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A Survey of the Literature on Environmental Innovation Based on Main Path Analysis

Nicolò Barbieri[*], Claudia Ghisetti[†], Marianna Gilli[‡], Giovanni Marin[§] and Francesco Nicolli[**]

Abstract

This paper reviews the literature on environmental innovation (EI) and systematizes it by means of an original methodology identifying the main directions in which the literature on EI has developed over time. In order to do so, two algorithms are adopted and used to analyze a citation network of journal articles and books. The main path analysis reveals that this literature revolves around the following topics: i) determinants of EI; ii) economic effects of EI; iii) environmental effects of EI; and iv) policy inducement in EI. Each of these topics is discussed and implications from the main findings as well as possible future research extensions are outlined.

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Keywords: Environmental Innovations; Green Technologies; Citation Network Analysis; Main Path Analysis.

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1. Introduction

The achievement of strong decoupling between economic growth and environmental degradation crucially depends on technological improvements which reduce environmental pressure from production and consumption (Popp et al., 2010). Differently from other complementary forces which contribute to improved environmental quality – such as structural changes in production and consumption patterns towards cleaner sectors and products or a reduction in the scale of the economy –, technological change aimed at improving environmental quality and at decreasing environmental pressure also reduces the cost of meeting environmental targets for society as a whole. Therefore, environmental technological change may potentially lead to win-win situations in which improvements in environmental quality and economic growth coexist. This potential for win-win outcomes has attracted the attention of policy makers, who have devoted an increasingly larger share of government budget to stimulating the generation and diffusion of environmentally beneficial technologies (EEA, 2014).

So far, a consistent research effort has been made to analyze environmental innovations (EI), interpreted according to one of the widely accepted definitions of the Measuring Eco-Innovation project as "the production, assimilation or exploitation of a product, production process, service or management or business methods that is novel to the firm [or organization] and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives" (Kemp & Pearson, 2007, p.7). Whereas the focus has mostly been on EI, the term eco-innovation can be defined as a sub-class of EI, which happens when innovations improve not only environmental but also economic performance (Ekins, 2010). Given the broad spectrum of contributions in this field, our paper is aimed at systematizing them by providing an original methodology to identify the main paths of development within this strand of the literature and to derive implications in terms of main findings and possible extensions of key emerging themes.

Ours is not the first article which attempts to offer a detailed review of the literature on EI. One of the most comprehensive reviews of this literature is a paper by Popp et al. (2010), in which a thorough analysis of the economics of environmental technological change is proposed. After defining the concept of environmental technological change and the mechanisms behind its functioning, the authors move on to describe the policy implications emerging from a better understanding of said technological change. The literature review by Ambec et al. (2013) also focuses on how environmental regulation affects innovation, but it differs from the work by Popp et al. (2010) since it centres around the argument that well-designed regulation can enhance competitiveness by stimulating the search for new, profitable opportunities through EI. This argument, known as the "Porter Hypothesis" (Porter & Van der Linde, 1995), is explored in Ambec et al. (2013) in both its theoretical foundations and empirical evidence. A discussion and review of the literature on the determinants of environmental technological change is presented by Del Rìo Gonzales (2009). This work combines qualitative and quantitative approaches and it concludes by providing suggestions for future research, to complement different theoretical perspectives and to account for "the interplay between the variables influencing environmental technological change and the interaction between the different stages of this process, including the invention stage" (Del Rìo Gonzales, 2009, p.871). An attempt in this direction is the paper by Cecere et al. (2014), in which the literature on EI is reviewed by using an evolutionary approach and by stressing the role of technological lock-ins and path dependence in order to better understand which barriers prevent the development and uptake of EI. The presence of initial advantages in relation to existing technological trajectories – which are often pollution intensive – can create lock-ins which come at the expense of EI uptake. These lock-ins prevent the uptake of radical innovations like, for instance, those represented by alternative engine technologies, such as electric or fuel cell vehicle technology (Oltra & Saint Jean, 2009). Still focusing on technological EI, the review by Allan et al. (2014) analyzes the last stage of the Schumpeterian innovation process connecting the "invention", "innovation", and "diffusion" phases (Schumpeter, 1942), since it is "through the process of diffusion that the (environmental) benefits of a new technology come to be widely enjoyed" (Allan et al., 2014, p.2).

Starting from these premises, the present contribution has several interrelated purposes, i.e.: i) presenting a broad and up-to-date review which includes academic contributions on the topic of EI; ii) developing and adopting a rigorous methodology in order to identify the main knowledge patterns in EI studies; iii) identifying the main macro themes in this specific field by means of the proposed methodology; and iv) proposing a research agenda based on future extensions and macro themes saturation. The methodology used in this paper builds on the empirical analysis of a citation network for scientific articles. Thanks to the methods proposed by Hummon & Doreian (1989; 1990), it is possible to weight the network based on the importance of its nodes and to identify the most representative sub-networks. This technique, called Main Path Analysis, helps us to define streams of knowledge of particular significance for the development of the literature on EI. Indeed, differently from other surveys, this methodology allows us to select papers regarding main knowledge advances in the field of EI, exploring their distinctive features. However, although this rigorously determines our initial set of articles, we have added other papers which cite those already included, in order to present a valuable and complete survey of knowledge trends in this field.

The structure of the article is as follows. Section two explores how the citation network is built and the methodology used to identify the most relevant papers contributing to the development of the literature on EI. Sections three to six analyze the topics deriving from the main path analysis. Lastly, section seven concludes and summarizes the main findings, while also discussing the need and potential for future contributions and the presence of possible saturation in a field where limited future extensions can be expected.

2. Knowledge advances related to EI

In order to reduce the arbitrariness which often affects these exercises, we identify the knowledge codified in scientific articles and books, upon which our discussion is built, through a combined process based on keyword searches and network analysis. This allows us, on the one hand, to outline a selection of scientific outputs related to EI and, on the other hand, to single out the main knowledge advances characterizing the literature.

Firstly, we conduct a keyword search in the Web of Science (Thomson Reuters - http://thomsonreuters.com/thomson-reuters-web-of-science/, last accessed: November 2014). This database provides up-to-date information on research outputs often used in bibliometric analyses. We then identify relevant documents for our survey by searching the main unstructured items (i.e. title and abstract) for keywords such as ‘environmental innovation’, ‘environmental technologies’, ‘environmentally-friendly technologies’, etc. using different combinations. The result of the search process is a collection of 2,033 articles and books, to which related citing documents are also added. Furthermore, in order to reduce the number of irrelevant items and to exclude those which do not cite any documents within the above sample, we focus on ‘internal’ citations among the documents. That is, following Martinelli & Nomaler (2014), we only include articles and books citing the initial sample of 2,033 items. After cleaning for missing information (some articles do not report the names of the authors, the title, etc.), the final sample comprises 833 items. We then collect the relevant articles and books and build the citation network, in which the documents are the nodes and the citations are the arcs connecting them. The result, shown in Figure 1, is a directed acyclic network with temporal dimension, made of 833 nodes and 2,055 citations among them.

Since the seminal works by Garfield (1955); Garfield et al. (1964); and De Solla Price (1965), citations have been used to detect main scientific advances within a network of scientific papers. Articles in academic journals provide a wealth of information. Among other things, citations play a pivotal role in tracing “prior art” upon which new knowledge is built. In addition, citations highlight the fact that connected articles share common content (Hummon & Doreian, 1989; Hummon &

Doreian, 1990). Following this approach, citation graphs can be used to analyze scientific and technological knowledge advances both synchronically and diachronically (among others: Mina et al., 2007; Consoli & Ramlogan, 2008; Epicoco, 2013; Martinelli & Nomaler, 2014). However, since networks are usually characterized by a complex structure of nodes and links, in a noteworthy study, Hummon & Doreian (1989; 1990) propose three indices to identify main streams of knowledge within directed networks, i.e. the Main Path Analysis.

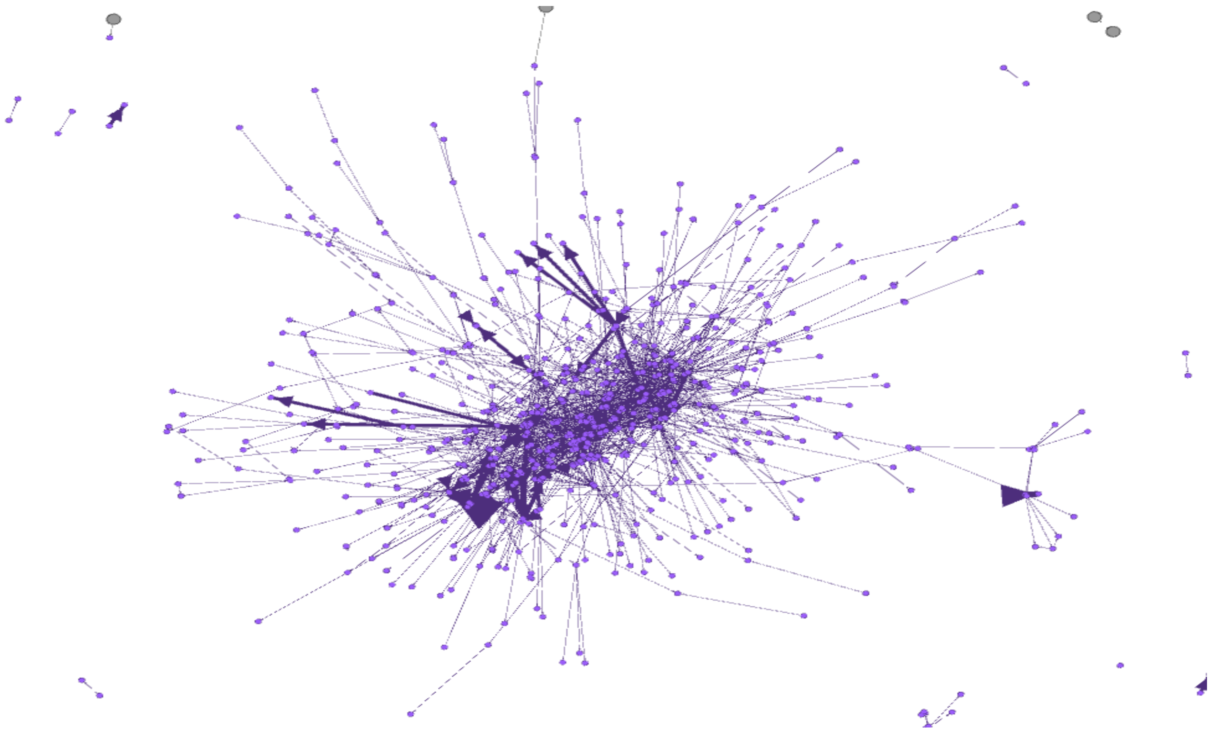
In order to trace the main advances in the literature on EI and to single out the most relevant documents, our survey uses the Critical Path Method (CPM) algorithm implemented in Pajek. Pajek is a software program for the analysis and visualization of large networks, adopted here to extrapolate the main directions along which knowledge trajectories evolve. While the technicalities of this method are detailed elsewhere (Batagelj et al., 2014), here we focus on describing the output generated using this technique. CPM identifies essential sub-networks by computing all the source-sink paths linking each start point to each end point. The former indicates nodes which do not cite any previous nodes but which are cited by following ones. The latter indicates nodes which are not cited by any following nodes but which are linked to previous ones. Then, CPM selects the source-sink path with the largest total sum of weights. The weights are used as a proxy for the importance of the unit/arc within the network. In relation to this, we calculate traversal weights using the Search Path Count (SPC) method (Batagelj, 1991;2003), which measures the importance of the arcs linking the nodes, following Hummon and Doreian’s main path analysis. This is done by counting the number of times a source-sink path passes though an arc, divided by the total number of source-sink paths in the network. That is, the higher the number of times an arc is included in source-sink paths, the greater its weight, and therefore, its importance. The output of this process is a set of articles representing the most important part of the network.

In addition, we propose a second application of the CPM algorithm assuming all nodes/arcs to be equally important, instead of calculating them by means of the SPC algorithm. In this way, we trace the longest source-sink path characterizing the literature on EI, which identifies the backbone structure of the network.

As shown in Figure 2, the most important sub-network detected via the first algorithm, which uses SPC weights to calculate arc importance (red nodes), is also included in the longest path outlined by the second application, which is based on equally weighted arcs (light-grey nodes).

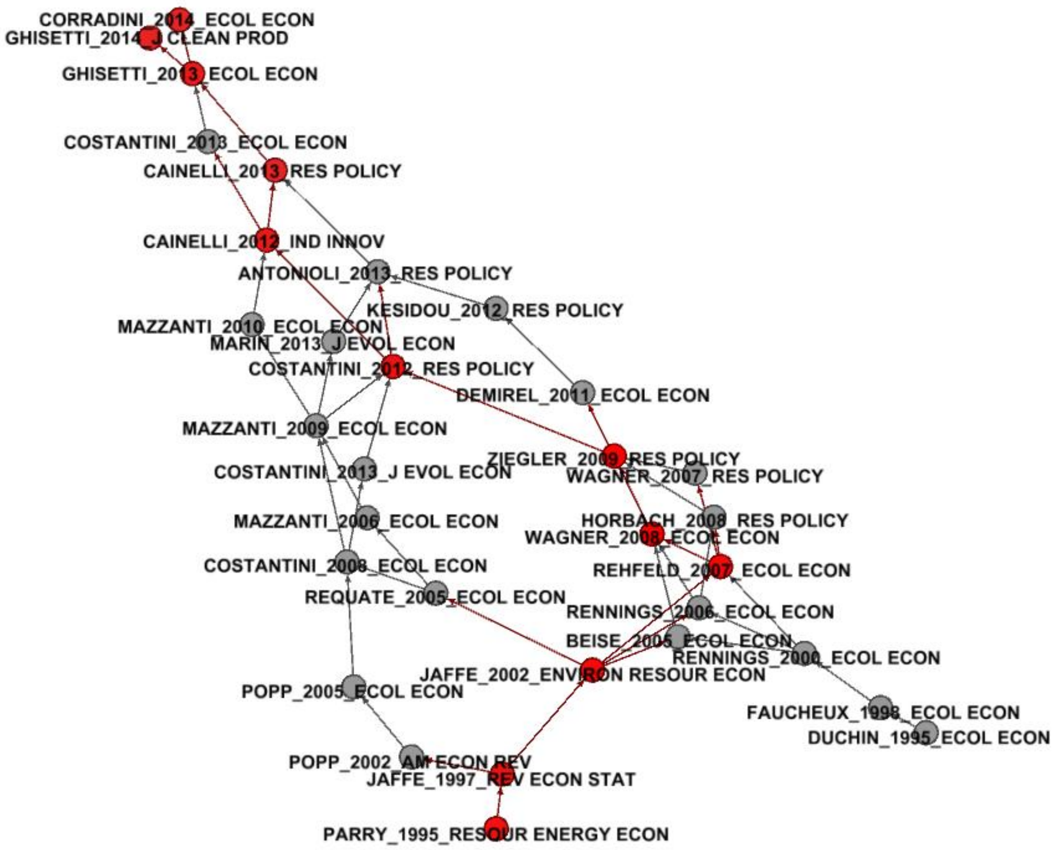
By collecting the documents identified using these two algorithms, we obtain a subset of 32 scientific articles which we adopt as a starting point to investigate how the literature on EI has developed over the last few decades. These articles are listed in Table 1 below. Interestingly, it is possible to detect four sub-topics or branches among these contributions. The first one refers to the drivers of EI, paying particular attention to Environmental Management Systems (EMS). The second stream of articles discusses the economic implications of EI production and adoption. The third topic relates to the effects of innovation on environmental performance, a rather unexplored line of investigation which has been growing in recent years. Finally, the last branch focuses on the inducement effect of environmental policies on EI, exploring the theoretical framework outlined by the Porter Hypothesis. In the following sections of this article we develop our analysis starting from this sub-classification and, in order to provide a more exhaustive discussion of these themes, we also consider some of the citing articles connected to the subset identified through our methodology. By doing so, we expand our sample to include the first set of citations, thus enhancing the value of our analysis but without impacting on its reliability. Indeed, citations represent knowledge links among articles and, thanks to this feature, they can be used to identify documents which share at least some common pieces of knowledge. Finally, for the sake of completeness, other related papers are included in the analysis of the main topics. The following sections discuss these main topics related to EI, focusing on the articles found using this combined process.

Figure 1 – Full network



Source: Own elaboration

Figure 2 – Longest source-sink path detected using the CMP method. In dark-grey the most important path within the whole network, identified by the CMP path with SPC weights.



Source: Own elaboration

Table 1 – Articles included in the main path

Articles	Sub-topics emerged
Demirel & Kesidou (2011) (Cainelli et al. 2012) Cainelli & Mazzanti (2013) Popp (2005) Kesidou & Demirel (2012) Rennings (2000) Rehfeld et al. (2007) Horbach (2008)	Determinants of EI
Wagner (2008) Ziegler & Seijas Nogareda (2009) Rennings et al. (2006) Wagner (2007)	Determinants of EI - EMS
Ghisetti & Rennings (2014) Mazzanti & Zoboli (2009) Faucheux & Nicolaï (1998) Duchin et al. (1995)	Economic effects of EI
Costantini et al. (2013) Marin & Mazzanti (2013) Mazzanti & Montini (2010) Corradini et al. (2014)	Environmental effects of EI
Costantini & Mazzanti (2012) Ghisetti & Quatraro (2013) Antonioli et al. (2013) Beise & Rennings (2005) Jaffe et al. (2002) Costantini & Crespi (2008) Costantini & Crespi (2013) Jaffe & Palmer (1997) Popp (2002) Requate (2005) Mazzanti & Zoboli (2006) Parry (1995)	Policy inducement mechanism

3. Determinants of EI

Environmental innovations (EI) are characterized by a so-called "double externality" (Rennings, 2000), since firstly they reduce the production of negative environmental externalities and secondly they might produce positive knowledge externalities. Indeed, the knowledge featured in these innovations might spill over the boundaries of the firms developing and/or adopting them and be beneficial to other firms. This special nature is the reason why a recent strand of literature has emerged with the purpose of investigating the determinants of EI adoption, i.e. the elements triggering success in EI uptake. Said strand of literature, represented by several contributions along the main path shown in Table 1 above, acknowledges that environmental innovations are not only technological, but also organizational, social, and institutional innovations (Horbach, 2008). Moreover, their understanding greatly benefits from merging multiple disciplines "including evolutionary economics and technological change theories, industrial economics, systems analysis and operations research, sociology and political sciences, actor-network and communication theories, organizational change, and knowledge management" (Del Rìo Gonzales et al, 2010, p. 542).

Consensus has emerged on the relevance of a set of elements which jointly stimulate EI adoption by firms. These can be grouped into four clusters of determinants labelled, respectively, "Market-pull", "Technology-push", "Firm specific factors", and "Regulation" (Horbach, 2008; Horbach et al., 2012). Market conditions, such as expectations of future turnover, previous economic performance, demand for new eco-products, or consumer preferences, have been confirmed to frame the "green" choices of firms. Technological conditions have been found to be as important as market conditions to stimulate EI adoption. They depend mostly on the knowledge-capital endowment of firms – which can be increased through R&D investments or activities – but also on organizational capabilities and organizational innovations. A sub-field of this literature, which proves to be a relevant research sector also in our paper sample, focuses on analyzing environmental management schemes (EMS) and their bidirectional effects on EI, as outlined in Section 3.1 below. The group of drivers defined as "Firm specific factors" includes all those elements, such as size, location, sector, and age, which generally influence – together with other more relevant determinants – a firm's environmental innovativeness. More so than standard innovations, environmental innovations are characterized by the so-called "regulatory (policy) push/pull effect" (Rennings, 2000), since they are mainly regulation driven, and regulation acts bilaterally on both the supply side (push) and the demand side (pull). By changing the relative prices of production factors or by setting new (environmental) standards, existing as well as forthcoming policies induce (environmental) innovations in each of the phases of the Schumpeterian innovation process, from invention to adoption and diffusion (Popp, 2005). Besides this standard inducement mechanism, Ghisetti & Quatraro (2013) detect the presence of corporate socially responsible behaviours by firms, consisting in innovation reactions to worse environmental performance when policy stimulus is weaker. The literature on the so-called "Porter Hypothesis", discussed in section 6, assesses the role and effects of said policy stimulus. Kesidou & Demirel (2012) extend the investigation on the determinants of EI by analyzing the different roles which these clusters of determinants play in the various phases of the innovation process. Market conditions, and in particular demand factors, are found to be key determinants for the initial phase of the (eco-) innovation process, as they significantly affect firm decisions concerning EI uptake.

However, they do not affect the (eco-) investment phase. In other words, market conditions encourage firms to enter the “environmental realm”, but the magnitude of their environmental investments depends on other determinants, specifically cost savings, organizational capabilities, and stricter regulations. The existing literature on the determinants of EI has centred around some or all of these clusters of determinants, with “Firm specific factors” usually acting as indispensable control variables in most studies to date. Nevertheless, these works widely differ not only for what concerns the core determinants under scrutiny, but also in the nature and coverage of their research as well as in the broadness of the concept of EI.

The papers included in our main path investigate the determinants of EI either in empirical terms (e.g. Cainelli et al., 2012; Cainelli & Mazzanti, 2013; Demirel & Kesidou, 2011; Horbach, 2008; Kesidou & Demirel, 2012) or from a theoretical point of view (e.g. Rennings, 2000; Popp, 2005). The analysis is carried out at multiple levels: not only the firm (micro) level (e.g. Horbach, 2008) but also different countries (macro) as well as sectors (meso) (e.g. Corradini et al., 2014). Furthermore, the focus is not only on the manufacturing sector but also on the service sector and its interplay with the former, although no evidence is found of an environmental policy transmission effect from manufacturing to services (Cainelli & Mazzanti, 2013). Another feature which is worth stressing is that the literature on the determinants of EI may examine either a single country, such as Germany (Horbach, 2008), the UK (Demirel & Kesidou, 2011; Kesidou and Demirel, 2012), and Italy (Cainelli et al., 2012; Cainelli & Mazzanti, 2013; Ghisetti & Quatraro, 2013), or multiple countries, such as the EU 15 (Corradini et al., 2014).

Lastly, broader definitions of EI encompassing all kinds of innovations leading to environmental improvements are found alongside studies which adopt more stringent criteria to define innovations. For instance, Demirel & Kesidou (2011) focus on the drivers of different typologies of EI: End-of-Pipe Pollution Control Technologies, Integrated Cleaner Production Technologies, and Environmental R&D. They find confirmation that different types of EI are indeed influenced by different determinants. Horbach et al. (2012) differentiate among twelve innovations depending on their environmental impacts (such as material, energy, air pollution, CO_2, water, soil, waste and other dangerous substances). They then assess the effects of the four clusters of determinants on different types of EI and come to a similar conclusion, i.e. different types of EI are affected by different determinants. More recently, this literature has broadened its scope by investigating the role of determinants which are interactive in nature, such as those stemming from knowledge acquired through cooperation in R&D or interaction with external information partners, suppliers, or knowledge sources, like research centres or universities. Cainelli et al. (2012) analyze the likelihood of EI adoption by firms operating within a local production system, in order to shed light on the role of inter-firm network relationships, agglomeration economies, and internationalization strategies in stimulating EI uptake. Their main findings confirm that cooperating in R&D is a relevant determinant of EI, but the actors with which a firm cooperates do matter as a stimulus for EI. As an extension of this concept, De Marchi & Grandinetti (2013) and De Marchi (2012) show that the knowledge required for EI adoption is far greater than the firms' traditional knowledge base, so that acquiring it from outside the boundaries of the firm – specifically by cooperating in R&D activities – becomes a core determinant of EI. Coherently, not only formalized cooperation in R&D but also strong reliance on external sources of information are relevant determinants of EI (Ghisetti et al., 2015).

A further strand of literature – which is closely related to the one outlined above, since it analyzes EI determinants and cites those included in the main path – focuses on testing the existence of complementarities among environmental and non-environmental innovation activities. Antonioli et al. (2013) study the presence of complementarities between organizational innovation and training and their joint effect on EI, in both non-ETS and ETS sectors (where the effect is stronger). Not surprisingly, such complementarities are not widespread, due to the still limited diffusion of eco-firms in Italy, the country analyzed in their research.

3.1 Environmental Management Systems

Organizational capabilities and practices concerning the environment which may favour the adoption of EI are found at the intersection between the "Technology push" cluster and the one called "Firm specific factors". Organizational capabilities and practices of the "green" type are usually developed contextually with the implementation of an environmental management system (EMS). An EMS represents a formalized change in the organization of a firm that is defined as "a collection of internal efforts at formally articulating environmental goals, making choices that integrate the environment into production decisions, identifying opportunities for pollution (waste) reduction and implementing plans to make continuous improvements in production methods and environmental performance" (Khanna & Anton, 2002, p. 541).

As the papers in our main path are EU-centric, it is worth noting that two main EMS frameworks are widely diffused across EU countries: the European Commission's Eco Management and Audit Scheme (EMAS) and the International Organization for Standardization's ISO 14001 standard.

As mentioned in section 2, a group of papers in our main path revolves around analyzing the linkages existing between organizational innovation, mainly EMS, and EI adoption. Most empirical studies find that the implementation of an EMS favours the adoption of EI (Wagner, 2007; 2008). Rehfeld et al. (2007) test the effects of environmental organizational measures on environmental product innovations in German firms. They conclude that having introduced either an EMAS or an ISO 14001 certification positively influences the adoption of environmental product innovations. Similarly, Wagner (2007) investigates the role played by environmental management systems in inducing EI and identifies a positive and significant effect on process EI, while no effect is found for product EI. This points to the conclusion that the implementation of an EMS stimulates EI, but only when innovations leading to environmental improvements alter production processes rather than firm products. As complementary evidence, Wagner (2008) shows that environmental product innovations are more heavily influenced by other elements than by EMS certifications. In particular, environmental product innovations are affected by market research on green products and eco-labelling instruments which inform consumers about the "green" content of products. Furthermore, the paper by Demirel & Kesidou (2011) introduces, among the determinants of EI, a variable which measures organizational capabilities in terms of the presence of any EMS. The authors find that an EMS can affect end-of-pipe technologies adoption and investment choices in environmental R&D, while no effect is detected on pollution abatement innovations. Lastly, Horbach (2008) controls for the role of an EMS in determining EI and finds a significant and positive effect not only on environmental innovations but also on general innovations.

A peculiarity of this literature is the ways in which an EMS is measured empirically. The more general framework including any organizational changes related to the environment (as in Horbach, 2008 or Rehfeld et al., 2007) is challenged by more detailed approaches in measuring EMS. For instance, Wagner (2007; 2008) constructs an index based on ten EMS elements: written environmental policy, procedure for identification and evaluation of legal requirements, initial environmental review, definition of measurable environmental goals, programme to attain measurable environmental goals, clearly defined responsibilities, environmental training programme, environmental goals are part of a continuous improvement process, separate environmental/health/safety report or environmental statement, and audit system to check environmental programme. Instead, Rennings et al. (2006) choose to focus only on EMAS-certified firms and analyze how different characteristics of the environmental management scheme – mainly, its maturity, its strategic importance, and its learning processes – affect EI adoption. The maturity of the EMS is assessed according to: the age of the EMAS, the existence of double re-validations of the EMAS, prior experience in the organization of environmental protection, and previous ISO 14001 certification. In confirming that an EMS is a key determinant of process EI, the authors also find that environmental process innovations depend in particular on the maturity of the EMS, pointing to the main conclusion that the careful designing of an EMS is crucial in order to stimulate EI.

An extension of this strand of literature is found in Ziegler & Nogareda (2009). They explore the potential reverse causality between EMS and EI to determine whether EMS adoption is a consequence of prior EI adoption. Despite some caveats due to the cross-sectional dataset which does not allow them to control for unobserved firm heterogeneity, the authors find evidence of a bidirectional link between EMS and EI. Overall, we might conclude that environmental innovations are stimulated by the existence of organizational capabilities within the firm, signalled by the presence of EMS certifications. Yet, also the opposite holds true: prior EI makes it easier for firms to decide to obtain an EMS certification. A further relevant extension is developed by Inoue et al. (2013) who, like Rennings et al. (2006), consider not only the mere presence of a certification but also its maturity: the longer a firm has been certified, the more it innovates. Their paper differs from the study by Rennings et al. (2006) in that its focus is on ISO 14001 rather than on EMAS, but, similarly to previous studies, the main conclusion is that firms with greater certification experience, i.e. ISO 14001-certified for a long time, do innovate more, as environmental R&D expenditure significantly increases. The crucial role of an EMS is also confirmed by evidence on small and medium enterprises (Cuerva et al., 2014).

4. Economic effects of EI

Assessing the economic consequences of EI development and adoption is particularly relevant for policy makers. Firstly, it constitutes a crucial component of ex-post evaluation of policies directly or indirectly aimed at stimulating EI. These effects should be considered among the net benefits of policies stimulating EI together with the benefits of reduced environmental externalities. Secondly, understanding the extent to which environmental innovations influence economic performance has important implications linked to the potential use of environmental and more specific EI-inducing policies as tools for industrial policy (e.g. EC, 2014).

Four papers included in the main path deal with the role played by EI in influencing economic performance. The theoretical work by Facheux & Nicolaï (1998) shows that the firms' strategies for the endogenization of technological change (for instance, EI) can give rise to 'win-win' situations. Their examination concludes that new forms of governance are needed in order to pursue ecological-economic sustainability through environmental technological change. In their study on international trade, Duchin et al. (1995) confirm that EI can have positive effects on trade, opening up new markets, even though this does not fully offset the costs of environmental regulation in terms of foregone profits. The paper by Mazzanti & Zoboli (2009) does not specifically refer to EI in its empirical analysis. It explores the connection between economic efficiency (labour productivity) and environmental performance (emission intensity) in several Italian sectors, finding a generally negative relationship between the two measures for a variety of air emissions. However, the section discussing the implications of the results is particularly interesting, as it provides an original conceptual framework which links environmental innovations to their potential for enhancing both economic and environmental performance. The authors point out that environmental technologies and innovations play a crucial role in the joint dynamics of environmental and economic performance. Finally, the article by Ghisetti & Rennings (2014) can be seen as a typical direct empirical assessment of the economic returns deriving from EI. The authors look at the extent to which EI adoption by German firms influences their financial performance, measured in terms of returns on sales (operating revenues from sales). Their econometric analysis, based on two waves of the Mannheim Innovation Panel, determines that, while environmental innovations aimed at improving resource and energy efficiency have a positive influence on financial performance, those aimed at reducing externalities tend to worsen the financial performance of adopting firms.

Besides the articles in the main path, the empirical literature linking EI to differences in economic performance has been growing rapidly in recent years. We group some relevant contributions according to the dimension of economic performance which they consider. The existing literature mostly tries to assess the effects of EI on some financial performance indicators (including measures of firm productivity). Among the citing papers, Lanoie et al. (2011) investigate the full chain of causality from environmental regulatory stringency to environmental and financial performance, identifying EI as the most relevant mediator in this relationship. Evidence based on a sample of about 4,200 facilities from 7 OECD countries shows that environmental R&D has a positive effect on a binary indicator of business performance, even though this does not fully offset the costs of environmental regulation in terms of foregone profits. Marin (2014) examines the effects of environmental innovations (measured in terms of environmental patents) on productivity by analyzing a panel of Italian manufacturing firms. The results, based on a CDM model accounting for simultaneity and endogeneity in the innovation variable, show that the return of environmental patents in terms of productivity is substantially smaller that the return of non-environmental patents. Finally, Cheng et al. (2014) detect a positive relationship between EI (process, product, and organizational EI) and business performance in a sample of Taiwanese firms. They find that the effect of organizational EI is mediated by process and product EI, while the effect of process EI is in turn mediated by product EI.

Some recent contributions also focus on the job creation potential of EI. Horbach (2010) looks at the net employment effect caused by the introduction of new environmental products or services in a sample of German firms belonging to the environmental sector. His findings point to a job creation effect of EI greater in magnitude than the one found for other kinds of innovations. In the same vein, Horbach & Rennings (2013) show that employment growth in German innovative firms is slightly stronger if these firms also introduce material and energy saving innovations, while environmental product innovations and end-of-pipe innovations play no role.

The evidence reviewed so far which looks at international competitiveness, employment, financial performance, and productivity and concerning the potential of EI for stimulating economic performance improvements yields mixed conclusions, also due to the variety of performance measures and empirical approaches adopted.

5. Environmental effects of EI

Research papers about the effects of innovation on environmental performance are still rather scant, both along the main path described in section 2 and in the literature in general. According to Jaffe et al. (2002), technological change is considered pivotal in the achievement of environmental sustainability. However, two considerations can be drawn from the analysis of the papers found along the main path: first, there is no single and common mechanism through which innovation exerts its effect on environmental performance; second, innovation alone is not sufficient to ensure a reduced environmental impact.

Green technological change can affect environmental as well as economic performance by intensifying the effects of other key variables. In relation to this, Mazzanti & Zoboli (2009) look at data for 29 sectors in Italy and 6 pollutants over the 1991-2001 period. Innovation effects are not observed directly but as elements contributing to increased labour productivity (i.e., labour productivity increases thanks to the introduction of new products or processes). In the study by Marin & Mazzanti (2013), which analyzes the relation between the environment and labour productivity in Italy in the years 1990-2007, innovation efforts are proxied including data on R&D. The results show the weak economic relevance of innovation efforts, indicating that it is not yet possible to regard them as drivers of improved environmental performance.

A second channel through which innovation can influence environmental performance is linked to administrative and geographical features. Local governments and regulations as well as local industrial specialization and innovative capabilities act by influencing the decisions of firms in neighbouring territories. Mazzanti & Montini (2010) analyze environmental performance in relation to a set of ten pollutants in Rome and in the region of Lazio, then compare it to the average Italian performance. They find that the regional environmental performance of Lazio tends to be better than the national one. This result is due to structural and economic conditions which make Lazio a less emission- and energy-intensive region in comparison to the national average. However, other factors too play a significant role in promoting emission reduction, like private and public expenditure in R&D and their interaction and, more importantly, technological change. Innovation, in particular, appears to be the predominant factor, assuming even greater importance than environmental policies. Costantini et al. (2013) consider the role of innovation, regional environmental spillovers, and environmental policies and look at the determinants of sectorial environmental performance in Italy. Their results show that innovation spillovers and environmental spillovers can drive regional and sector-specific environmental outcomes. According to the authors, this may indicate the presence of sector agglomerations in restricted areas as well as common innovation patterns within regions (i.e. common choices in the adoption of cleaner or dirtier technologies within certain geographical areas). They conclude that spillovers may play an even greater role than innovation itself in defining environmental performance.

The third and final channel through which innovation affects environmental sustainability is linked to the presence of cross-sectorial spillovers. As underlined by Dopfer (2012), it is at the “meso” (i.e. sector) level that innovations spread more significantly. Therefore, cross-sectorial spillovers may allow innovations to be more widely adopted and, consequently, contribute to increasing potential environmental benefits. Corradini et al. (2014), who investigates the link between environmental protection and innovation, analyze 23 manufacturing branches in the EU 15 from 1995 to 2006. They find a positive relation between investment decisions concerning innovation by one sector and pollution abatement efforts by other sectors. For example, R&D investments in one sector positively react to pollution abatement choices in other sectors. Moreover, the authors underline that, also in this case, environmental spillovers prove to be more important than knowledge spillovers in determining environmental performance.

The review of the papers found along the main path reveals the existence of three main mechanisms through which innovation can affect environmental performance: first, by intensifying the effect of other variables which are relevant to achieve improved environmental outcomes; second, by influencing decisions by agents in neighbouring areas and regions (spatial spillovers); third, by affecting environmental and investment decisions by agents (sectorial spillovers).

As a corollary, we wish to underline that the citing papers provide a limited contribution to the existing literature, tackling the topic only partially. Gilli et al. (2013) describe the joint environmental, economic, and innovation performance of five main European countries, namely Germany, France, Italy, the Netherlands and Sweden, which display different economic and institutional characteristics. The resulting picture highlights two main issues: firstly, there exists a discrepancy among northern and southern European countries in terms of both innovation and environmental performance; secondly, a link between worse environmental performance and more limited adoption of innovation is systematically found, suggesting that innovation can be crucial in the achievement of improved environmental outcomes.

Another area of research explores the interactions or complementarities between different factors at the firm level and their joint effect on environmental performance. Gilli et al. (2014) use a sample of European countries to investigate the existence of integration between the adoption of environmental innovations and other innovation practices (i.e., organizational innovation, product innovation, and process innovation) at the sectorial level. Their results show that complementarities are not always a prevalent factor supporting improved environmental performance, except in the case of the manufacturing sector, which has the ability to best integrate environmental innovation with product innovation.

The analysis of complementary effects triggered by several factors also looks at the integration between the manufacturing and service sectors, based on the idea that innovation adoption in the manufacturing sector induces the introduction of cleaner practices in several branches of the service industry connected to manufacturing. Using a sample of 8,161 Italian firms in the service sector, Cainelli & Mazzanti (2013) find that policies targeting the manufacturing sector are likely to induce innovation adoption in the service sector, especially when considering innovation practices aimed at abating CO_2 emissions and improving energy efficiency.

It is worth considering a few relevant studies which do not emerge directly or indirectly from the main path analysis but primarily focus on investigating the effects of innovation on air pollution. These papers share the idea that the diffusion of innovations makes the adoption of new technologies less expensive for firms, improving overall environmental performance. Wang et al. (2012) analyze the impact of both fossil fuel and carbon-free technological advancements on CO_2 emissions across 30 Chinese provinces between 1997 and 2008. They find that, while dirty technologies do not appear to affect CO_2 levels, green technologies have a significant influence on pollution abatement, particularly in western China. Carrión-Flores & Innes (2010) study the bi-directional link between environmental innovation and air pollution in 127 American manufacturing industries over the 1989-2004 period. Their findings confirm that there is a negative and significant relation in both directions: innovation reduces the cost of meeting pollution targets, while more stringent pollution targets increase the potential cost-saving benefits of environmental R&D, leading to more innovation.

Finally, a recent working paper by Weina et al. (2014) analyzes the relation between CO_2 emissions and green technologies in 95 Italian provinces over the 1990-2010 period. The authors conclude that, although green technologies do not play a significant role in improving environmental outcomes, innovation can improve overall environmental efficiency, measured as the ratio between polluting emissions and value added. Finally, they show that this evidence is consistent across different areas of the country.

6. Policy inducement mechanism

Policy inducement is one of the most consolidated mechanisms described in the literature on environmental innovations, which, starting from the original idea by Porter (1991) and Porter & Van der Linde(1995), postulates that a properly designed policy framework may provide firms with the right incentives to develop new innovations and promote technological change (a recent detailed survey of the Porter Hypothesis can be found in Ambec et al. (2013)). This theory is in contrast with conventional wisdom, dominated by the idea that environmental regulations necessarily increase internal costs for compliant firms and, as a consequence, negatively influence a country’s ability to compete on the international markets (see, among others: Pethig, 1976; McGuire, 1982). Porter and Van der Linde criticize this idea starting from the basic assumption of static technology, typical of traditional studies on environmental regulation and competitiveness. They show that, when shifting to a dynamic context, the loss of competitiveness ascribable to increased compliance costs is partially offset by an increase in innovation performance induced by the regulation. In particular, their 1995 article describes several channels through which this mechanism can act. Firstly, well-designed policies advise companies about possible inefficiencies or better technological options; secondly, they reduce uncertainty regarding innovative abatement activities; and thirdly, they put pressure on firms’ cost functions, thus stimulating cost-saving innovations.

Among the papers in our main path, the seminal contribution by Jaffe & Palmer (1997) further develops this idea, proposing a taxonomy of the different versions of the original Porter Hypothesis which can be adopted in empirical research. The first perspective, known as the “Narrow Porter Hypothesis”, states that only certain types of environmental policies are actually able to stimulate both innovation and overall competitiveness, following the idea that instrument design does matter. A second perspective, also known as “Weak”, postulates that environmental regulatory systems do not have a predetermined effect on competitiveness but always stimulate certain kinds of innovation (which partially offset the loss of competitiveness due to compliance costs). Finally, the last version of the Porter hypothesis, i.e. the “Strong” one, says that efficiency gains due to induced innovation effects are able to completely offset the loss of competitiveness caused by increased marginal costs related to compliance with environmental regulations. In other words, this approach suggests that stringent environmental regulations promote competitiveness across firms and countries.

Two articles included in our main path concentrate specifically on the “Narrow” version. Requate (2005), in particular, presents a review of the existing literature on the effects of different policy designs on innovation performance. The main conclusion is that, under competitive conditions, instruments which provide incentives through the price mechanism usually perform better than command and control policies, since they give firms more freedom to find the best technological solutions to minimize compliance costs and they also provide continuous innovation stimulus. On the contrary, in the case of imperfect market conditions, policy conclusions are less clear-cut. Moreover, the survey presents a ranking of different policy options based on the existing literature, showing, for instance, that under competitive conditions there is no difference between auctioning permits and grandfathering. Finally, the main literature surveyed in Requate’s paper confirms that, in case of myopic environmental policies or long-term commitment to the level of policy instruments, emission taxes are more effective than allowances in inducing innovation, because permit prices fall after the diffusion of a new technology, providing a weak incentive for firms to invest in further abatement technologies. These results are in line with the original predictions by Porter and Van der Linde, who argue that command and control instruments are able to induce innovation only if they have some particular characteristics: 1) they must not force firms to adopt a specific (best) technology; 2) the stringency of the instruments must increase continuously; and 3) the regulatory process must be certain and consistent over time. A more recent paper by Costantini & Crespi (2013) tackles the narrow hypothesis from a broader perspective, showing that, also in the case of the energy policy mix, efficient design does indeed matter and an incoherent policy portfolio may actually have negative effects on the development and diffusion of environmentally-friendly technologies. On the contrary, when environmental policies are efficiently supported by technology policies, which help firms to respond to changes in external constraints, environmental regulation may positively affect international competitiveness in the export of energy technologies, providing evidence of the relevance of a narrow Porter-like effect.

The “Weak” hypothesis is probably the version that has been more thoroughly investigated by the academic literature – a tendency confirmed by the presence of three papers in our main path. These works study the phenomenon from different perspectives: two of them focus on the meso level and the third one on the micro level. The citing papers also include several empirical macro analyses. The above-mentioned contribution by Jaffe & Palmer (1997), for instance, is based on a panel of U.S. manufacturing industries over the 1973-1991 period. Their analysis finds evidence supporting the weak Porter hypothesis when using R&D expenditure as a proxy for innovation activities, while no effect is found when considering total patents (the choice of using total patents rather than green patents is the most criticized aspect of this work and is supposed to be the cause of the non-significant effect). The second article in our sample adopting a meso approach, Popp (2002), studies the standard inducement mechanism using data on the U.S. energy market from 1970 to 1994. It confirms that both energy prices and the quality of the stock of knowledge exert a significant and positive effect on patenting. Among the citing papers, for instance, Brunnermeier & Cohen (2003) detect a significant impact of pollution abatement expenditure and a non-significant effect of the number of air and water pollution inspections on the number of green patent applications in a dataset covering 146 U.S. manufacturing industries at the three-digit SIC level from 1983 to 1992. In a more recent work, Mazzanti et al. (2014) study EU sectors in 2006-2008 and find that, on the one hand, more regulated sectors are more likely to adopt CO_2-reducing innovations and, on the other hand, inter-sector integration and knowledge sources matter, meaning that sectors with more emission-intensive upstream 'partners' innovate more to reduce their CO_2 footprint. Moving on to the micro perspective, Popp (2003) finds a positive effect of the tradable permit scheme for Sulphur Dioxide on environmental innovation in a sample of 186 U.S. plants over the years 1972-1997. In addition, Mazzanti & Zoboli (2006) analyze the innovation inducement mechanism of the EU End-of-Life Vehicles (ELVs) Directive. Their paper shows that the effects of economic instruments 'in systemic and dynamic settings critically depend on where, along the "production chain", and how, in terms of net cost allocation, the incentive is introduced' (Mazzanti & Zoboli, 2006, p.334). The authors highlight that the effectiveness of economic instruments (in this case, free take-back of ELVs) in achieving policy objectives, and therefore in creating innovation and innovation paths in complex industrial system, depends on inter-industry incentive transmission. In other words, incentives provided by the economic instrument may be transmitted from an industry which has received them to upstream or downstream industries along the production chain. The final effectiveness of the instrument builds upon the ability of innovations to create self-sustaining markets.

Finally, two of the most commonly cited cross-country studies are by De Vries & Withagen (2005) and Johnstone et al. (2010). The former finds some evidence of the weak version of the Porter hypothesis by studying the effects of SO_2 environmental regulation on national patent counts in related technological classes. The latter finds generally strong evidence of a policy inducement mechanism in the renewable energy sector. Interestingly, the paper by Johnstone et al. (2010) concludes that different instruments have heterogeneous inducement effects on different renewable energy technologies, depending on their degree of technological maturity, a result which is strictly linked to the narrow version of the Porter Hypothesis. In a more recent paper, Nesta et al. (2014) extend the work by Johnstone et al. (2010) by accounting for the possible simultaneity bias of the innovation-policy relationship, an issue often overlooked in previous empirical studies. They also show that the inducement effect of renewable energy policies is stronger when applied to competitive markets.

Finally, the “Strong” version of the Porter Hypothesis tests whether there is a link between environmental regulation and firm competitiveness. This research question has been the starting point of the entire inducement debate, and a good survey of early contributions can be found in Jaffe & Stavins (1995), in which most of the papers considered point to a negative effect of environmental regulation on productivity. The research articles in our main path, however, reject this early evidence, confirming the presence of a Porter-like mechanism. Furthermore, they all focus on the macro level. Costantini & Mazzanti (2012) apply a gravity model to the EU 15, considering the years 1996-2007. They find that environmental policies do not seem detrimental to export competitiveness and, specifically, some energy tax policies positively influence trade patterns. Expanding on standard lead market models, Beise & Rennings (2005) show that, under certain conditions (increasing global demand and regulatory support), environmental regulation can incentivize the development of market opportunities in foreign countries, due to a first mover advantage linked to the development of policy induced eco-efficient innovations. Similarly, Costantini & Crespi (2008) adopt a gravity model for trade and conclude that environmental regulation represents a significant source of comparative advantages, due to its positive effect on innovation. Moving on to the citing papers, some complementary evidence can be found at the meso level. Berman & Bui (2001) and Alpay et al. (2002) study refineries in the Los Angeles area and food processing industries in Mexico respectively, and find evidence of the strong version of the Porter hypothesis. In their study on 17 Quebec manufacturing sectors, Lanoie et al. (2008) detect a modest but significant effect of regulation on competitiveness once the dynamics of the process (i.e. lag of regulation) are taken into account.

7. Discussion, further developments, and conclusions

Drawing a single conclusion for such a vast research field is certainly no easy task. If we keep to our division of contributions among sub-tasks, several different remarks can be made. Firstly, the “determinants of EI” and “inducement mechanism” sub-fields have a long tradition in academic research, which is reflected by the large number of available contributions and by coherent and robust evidence in the literature. On the other hand, the “environmental effects” field is still in the early stages of development, with several open lines of research. Similarly, the literature on “economic effects” can be expanded in numerous ways. We believe it important to mention here some possible future directions of research.

For what concerns environmental effects, if the contributions summarized in section 5 are considered, it is evident that they mostly focus on the regional level, with the majority being based on a single-country case study. Although these works highlight some interesting mechanisms through which EI can influence environmental quality, similar studies at the cross-country level (i.e. European Union or OECD) are potentially of far greater interest, in view of the heterogeneous economic and institutional conditions as well as varying degrees of environmental responsibility awareness which can be analyzed using longitudinal data. In addition, papers studying non-OECD countries are also extremely limited in number. A possible reason for the lack of European and worldwide investigations might be the scarcity of adequate and relevant data. A second point emerging from our research is the absence of a framework of reference, probably because of the relative novelty of this research strand in the literature. Moreover, most of the articles presented in this section use an indicator of environmental productivity (computed as the ratio of value added to CO_2 or other polluting emissions, Repetto (1990)) which is informative from an economic point of view but, from a mere environmental perspective, it is more relevant to study total CO_2 (or other emissions). Variations in the environmental productivity indicator may in fact be due to changes in value added rather than changes in emission. A third and final remark is that papers in this field often consider only the sectorial level of analysis. This is certainly the most appropriate dimension for these studies because of its importance in the diffusion of innovation. Nevertheless, efforts should be directed, on the one hand, at firm-level analyses to better understand the microeconomic dynamics leading to the achievement of better environmental outcomes and, on the other hand, at country-level investigations, which would shed light on the macroeconomic dynamics driving aggregate environmental performance.

A second strand of literature with potentially interesting extensions is the one regarding economic effects, in which many theoretical and empirical issues remain open to further investigation. The first issue concerns the dimensions of economic performance to be analyzed. While many papers deal with measures of financial performance and productivity, little evidence is currently available about the job creation potential of EI and, to the best of our knowledge, no evidence is available about international competitiveness investigated at the micro level. Other open lines of research regard methodological advances which may improve the understanding of the link between EI and economic performance. One of the most promising lines of research tries to provide a joint assessment of the full link of causality among environmental regulation, EI, and economic performance (e.g. Lanoie et al., 2011; van Leewen & Mohen, 2013). The combination of these three dimensions allows scholars to draw on the theoretical and methodological advances achieved by two parallel strands of literature, i.e. the one looking at the drivers of EI and the one looking at the effects of EI. It should be noted, however, that these approaches require fairly complex modelling efforts and detailed data on regulatory stringency, innovation, and performance. Finally, while firm-level empirical analyses are crucial to identify causal links between EI and economic performance, little effort has been made to evaluate how EI affects players (e.g. firms, workers, etc) not developing or adopting EI and, more generally, the overall equilibrium effects of EI. This kind of evidence is important to identify winners and losers in EI development and adoption as well as the distributional impact of EI.

Regarding employment, a growing stream of literature follows Horbach (2010) and Horbach and Rennings (2013) in looking at the net job creation of EI (Gagliardi et al., 2014; Licht & Peters, 2013; 2014). Yet, evidence is absent on gross job creation and job destruction – particularly relevant due to the asymmetry between the social costs of destroying existing jobs and the social benefits of creating new jobs – and on the types of jobs created and destroyed by EI. The recent discussion on green jobs (ILO, 2013; OECD, 2014) shows that jobs created by environmental technologies are not necessarily high-wage and highly-skilled jobs. Moreover, besides differentials in work conditions and earnings in jobs induced by EI, differences in required skills need to be assessed, with the aim of identifying potential skill gaps to be filled through education and training. Further theoretical and empirical analysis is needed in this regard to provide policy makers with appropriate guidance. For what concerns international competitiveness and trade, the increasingly popular analyses at the macro and sectorial level (e.g. Costantini and Mazzanti 2012) have not yet been complemented by firm-level investigations. Micro-level analyses are especially significant to obtain more robust evidence on the causal links between EI and competitiveness – which may be influenced by various confusing factors in more aggregate studies – and, more importantly, to understand the mechanisms through which environmental innovations affect competitiveness. To name but a few, we may think of the distinction between intensive and extensive margins of exporting firms or the assessment of the relationship between EI and distribution of partner countries and competitors, which can assist policy makers in the fields of trade regulation and industrial policy.

As for the remaining sub-fields, i.e. policy inducement mechanism and determinants of EI, there is much less room for further research, since the debate has reached a certain level of maturity, at least in the empirical analysis. Nevertheless, as already underlined by Jaffe et al. (2002), the complex mechanisms linking technological change, EI, environmental policies, and climate change "cannot be resolved at a purely theoretical level or on the basis of aggregate empirical analysis alone", but require detailed investigation in order to truly understand sectorial differences and circumstances which can influence the scale of these effects and not only lead to their potential presence. According to Jaffe et al. (2002), this is feasible only by increasing research efforts from multiple, extended points of view. In conclusion, we believe that the literature can indeed be expanded in this direction, enriching the existing debate with more qualitative evidence from case study research or other approaches.

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