consider both the impact of general innovation activities and environmental-specific technological innovation on environmental performance, the first interesting result we notice is the strong *direct* effect of eco-innovation that reduces emission intensity, whatever pollutant is under scrutiny. It is worth mentioning that in our econometric modelling approach, a negative coefficient associated with innovation means that the pollution

Table 1
Direct linkages between internal EI and EP.

	(1)	(2)	(3)	(4)
	(GHG/L)	(CO2/L)	(NOx/L)	(SOx/L)
Value added per employee (Y/L)	0.381***	0.407***	0.460***	0.264***
	(0.059)	(0.059)	(0.053)	(0.085)
Patent stock (TOT)	−0.054*	−0.070**	−0.074***	0.065
	(0.028)	(0.028)	(0.027)	(0.047)
Patent stock (EI)	−0.077***	−0.081***	−0.054***	−0.082***
	(0.016)	(0.0161)	(0.016)	(0.029)
No. obs.	3869	3869	3869	3869
R-sq.	0.761	0.748	0.684	0.595
F test excl IV	255.5	255.5	255.5	255.5

IV Estimator adopted. Robust standard errors in parentheses. Sector, country and year dummies included.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 2
Drivers of EP by emissions type, including upstream spillovers.

	(1)	(2)	(3)	(4)
	(GHG/L)	(CO2/L)	(NOx/L)	(SOx/L)
Value added per employee (Y/L)	0.405***	0.434***	0.480***	0.298***
	(0.061)	(0.061)	(0.055)	(0.087)
Patent stock (TOT)	−0.049*	−0.064**	−0.071**	0.061
	(0.028)	(0.028)	(0.028)	(0.048)
Patent stock (EI)	−0.054***	−0.057***	−0.024	−0.059**
	(0.016)	(0.016)	(0.016)	(0.029)
Patent stock (EI-DU)	−0.094***	−0.099***	−0.130***	−0.099**
	(0.022)	(0.022)	(0.023)	(0.040)
Patent stock (EI-FU)	−0.100**	−0.093*	−0.235***	−0.322***
	(0.051)	(0.052)	(0.050)	(0.085)
No. obs.	3869	3869	3869	3869
R-sq.	0.763	0.750	0.689	0.599
F test excl IV	38.47	38.47	38.47	38.47

IV Estimator adopted. Robust standard errors in parentheses. Sector, country and year dummies included.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 3
Drivers of EP for CO2 emission intensity, with disentangled EI domains.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Value added per employee (Y/L)	0.400***	0.402***	0.430***	0.414***	0.432***	0.429***	0.406***
	(0.059)	(0.059)	(0.059)	(0.059)	(0.059)	(0.057)	(0.058)
Patent stock (TOT)	−0.078***	−0.073***	−0.073***	−0.062**	−0.084***	−0.046*	−0.077***
	(0.025)	(0.027)	(0.025)	(0.025)	(0.024)	(0.025)	(0.025)
Renewables (EI)	−0.106***						
	(0.013)						
Environ. manag. (EI)		−0.086***					
		(0.016)					
Energy efficiency (EI)			−0.078***				
			(0.012)				
Transport (EI)				−0.107***			
				(0.011)			
Climate change mitig. (EI)					−0.044***		
					(0.015)		
Emission mitigation (EI)						−0.124***	
						(0.013)	
Comb. tech. mitig. pot. (EI)							0.003
							(0.027)
No. obs.	3869	3869	3869	3869	3869	3869	3869
R-sq.	0.748	0.747	0.746	0.749	0.746	0.751	0.749
F test excl IV	321.0	268.2	293.7	314.2	347.0	338.7	386.3

IV Estimator adopted. Robust standard errors in parentheses. Sector, country and year dummies included.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 4
Drivers of EP for NOx emission intensity, with disentangled EI domains.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Value added per employee (Y/L)	0.459***	0.447***	0.472***	0.465***	0.478***	0.477***	0.458***
	(0.053)	(0.053)	(0.052)	(0.053)	(0.052)	(0.052)	(0.053)
Patent stock (TOT)	−0.071***	−0.073***	−0.061**	−0.066***	−0.081***	−0.051**	−0.080***
	(0.025)	(0.026)	(0.025)	(0.024)	(0.024)	(0.025)	(0.024)
Renewables (EI)	−0.068***						
	(0.015)						
Environ. manag. (EI)		−0.082***					
		(0.016)					
Energy efficiency (EI)			−0.063***				
			(0.013)				
Transport (EI)				−0.077***			
				(0.011)			
Climate change mitig. (EI)					−0.072***		
					(0.017)		
Emission mitigation (EI)						−0.105***	
						(0.013)	
Comb. tech. mitig. pot. (EI)							−0.066***
							(0.025)
No. obs.	3869	3869	3869	3869	3869	3869	3869
R-sq.	0.683	0.686	0.684	0.684	0.683	0.687	0.683
F test excl IV	321.0	268.2	293.7	314.2	347.0	338.7	386.3

IV Estimator adopted. Robust standard errors in parentheses. Sector, country and year dummies included.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

intensity is decreasing, thus representing a positive environmental effect.[8]

The coefficients associated with total and EI patent stocks are negative for each pollutant considered. Nonetheless, the variable capturing the general innovation effort is not always associated with emissions reduction since the statistical significance of the estimated coefficient is acceptable only when considering CO2 and NOx emissions. On the contrary, when considering the specific eco-innovation domain, the coefficients turn out to be statistically robust whatever environmental intensity measure is adopted. [9] This result could suggest that in the case of SOx and GHG emissions only specific eco-innovation efforts are capable of improving environmental performance or that the broad eco-innovation variable in these cases partly captures the effect played by general innovation activities.

[8] The effective number of observations used in the econometric estimation is 3,869, while the potential number is 4914. This partial reduction is explained by two factors. First, in order to have the same balanced panel applied to all estimated models (thus providing a full comparability between coefficients in different models), selected observations missing from some sectors in Luxembourg and Romania have been uniformly dropped out. Second, the adoption of a two-stage instrumental variable estimator with instruments represented by one and two-year lags automatically reduces the number of observations for two years uniformly for all sectors and countries.

[9] The F-test for the excluded IV is an indicator of the strength of the instrumental variables in first stage regression. In all specifications, the F-test is well above the rule-of-the-thumb threshold of 10.

Table 5
Drivers of EP for CO2 emission intensity, with specific EI and upstream EI.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Value added per employee (Y/L)	0.401***	0.429***	0.443***	0.422***	0.438***	0.439***	0.396***
	(0.060)	(0.062)	(0.059)	(0.060)	(0.060)	(0.058)	(0.058)
Patent stock (TOT)	−0.077***	−0.065**	−0.060**	−0.050**	−0.079***	−0.043*	−0.063**
	(0.026)	(0.027)	(0.026)	(0.025)	(0.024)	(0.025)	(0.025)
Renewables (EI)	−0.105***						
	(0.014)						
Renewables (EI-DU)	−0.015						
	(0.025)						
Renewables (EI-FU)	−0.042						
	(0.050)						
Environmental manag. (EI)		−0.058***					
		(0.017)					
Environmental manag. (EI-DU)		−0.100***					
		(0.023)					
Environmental manag. (EI-FU)		0.037					
		(0.050)					
Energy efficiency (EI)			−0.080***				
			(0.013)				
Energy efficiency (EI-DU)			0.029				
			(0.023)				
Energy efficiency (EI-FU)			0.167***				
			(0.047)				
Transport (EI)				−0.089***			
				(0.012)			
Transport (EI-DU)				−0.095***			
				(0.023)			
Transport (EI-FU)				−0.094**			
				(0.039)			
Climate change mitig. (EI)					−0.050***		
					(0.016)		
Climate change mitig. (EI-DU)					0.022		
					(0.022)		
Climate change mitig. (EI-FU)					0.101**		
					(0.048)		
Emission mitig. (EI)						−0.116***	
						(0.013)	
Emission mitig. (EI-DU)						−0.044**	
						(0.021)	
Emission mitig. (EI-FU)						−0.008	
						(0.044)	
Comb. tech. with mitig. pot. (EI)							0.020
							(0.027)
Comb. tech. with mitig. pot. (EI-DU)							−0.156***
							(0.028)
Comb. tech. with mitig. pot. (EI-FU)							−0.162***
							(0.041)
No. obs.	3869	3869	3869	3869	3869	3869	3869
R-sq.	0.748	0.749	0.747	0.750	0.747	0.751	0.752
F test excl IV	140.8	35.98	124.0	83.65	171.5	27.28	213.5

IV Estimator adopted. Robust standard errors in parentheses. Sector, country and year dummies included.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Even though the link is statistically strong, the magnitude of the estimated elasticities of environmental performance with respect to the eco-innovation is generally modest, ranging from a minimum of 0.054 (NOx) to a maximum of 0.082 (SOx).[10] This means that an increase in the eco-innovation patent stock of 10 percent will result in a reduction in the SOx (NOx) emission intensity per employee of about 0.82 (0.54) percent. However, to put these numbers into context, we should contrast these small elasticities with overall change in eco-innovation: small sensitivity to large changes would still entail an important role of eco-innovation as a driver of environmental performance. In presence of an overall increase in the eco-innovation patent stock of 89 percent over the period 1997–2007, this would have predicted a great part of the observed reduction in emission intensity. More specifically, the change in the eco-innovation patent stock predicts a reduction in emission intensity of 6.8 percent for GHG (in presence of a total reduction of 8.43 percent over 1997–2007), of 7.2 percent for CO2 (in presence of a substantial stability in CO2 intensity in the period 1997–2007), of 4.8 percent for NOx (in presence of a total reduction of 12.5 percent over 1997–2007) and of 7.3 percent for SOx (in presence of a total reduction of 47.4 percent over 1997–2007).

This first set of results confirms our first hypothesis on the crucial role played by technological change in fostering environmental sustainability and suggests that specific types of innovations, i.e. eco-innovations, have a significant *direct* impact on a reduction in emissions. From an analytical point of view, this implies that when studying the role of innovation activities in green transition, the use of specific indicators gathering information on

[10] We would like to thank one anonymous referee for suggesting us to reflect on this issue.

Table 6
Drivers of EP for NOx emission intensity, including specific EI and upstream spillovers.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Value added per employee (Y/L)	0.456***	0.469***	0.489***	0.474***	0.478***	0.496***	0.445***
	(0.054)	(0.056)	(0.054)	(0.054)	(0.053)	(0.053)	(0.053)
Patent stock (TOT)	−0.074***	−0.074***	−0.0442*	−0.055**	−0.086***	−0.0458*	−0.066***
	(0.025)	(0.026)	(0.025)	(0.025)	(0.024)	(0.025)	(0.024)
Renewables (EI)	−0.065***						
	(0.015)						
Renewables (EI-DU)	−0.041						
	(0.026)						
Renewables (EI-FU)	−0.147***						
	(0.048)						
Environmental manag. (EI)		−0.052***					
		(0.017)					
Environmental manag. (EI-DU)		−0.126***					
		(0.025)					
Environmental manag. (EI-FU)		−0.145***					
		(0.051)					
Energy efficiency (EI)			−0.049***				
			(0.014)				
Energy efficiency (EI-DU)			−0.065***				
			(0.024)				
Energy efficiency (EI-FU)			0.088**				
			(0.044)				
Transport (EI)				−0.055***			
				(0.012)			
Transport (EI-DU)				−0.112***			
				(0.023)			
Transport (EI-FU)				−0.137***			
				(0.040)			
Climate change mitig. (EI)					−0.082***		
					(0.019)		
Climate change mitig. (EI-DU)					0.030		
					(0.028)		
Climate change mitig. (EI-FU)					−0.044		
					(0.048)		
Emission mitig. (EI)						−0.090***	
						(0.013)	
Emission mitig. (EI-DU)						−0.082***	
						(0.022)	
Emission mitig. (EI-FU)						−0.022	
						(0.050)	
Comb. tech. with mitig. pot. (EI)							−0.049*
							(0.025)
Comb. tech. with mitig. pot. (EI-DU)							−0.189***
							(0.027)
Comb. tech. with mitig. pot. (EI-FU)							−0.296***
							(0.041)
No. obs.	3869	3869	3869	3869	3869	3869	3869
R-sq.	0.685	0.690	0.685	0.689	0.683	0.688	0.692
F test excl IV	140.8	35.98	124.0	83.65	171.5	27.28	213.5

IV Estimator adopted. Robust standard errors in parentheses. Sector, country and year dummies included.
$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

the evolution of environmental technologies is important for achieving a correct assessment of the phenomena under scrutiny. Moreover, the provided evidence confirms the idea that it is worth investing in policies capable of inducing eco-innovations and, more generally, in adopting corporate sustainability strategies linked to the development and adoption of green technologies since they represent a major source of environmental gains.

The second step of the empirical analysis consists in evaluating the *indirect* effects of eco-innovation activities played by upstream sectors and embedded indirectly in the sectoral production function via the adoption of intermediate inputs along the supply chain containing environmental technological improvements. In the regression analysis, we are able to test our hypothesis (HP2) concerning the *indirect* role played by eco-innovations in emissions mitigation activated through inter-sectoral market transactions along the supply chain. In particular, we evaluate the effects linked to domestic upstream eco-innovation and associated with green technologies developed by upstream sectors in foreign countries on different environmental domains.

As reported in Table 2, the direct effects played by internal eco-innovation efforts in each sector still move in the direction of improving environmental performance and their strength in reducing environmental pressure is not affected by the introduction of indirect effects in the econometric model with the only exception being NOx pressure.[11] In the latter case, indirect effects appear to prevail on direct ones, however, as will be shown in Table 6, this result is affected by the type of specific eco-innovation

[11] By including the upstream dimensions related to the indirect effects, we introduce a potential source of multicollinearity in the econometric estimation. Accordingly, we computed Condition number and mean VIF tests in order to refuse the hypothesis of multicollinearity. In addition, the optimal lag structure for the innovation-related variables is one year lag according to BIC tests. All results on econometric robustness tests are available upon request from the authors.

domain considered.

Interestingly, the strength of spillover effects linked to upstream sectors' eco-innovation efforts is differentiated across both the domestic and the foreign dimensions considered. On the one hand, green technologies embedded in intermediate goods produced by domestic upstream sectors have an equivalent effect in reducing environmental pressure with respect to the internal eco-innovation. On the other hand, the influence played by foreign clean technologies incorporated in the inputs acquired through the global supply chain appears to be even stronger, especially for those environmental domains characterized by local damage effects such as NOx and SOx. Estimated elasticities for upstream eco-innovations are in general larger than the ones estimated for direct effects. This result, coupled with the very large increase in the stock of upstream eco-innovation patents, 109 and 142 percent for domestic and foreign patent respectively, highlights the important role played by knowledge generated in other sectors as a driver of improved environmental performance.

The positive influence in terms of emissions reduction of domestic and foreign upstream inter-sectoral linkages found in this general model reveals the importance of analysing the whole supply process since the effects exerted by “external” eco-innovation through market transactions along the supply chain may strongly complement the effects associated with “internal” sector-based eco-innovation. Interestingly enough, both the domestic and international indirect channels of propagation of environmental benefits exerted by eco-innovations appear to be relevant and even more relevant in the case of local pollutants when a global value chain approach is adopted, as indicated by the foreign upstream effect. This evidence confirms the hypothesis that the inclusion of supply chain considerations in corporate strategies related to sustainability and the adoption of appropriate governance systems are of paramount importance in achieving environmental goals.

The magnitude of estimated elasticities of environmental performance to upstream eco-innovations is generally larger than for direct eco-innovations. The domestic upstream eco-innovation stock more than doubled over the period 1997–2007 (+118%) while foreign upstream eco-innovation stock more than tripled (+221%) over the same period. The contribution of upstream eco-innovation, especially in its 'foreign' component (both in magnitude of the elasticities and overall growth in our period of reference) is very large. Overall, the observed change in upstream eco-innovation stock (both domestic and foreign) would have predicted a reduction in emission intensity of 33 percent for GHG, 32 percent for CO2, 67 percent for NOx and up to 83 percent for SOx.

The significant differences observed in the magnitude of foreign upstream innovation effects for different environmental pressure measures confirm the importance of carefully considering the specificities of different emission intensities and different environmental-technology domains. In this respect, we proceed in our econometric analysis by focusing on two examples of diffused (CO2) and local (NOx) pollutants and by adding another source of information related to the specific technological content of the eco-innovation stock included in the model. We therefore distinguish between specific technological domains in the general eco-innovation stock measure. Tables 3 and 4 report results on the direct effect of specific types of EI patent stocks on the two selected environmental performance measures.

By considering the *direct* EI impact, it is worth mentioning that the magnitude of the effects on the environmental performance measured for single pollutants strictly depends on the type of eco-innovation developed by the specific sector. In the case of CO2 emissions, results show that environmental performance is influenced by a wide range of eco-innovation domains (Table 3). More specifically, EI appears to play the most effective influence on CO2 intensity reduction in three domains, Renewables, Transport and Emission mitigation, which represent key technological sectors specifically aimed at substantial reduction in CO2 emissions. On the contrary, the impact of EI in the combustion technologies with mitigation potential appears to be negligible since it is mostly related to energy production activities that are not included in the list of industries forming our panel dataset.

In the case of NOx emissions, there is a general positive response with regard to the whole range of technologies, including the case of combustion technologies with mitigation potential. Though interesting, this result is not surprising since this technological domain specifically addresses, mainly through end-of-pipe devices, emissions reduction associated with those industries using fossil fuels in combustion activities in which NOx is a dominant negative externality.

Moreover, the comparison between Tables 3 and 4 allows us to appreciate the difference between the magnitudes of the impact of different clean technologies on the two investigated emission pressure measures. In particular, results suggest that, in the case of CO2 emissions, the coefficients associated with different types of eco-innovations are higher than the case of NOx, for renewables and transport technologies.[12] Hence, we can conclude that a number of different but complementary technological solutions are needed to obtain significant emission reductions in economic production activities. However, in the case of diffused pollution, cross-cutting technologies appear to play a major role while, when local pollutants are considered, *ad hoc* innovations able to act directly in a specific production process are very important.

Finally, in Tables 5 and 6, we include in the analysis the *indirect* impacts on C02 and NOx emissions of different eco-innovation types associated with domestic and foreign inter-sectoral linkages in industrial activities.

With respect to the distinguished environmental domains, it is worth mentioning that the effect of intra-sector eco-innovation remains stable in improving environmental performance. However, the role of domestic and foreign upstream innovation appears to be highly differentiated between the types of pollutant under investigation and across the different eco-innovation specific domains.

When a global pollutant such as CO2 (Table 5) is considered, in two cases, i.e. transport and combustion technologies with mitigation potential, we find a significant impact of both foreign and domestic eco-innovation activities coming from the production linkages with upstream sectors in the supply chains.

Only domestic market transactions across sectors show that they are able to activate eco-innovation indirect effects on reducing C02 intensity in the case of environmental management technologies and emission mitigation technologies. Moreover, the role played by foreign developed innovations in the domains of energy efficiency and climate change mitigation technologies appears to be even detrimental from an environmental point of view, suggesting that in these cases some coordination problems across policies and corporate sustainability strategies may have occurred.

When looking at an example of a local pollutant such as NOx (Table 6), there is evidence of a more widespread role played by the inter-sectoral diffusion of environmental benefits related to the adoption of new green technologies. In almost all technological domains, the indirect environmental benefits of eco-innovations channelled through inter-sectoral transactions along the national and global supply chains are statistically greater in the NOx case than in the CO2 one. Negligible indirect effects at both domestic and international levels are only found when climate change

[12] The difference in coefficients' magnitude is statistically significant at 5% level.

mitigation technologies are considered.[13]

The provided evidence hence confirms the importance of accounting for inter-sectoral linkages in corporate and policy strategies for increasing sustainability. The design of effective governance systems of the supply chain should take care of the coordination of green innovation efforts along the supply chain. Interestingly enough, in the considered cases, the indirect effects related to domestic and foreign upstream spillovers strongly exceed the direct influence played by internal EI efforts.[14] Accordingly, strong coordination across different sources of green innovations may help increase the efficiency of the whole process and thus maximize collective environmental benefits. Taking into account the differences emerging from a separate analysis of global and local pollutants, in the latter case, such considerations appear to be particularly relevant.

5. Conclusions

The empirical results presented in this paper show that eco-innovation is an effective way of favouring the transition to a low-carbon sustainable economy. With respect to previous literature addressing the influence of technological innovation on environmental performance, our analysis contributes by providing systematic quantitative evidence on two channels (*direct* and *indirect*) through which the generation and diffusion of green technologies affect environmental performance. Building on a wide dataset covering a large sample of sectors and countries in a long time span, we find that eco-innovations seem to be capable of directly reducing the environmental impact of production in the sectors where they originate, but also of positively shaping the environmental performance of other sectors via market transactions. Moreover, this indirect channel has been shown to be relevant both in relation to domestic and international industry linkages. Indeed, green technologies developed in upstream sectors both at the national and international level help to foster environmental performance, whatever GHG emissions type is considered. In this respect, sustainable supply chains appear as a key mechanism through which environmental technologies spread throughout the economy and shape environmental performance.

Estimated elasticities of environmental performance with respect to eco-innovation are generally small in magnitude. However, if we put these small numbers into context, also considering the rapid growth in the stock of eco-innovation that we observe of the period 1997–2007, still eco-innovation predicts large decrease in emission intensity, especially the upstream eco-innovation.

These results have implications for firm and policy level choices regarding the system of governance of sustainable supply chains. From the first perspective, the provided econometric evidence suggests that corporate sustainability depends not only on internal capabilities but also on the environmental gains made in the whole supply chain. Hence, an effective governance of sustainable supply chain may help achieving superior environmental performance. More specifically, our results provide indication that corporate governance mechanisms that positively manage inter-firm collaborations in the form of user-producer interactions in the green innovation value chain may favour the exploitation of the environmental benefits of green technologies. Within this context, our empirical findings on positive role of foreign EI spillovers reveal that international linkages turn out to be additional a potential source of environmental gains. Accordingly, specific capabilities are needed for the design and effective implementation of coordinated governance mechanisms that manage the increasing complexity of suppliers' involvement in sustainable production.

From a public policy point of view, our results seem to be relevant since inducing eco-innovation activities in industrial sectors via public policies specifically oriented towards environmental (and climate) protection could represent an effective way of improving environmental performance at the sector level. Mitigation policies are flourishing as a means of contrasting climate change and investment flows in environmental technologies and eco-innovation are key drivers for ensuring compliancy with abatement targets set at the international or domestic level.

Moreover, the provided empirical evidence suggests that specific attention should be paid to including sustainable value chains considerations in the design of a policy mix. In particular, it appears necessary to design policy instruments that are capable of generating appropriate incentives to generate eco-innovations and environmental gains at each stage of the production chain.

Finally, another contribution of our analysis is given by the differences that emerge in terms of the effectiveness of alternative technologies in reducing emission intensity. To some extent, different reactions can be envisaged in environmental performance improvements with respect to the specific technology developed and the pollutant type under scrutiny. For both global and local pollutants, there are potential complementarity effects that should be better investigated in order to reduce the economic costs of innovation thus reducing the risk to disperse precious economic resources that could be implemented in a more fruitful way.

The empirical evidence found in this work is limited with respect to the following main issues that need to be solved by future research efforts. The first one refers to the unit of analysis that is based on aggregated sector level. Further insights could be possible working at the firm level, even though data availability for environmental pressure is scarce. A possible solution is to narrow the focus of the analysis on CO2 emissions at the plant level for the firms involved in the EU Emission Trading Scheme (ETS) where environmental intensity is fully available for the time span covered by the first and second phase of the ETS. This complementary evidence could help overcoming a second limitation of this study, which is related to the exact identification of the magnitude of the effects among the analysed variables. Moreover, further empirical analysis is needed to better investigate and explain the sources of the identified differences between both direct and indirect effects of alternative technologies on emission intensity reduction.

Finally, another shortcoming derives from the inclusion of innovation measures strictly based on the technological content of the production process as represented by the patent analysis. Further investigation should be carried out on the other innovative behaviours at the firm level represented by non-technological managerial innovation such as corporate social responsibility tools and auditing schemes such as the adoption of quality control systems and labelling procedures. These additional elements would help to better disentangle the contribution of each step in the sustainable value chain to improving environmental performance.

[13] The limited information available from our data prevents us to provide a proper interpretation for the identified differentiated effects of inter-sectoral transactions across different technological domains. However, this result could represent an issue to be investigated through a more fine-grained specific analysis.

[14] As evidenced by one anonymous referee we recognise that the changes in R-squared between different model specifications are modest. The R-squared we report in the estimates is dominated by sector, country and year dummies. However, considering the adopted econometric strategy (i.e. using country and sector dummies) we could not compute a pure 'within' R-squared. This means that the R-squared as a measure of fitness of the model may not be very informative in our case. As a robustness check, by running our regressions just including as covariates innovation-related variables (i.e. excluding all sector, year and country dummies as well as labour productivity), R-squared values range between 0.1 and 0.3, depending on the pollutant and the model specification.

Appendix

Table A1
Descriptive statistics

Variable in logarithm	Mean	Median	SD
Employee (L)	3.3601	3.5775	1.8895
Value Added per employee (Y/L)	3.4538	3.6991	1.1467
GHG/L	9.4209	9.1693	1.9396
CO2/L	2.3952	2.1446	1.9425
NOx/L	3.4692	3.2597	1.7037
SOx/L	2.8360	2.8832	2.4863
Patent stock - TOT	2.9064	2.6756	2.8522
Patent stock - EI	0.6403	0.0000	2.2168
Patent stock - EI-DU	−1.1232	−0.8537	3.7038
Patent stock - EI-FU	5.8976	5.9887	0.9797
Renewables	−0.0329	0.0000	1.5283
Renewables - DU	−1.9734	−1.2520	2.8347
Renewables - FU	3.6314	3.7195	1.0367
Env. management	0.3851	0.0000	1.8237
Env. management - DU	−1.6637	−1.2260	3.5242
Env. management - FU	4.6696	4.7794	0.8050
Ener. efficiency	−0.1115	0.0000	1.4513
Ener. efficiency - DU	−2.0333	−0.7382	3.0500
Ener. efficiency - FU	3.8228	3.9433	1.0449
Transport	0.0222	0.0000	1.5992
Transport - DU	−1.8241	−0.9226	3.4433
Transport - FU	4.6641	4.7577	1.1327
CC mitigation	−0.1366	0.0000	0.8850
CC mitigation - DU	−1.7494	0.0000	2.6427
CC mitigation - FU	1.4828	1.5679	0.9090
Emiss. mitigation	−0.0679	0.0000	1.4139
Emiss. mitigation DU	−2.1291	−1.3012	3.0541
Emiss. mitigation FU	4.0056	4.0027	1.2863
Comb. tech. mitig. pot.	−0.1195	0.0000	1.0443
Comb. tech. mitig. pot. - DU	−2.0508	−0.5681	2.9202
Comb. tech. mitig. pot. - FU	2.0616	2.1100	0.9926

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