Journal of Cleaner Production 444 (2024) 141180

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Do global value chains spread knowledge and pollution? evidence from EU regions

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ARTICLE INFO

Handling editor: Jian Zuo

JEL classification:
R11
F18
O33
Q53

Keywords:
Global value chains
Green technologies
Emissions
EU regions
Pollution haven hypothesis

ABSTRACT

In this paper we investigate the relationship between participation in global value chains and the environment from a spatial perspective. By drawing on an original dataset on global value chain participation, emissions of nitrogen oxides and sulphur oxides, and green patents for European regions, we present novel evidence about the relationship between global value chains, green technologies and air pollution at the regional level. Our findings suggest that although participation in global value chains may lead to lower polluting emissions, this effect largely depends on the capacity of regions to exploit the green knowledge deriving from participation and on the specific form of participation. When European regions are integrated with backward linkages (i.e., importing inputs to produce exports) they record lower levels of air pollution; conversely, participation through forward linkages (i.e., exporting inputs for other places' exports) leads to an increase in air pollution. Backward participation also come out to support the development of green technologies that mediate the effects of global value chains on the environment posited by the "Pollution Haven" hypothesis. Overall, the relationship between global value chains participation and air pollution will depend on the type of participation and on the capacity of territories to profit it for the development of green technologies.

1. Introduction

The last three decades have been characterized by an increasing delocalization of production's phases across countries, seeking to pursue better opportunities through enhanced specialization and the use of local production factors. This process led to the configuration of geographically fragmented and functionally integrated chains of production and trade, also known as Global Value Chains (GVCs), in which firms and industries from different countries contribute to the production of final goods and services (Gereffi and Korzeniewicz, 1994).

In this work, we focus on the relation between GVCs and the environment by considering the development of green technologies and the emission of pollutants in EU regions in the aftermath of the adoption of the Gothenburg protocol. The Gothenburg protocol was adopted in 1999 to abate acidification, eutrophication and ground-level ozone, setting emissions ceilings for sulphur oxides (Sox), nitrogen oxides (NOx), volatile organic compounds and ammonia to be met by 2010. The reduction of local emissions could be the result of two possible mechanisms. On the one hand, green technological development could reduce local emissions; on the other, economies could exploit GVCs and international trade to shift polluting activities to third locations, in less-advanced areas. In the latter case, the reduction of local emissions can end-up with a zero-sum game or even with an overall increase of emissions at the global level (Copeland and Taylor, 1995).

The so-called "Pollution Haven Hypothesis" (PHH) frames out this process, according to which the participation in GVCs would lead advanced economies to improve their environmental footprint at the detriment of less-advanced economies, whose prevailing interest would be instead capital accumulation and economic development (Duan et al., 2021). Indeed, recent empirical contributions support the existence of a significant relationship between the participation in GVCs and the reduction of pollutants emissions (Qian et al., 2022), entailing spillovers across countries (Zhu et al., 2022).

However, participation in GVCs may also play an important role in the dissemination of knowledge across economies, facilitating the development and adoption of new technologies. Firms and territories do

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https://doi.org/10.1016/j.jclepro.2024.141180
Received 9 September 2023; Received in revised form 15 January 2024; Accepted 7 February 2024

not only trade components and parts but also share information and knowledge, which can eventually benefit less advanced areas bounded to source technology internationally (Morrison et al., 2008; Pietrobelli, 2022). In this sense, knowledge flows within the value chain may also support the development of local innovation systems, helping economies to upgrade and become more competitive (Jurowetzki et al., 2018).

Although a large body of studies on the geography of GVCs has been carried out at the country level, GVCs powerfully interact with the local economies (Pietrobelli and Rabellotti, 2007). The international fragmentation of production is accompanied by geographical agglomeration of production in specific regions within countries (Tselios and Stathakis, 2020). Indeed, the characteristics of regional innovation and production systems matter in determining participation and positioning in GVC, favouring the agglomeration of activities in contiguous areas (Bolea et al., 2022). Such processes of fragmentation and agglomeration often imply remarkable international knowledge flows that are likely to be especially relevant for the development of green\clean technologies, which rely on the combination of more diverse and novel technological components (Barbieri et al., 2020). The development and diffusion of green technologies through inter-sectoral linkages along value chains has been shown to contribute to improve regions' environmental performance (Costantini et al., 2017).

In this work, we contribute to the growing literature on GVCs at the regional level (Chen and Jia, 2017) by exploring the relationship between GVCs and the environment in EU regions (NUTS-2). We look at the two-sided role of GVCs for production and knowledge, considering the extent to which GVCs are associated to lower emissions and to a higher degree of "green" technological development. Our estimation framework considers that GVCs participation can have a direct effect on the reduction of regional emissions, but also an indirect effect through an enhanced capacity to develop green technologies, which in turn lead to further emission reductions. In addition, such processes of green technologies creation and dissemination appear to be influenced also by geographical spillovers, that we analyse in this paper. Evidence on this latter phenomenon is still very limited and mainly related to innovation activities in general (Moreno et al., 2006).

The analysis is performed on an original dataset on air pollution, GVCs, and patent data for EU regions over 2000–2010, the period interested by the provisions of the Gothenburg protocol. Regional GVC participation considers exchanges in intermediate good and services both between EU regions and between EU regions and main trade partner countries outside the EU. Our evidence shows that the positive relationship between GVCs and pollution reduction is confirmed only when considering backward participation (i.e. importing inputs to produce exports), while forward participation (i.e. exporting inputs for other places' exports) appears to be linked to higher emissions. Moreover, given that it is only backward GVC participation that favours the development of green technologies, it could play a dual role here: on the one hand, signalling a PHH (i.e. offshoring pollution to other places); on the other hand, fostering the development of green technologies, thereby creating a "technological heaven" in the region. In sum, the final effect of GVC participation on pollution will depend on whether the haven or the heaven effects prevail. Additionally, we use spatial analysis to show that backward GVC participation generates spillovers among EU regions, which further contribute to lowering pollution emissions.

The article is organized as follows. In the next section, we discuss previous literature and present the research questions. In section 3, we present the dataset, the methodology used for the construction of our main variables and our estimation framework. The results are presented in section 4, and section 5 concludes by drawing some implications of our analysis.

2. The relation between GVCs, green technologies and air pollution

For years environmental and business goals have been seen as incompatible. Being green was largely seen as a cost of doing business with potential negative effects on firm-competitiveness, thus limiting firms investments in environmentally friendly production processes (Porter, 2011). The removal of trade barriers would further reduce the incentive to adopt green practices due to the option of delocalizing the most polluting activities to less developed countries, where environmental regulations are typically less stringent. This would possibly lead to global environmental degradation (Dean, 1992).

The Brundtland Report (WCED, 1987) introduced environmental concerns into the political development sphere, starting a rethinking of production models. Being green was no longer perceived only as a cost but also as a catalyst for innovation and wealth creation (Walley and Whitehead, 1994). Nowadays, environmentally friendly production processes are increasingly seen as an opportunity, because by addressing issues related to climate change, they allow also to build new competitive advantages (Hermundsdottir and Aspelund, 2021). Environmental upgrading trajectories may be favored by the inter-firm relationships generated along value chains (De Marchi et al., 2013). Indeed, GVCs integration may offer not only access to new markets and new customers, but also to new green technologies and competences. Moreover, a firm reputation may also be enhanced by this greening process and stimulate the emulation by others (Poulsen et al., 2018).

Studies on GVCs mostly focus on the micro (firms) or macro (countries) level. However, economic activities are unevenly distributed within countries, which makes it relevant to consider spatial (regional) aspects of the sustainability transitions (Truffer and Coenen, 2012). In recent years regions have become relevant policy targets, as in the case of the EU Cohesion and Science and Technology (S&T) policies (Archibugi et al., 2022). The EU represents also a strongly integrated area with high share of exports of intermediate goods and services within the continent (Baldwin and Lopez Gonzalez, 2015), which has experienced several reorganizations of production networks among its territories over time. For example, Eastern Europe's integration brought a competitive pressure in the German automobile industry, leading to relocation and offshoring of assembly operations and of automotive parts production (Nunnenkamp, 2006).

Due to regional specificities, environmental policy tools may have heterogeneous effects on regional pollution and green development (Shen et al., 2020). Similarly, the role of GVCs in enhancing the development of complex knowledge has been shown to be heterogeneous across EU regions (Colozza et al., 2022), and this also applies to green technologies. The EU regions with the most advanced green capabilities (as proxied by their development of patentable green technologies) are mainly in central and western Europe, with a handle of regions standing out (Barbieri et al., 2022). However, new specializations in green technologies appear less dependent on pre-existing local knowledge than non-green technologies (Montresor and Quatraro, 2020); in other words, interregional and international spillovers do play an important role in the development of green technologies.

The effect of GVC on the environment has been considered along two main channels. On the one hand, participation to GVC can have a direct effect on the emission of pollutants lowering the environmental impact of production, because emissions at home decrease with the offshoring of some production phases, while in-shoring locations try to improve their production processes to meet international standards (Liu and Zhao, 2021). On the other hand, GVCs integration could support the development of green technologies, necessary to strengthen the competitive advantages of regional exports. The access to green technologies would thereby generate a positive impact on the emissions of economic activities (Lema and Rabellotti, 2023). We define this an indirect effect, because it connects GVCs to environmental performances through more and better green technologies.

It should be noted however that GVCs integration does not always trigger reductions in air pollution (Della Santa Navarrete et al., 2020). The literature on the Pollution Haven Hypothesis (PHH) suggests that the process of pollution reduction may be controversial. Indeed, offshoring can lead to an overall increase in emissions when it implies just moving polluting processes to third countries (Dinda, 2004), in addition to the environmental costs related to growing shipments of intermediate products around the globe. Assessing the PHH requires a GVC approach to consider trade in intermediate goods and different types of participation in international production networks (Duan et al., 2021).

Along these lines, recent research has shown how the reduction of carbon emissions resulting from GVC participation may derive especially from backward linkages (Zhu et al., 2022). Countries that substantially rely on intermediate inputs sourced internationally tend to display lower levels of emissions. In general, we expect backward and forward participation into GVCs to have different environmental impacts: *(i)* backward participation (i.e., importing inputs used in the production for exports) tends to be associated to advanced stages of production – closer to final markets – and therefore more easily associated to innovation and new technologies; *(ii)* forward participation (i.e., exporting inputs used for other places' processing and exports) tends to be associated to early stages of production, often with competitiveness mainly driven by costs (Porter and Stern, 2001), and thus with less expected effects on the greening of production. However, backward participation can also be associated with traditional (and more polluting) production activities, especially for large "factory-type" economies like China. These considerations motivate our research question:

Q1: Do EU regions more integrated in GVCs have lower emissions?

Considering that the EU is an advanced world region largely characterized by high-end manufacturing activities, we expect this to hold true, especially for backward participation.

GVCs are networks of trade and production of intermediate goods, and through their linkages can also constitute pipelines of knowledge transfer across distant territories. Indeed, the larger the internationalization of a firm or territory, the greater the exposure to international innovation activities (Castellani and Pieri, 2013). More specifically, GVC participation may enhance the diffusion of green knowledge across economies (Glachant et al., 2013). This is particularly relevant considering that green technologies tend to be complex and incorporate elements of novelty with pervasive impacts on subsequent inventions (Barbieri et al., 2020). Such complexity may require the integration of knowledge from different sources, that could be hindered by weak intellectual property regimes and restrictions to international trade (Dechezleprêtre et al., 2013).

Additional new evidence suggests that knowledge flows coming from distant places – through GVC linkages – foster the development of renewable energy technologies, as measured by patents (Ocampo-Corrales et al., 2021). When looking at GVCs at a territorial level, one should not only think in terms of capabilities of a single firm, but also in terms of capabilities of the whole territorial system, where different firms may serve the same industry (e.g., suppliers of advanced materials, tools, production equipment, and components). In this perspective, the colocation of R&D and high-end manufacturing particularly matters when product innovation is process-embedded - e.g., advanced materials; heat-treated metal fabrication - or process-driven - e.g., nanomaterials, biotech drugs, automotive gigacasting (Pisano and Shih, 2012), entailing the development of green technologies. When GVC participation is linked to processes of industrial upgrading, one may expect that it will also favour the development of green innovation capabilities.

Moreover, while the relationship between GVCs and innovation systems is largely product- and sector-specific, innovation capabilities are in general more relevant for more complex production phases (OECD, 2013; Caliari et al., 2023).

Q2: Does participation into GVCs favour the development of green technologies?

Once again, considering the type of industrial setting characterizing the EU, where backward participation may favour technological development through the embodiment of foreign knowledge into the products and services imported for production, we expect that backward linkages may favour green technological development to a greater extent than forward linkages.

It is well established that the environmental impact of social and economic activities is greatly affected by the rate and direction of technological change (Jaffe et al., 2003). Already at the begin of the 2000s, the EU took a systemic approach to the environment with an integrated product policy aiming at the reduction of cumulative environmental impacts of products during their life-cycle, and strongly relying on innovation and on the development of a market for greener products (EU, 2003). Nowadays, meeting the global targets of emission reduction is largely seen as dependent on the development of new clean technologies (IEA, 2021). The influence of green technologies in reducing air pollutants may depend on the countries' level of development, with a stronger influence in more advanced economies (Tö; belmann and Wendler, 2020). This may be because advanced economies tend to couple productivity increases with pollution reduction, due to both demand and supply effects: a higher demand for a healthy and clean environment, together with more stringent environmental regulations, such as the Gothenburg Protocol, that can incentivize R&D investments into green technologies (Wang et al., 2021). Indeed, within a supply-chain approach, Costantini et al. (2017) show that green technologies help reducing air pollutants emissions in EU regions through intersectoral spillovers; this implies that the capability of developing and absorbing new technologies matters in the GVCs-pollution relationship.

Importantly, the effect of GVCs participation on air pollution can be mediated by green technologies. Both resources and knowledge flowing through the GVCs favour the development and the adoption of green technologies, allowing for improved efficiency and reduced material use. However, this positive link is conditional on the capacity of the innovation systems to absorb and develop new knowledge (Lema et al., 2019). In other words, the pollution haven hypotheses might be complemented by a "technological heaven" process. The development and adoption of green technologies favored by GVC participation would lead to a reduction in pollutant emissions in local production processes; moreover, learning and imitation processes may occur geographically, across contiguous areas, through the so-called knowledge spillovers. We therefore propose our last research question:

Q3: Do green technologies moderate the relationship between GVC participation and pollution emissions?

3. Data and methodology

To address our research questions, we build a dataset containing information for EU regions (NUTS-2 level), which combines data on GVCs participation, air pollutants emissions (NOx and Sox), technological innovation (proxied by patents and green patents), human capital and the composition of economic activities. The estimation dataset comprehends 2706 observations from 246 EU regions, covering the 2000–2010 period as in the regional input-output database (Thissen et al., 2018). In the following sections we first describe the construction of our main variables of interest and then present the estimation strategy.

3.1. Main variables of interest

3.1.1. GVC participation at regional level

The regional participation to GVC is given by the sum of its backward and forward participation. Following the value-added approach (Montalbano et al., 2018), we draw information from the regional input-output tables (Thissen et al., 2018) to compute the indexes of GVC participation for the EU NUTS-2 regions. These EU regional input-output tables represent the regionalized version of the World Input-Output Tables (WIOT) and represent the flows of sales and purchases for 14 economic sectors. They provide information on import-export relationships between EU NUTS-2 regions and consider also exchanges with main non-EU economies and with a residual aggregated denominated rest of the world. These tables allow to compute indicators of participation in GVCs, which consider trade relationships in intermediate goods and services not only between EU regions but also with other trade partners. For this reason, regional input-output tables have been used to analyse several EU issues, such as the spatial patterns of regional growth (Thissen et al., 2016a) or the EU regional policy impact assessment (Mercenier et al., 2016).

To compute backward and forward regional participation into GVC we use the *icio* decomposition (Belotti et al., 2021), which builds on the methodology to decompose gross-exports and imports proposed by Koopman et al. (2014). The mathematical definition of backward and forward can be found in section 1 of the online appendix. In short, backward participation represents the foreign value-added embodied in the intermediate and final exports of region *r* (i.e., the degree of dependence of region r exports on imports from third regions), while forward participation represents the domestic value-added of a region r embodied in the final exports of third regions (i.e., the degree of dependence of third regions exports from region r exports). Thus, backward and forward participations allow us to measure the value added by regions through interregional or international connections but not to account for the exact *kind* of transaction.

The relative GVC participation of a region can be computed by summing the backward and forward participation components and dividing by gross exports:

$$GVC\ index_{r,t} = \frac{backward\ GVCs + forward\ GVCs_{r,t}}{Gross\ Export_{r,t}} \quad [1]$$

Similarly, in the empirical analysis we also normalize the backward and forward participation by the gross exports of a region. These indicators allow us to consider the overall degree of participation into GVCs of EU regions, as well as the perspective of regions that rely more on external intermediate goods to produce their exports (backward) and of those that carry out production activities incorporated into exports of third regions (forward).

3.1.2. Air pollution (AP) and green patents at regional level

Our main dependent variable is the emission of NOx (Nitrogen Oxides) and SOx (Sulphur Oxides) particles at the regional level. To compute regional AP, we draw from the commodity balance method, CBM (Isard, 1953); in particular we allocate national figures of emissions of air pollutants at regional NUTS-2 level according to the regional shares of sectors involved in the industrial activities (i.e. manufacturing including mining-quarrying and energy sectors). From the dataset of the European Environmental Agency (EEA) we first calculate the overall national emissions by aggregating EEA sectoral figures, and then distribute the national emissions across regions (NUTS-2) according to the share of regional gross value added (GVA) of each region in the sectors, as reported by the dataset produced by the European Statistical Office (a list of macro-sectoral groups used by EEA can be found in the online appendix, Table A1).

Starting from EEA data, we first generate the variable APC, which is the sum of NOx and SOx emissions for each country i and time t produced by the s sectors of EEA related to production activities:

$$APC_{i,t} = \sum\nolimits_{s} AP_{i,s,t} = NOx_{i,s,t} + SOx_{i,s,t} \quad [2]$$

$APC_{i,t}$ represents the yearly emissions of a country i at time t. We disaggregate this national figure at the level of regions according to the share of GVA that sector s in region r represent, with respect to the total

Table 1
Air pollution, green patents and GVC in EU regions, OLS with fixed effects.

	Model 1		Model 2		Model 3	
	GreenPat pop	AP pop	GreenPat pop	AP pop	GreenPat pop	AP pop
GVCs index	2.637***	−0.151				
	(0.584)	(0.130)				
Backward GVCs			1.978***	−0.184**		
			(0.363)	(0.0893)		
Forward GVCs					−0.342	0.317***
					(0.317)	(0.106)
Green Patents per capita		−0.168***		−0.166***		−0.169***
		(0.00686)		(0.00698)		(0.00661)
Patents per capita	0.370***		0.365***		0.401***	
	(0.0365)		(0.0363)		(0.0355)	
Education rate	1.153***	−0.125***	1.131***	−0.124***	1.164***	−0.113***
	(0.0538)	(0.0157)	(0.0544)	(0.0158)	(0.0540)	(0.0154)
Manufacturing RCA (ISP)	−0.769***	0.237***	−0.769***	0.239***	−0.817***	0.237***
	(0.261)	(0.0751)	(0.259)	(0.0754)	(0.257)	(0.0762)
Constant	−19.77***	−5.424***	−16.61***	−5.328***	−8.036***	−7.013***
	(2.416)	(0.543)	(1.443)	(0.365)	(1.061)	(0.318)
Observations	2436	2491	2436	2491	2436	2491
R-squared	0.975	0.927	0.976	0.927	0.975	0.928
R-squared Within	0.3065	0.4177	0.3129	0.4193	0.2853	0.4216
Fixed Effects	Regions	Regions	Regions	Regions	Regions	Regions
Effect of GVC participation indicators on pollution emission						
(a) Direct	−0.151		−0.184**		0.317***	
(b) Indirect	−0.442***		−0.328***		0.058***	
Total (a+b)	−0.593		−0.512*		0.313*	

Note: Robust standard errors in parentheses; ***: $p < 0.01$; **: $p < 0.05$, *: $p < 0.1$. All variables are in logarithms (except Manufacturing RCA) and lagged by one year. To assess the statistical significance of indirect and total effects, we use nonlinear hypothesis tests combining the estimation results with a seemingly unrelated approach.

GVA of sector s at country level:

$$AP_{r,t} = APC_{i,t} * \frac{GVA_{r,s,t}}{GVA_{i,s,t}} \qquad [3]$$

In other words, the regional contribution to national emissions is considered as proportional to the value added of industrial sectors in the region; sectoral rates of emissions per unit of value added are assumed homogenous across regions of the same country. $AP_{r,t}$ measures the regional emissions of NOx and SOx in year t. In equation [3] the GVA provides a lower level of sectoral detail than the EEA, because the two agencies use a different classification system (see table A1 in the appendix for the correspondence among EEA and GDP sectors).

The other variable related to the environmental dimension is the number of green patents per capita. Figures on green patents at the regional level are taken from Regpat, the OECD regional patent dataset. Patents are classified as green when they are attached to the Y02 category of the cooperative patent classification, which groups patents related to climate change mitigation technologies.

3.2. Estimation framework

To answer our research questions on the relationship between air pollution, GVCs participation, and green technologies, we use a two equations approach. The model we use expresses both pollution emissions and green patents as a function of GVC participation. Our model assumes that green patents are an explanatory variable in the emission regression:

$$GreenPatpop_{r,t} = \alpha_0 + \alpha_1 GVCindex_{r,t-1} + X^{'}\gamma + \delta_{1r} + u_{1r} \qquad [4]$$

$$APpop_{r,t} = \beta_0 + \beta_1 GVCindex_{r,t-1} + \beta_2 GreenPatpop_{r,t-1} + X^{'}\theta + \delta_{2r} + u_{2r} \qquad [5]$$

where *r* and *t* are the region and time suffixes, respectively. *GreenPatpop* stands for the number of regional green patents per capita in year t, *APpop* for the emissions per capita, and *GVCindex* for the degree of participation into Global Value Chains.

X' includes a series of control variables that we deem relevant to consider salient regional characteristics that can influence the relationships we test. In particular we include: (i) the index of Revealed Comparative Advantages in manufacturing value added, "Manufacturing RCA" (the mathematical definition of the indicator (Lo Cascio et al., 2008) can be found in the appendix, section 1.1, part b), as the manufacturing sector accounts for both a large share of pollutants emissions and for green patents (Cole, 2000); (ii) the share of population with tertiary degree (Education rate, extracted from Eurostat) to proxy for regional human capital, as this is relevant for the development of green patents (Barbieri et al., 2022) and for the reduction of air pollution (Costantini et al., 2017); (iii) in the green patent equation [4] we also include the overall number of patents per capita (Patents per capita) to control for the possibility that the capacity to develop green patents at least partly depends on the overall regional technological strength. Both patent-related variables are meant to proxy the regional stock of technical knowledge and are computed using the Perpetual Inventory Method with a depreciation rate of 20% and an initial growth rate of 15% (Meinen et al., 1998; Braun et al., 2010). Moreover, we include regional fixed effects (δ_{1r} and δ_{2r}) to control for unobserved regional idiosyncrasies and report robust standard errors. All right-hand side variables are lagged by one year to avoid possible simultaneity issues and ordinary least squares are used to estimate equations [4] and [5].

The two equations regression model allows us to estimate the direct and indirect effect of GVC participation on pollutants' emissions at the regional level. The direct effect of GVC participation on AP is given by the coefficient β_1, its sign and statistical significance provide evidence to answer our first research question. The coefficient β_2 allows us to address our second research question on the contribution of green technologies to the reduction of emissions. Finally, the indirect effect of GVC participation on AP, the effect passing through a higher capacity to develop green patents, is instead provided by the multiplication of the coefficients α_1 and β_2, and its sign and statistical significance will be used to answer to Q3.

To account for spatial spillovers, we estimate equations [4] and [5] also relying on a spatial Durbin model. Localised knowledge spillovers and spatial effects have been proven relevant in the analysis of regional performances and on the configuration of innovation and production activities (Evangelista et al., 2018). This methodology allows us to consider the possibility that regional green technologies and AP emissions can be influenced also by the performances and characteristics of neighbouring regions; we estimate equations [4] and [5] also using a fully specified spatial model, i.e. a model that allows us to investigate also on the effect of explanatory variables on contiguous spatial units:

$$Y_{r,t} = \beta_0 + \sum\nolimits_{n=1}^{N} \beta_n X_{r,t-1} + \delta_1 \sum\nolimits_{c=1}^{C} W_{r,c} Z_{c,t} + \delta_n \sum\nolimits_{c=1}^{C} W_{r,c} X_{c,t-1} + u_r \qquad [6]$$

Where Y indicates our dependent variables, alternatively green patents or AP emissions per capita, β_0 the intercept, and X the right hand side variables as in equations [4] and [5]. $W_{r,c}$ represents the matrix of contiguity between the focus region *r* and neighbouring regions *c*; namely, it is a *r*c* square matrix that assumes value 1 when regions share a border with region *c*, and 0 otherwise. Z includes both the dependent variable and the variables in X. The coefficients δ_1–δ_n capture the spatial dependence of AP and green patents on the values of the dependent and explanatory variables of contiguous regions. As before, u_r stands for the model residuals. The spatial regression estimation provides two sets of coefficients measuring: (i) the relation between dependent and explanatory variables for the same spatial unit, embodied in the coefficients β_n and representing the *within region effects*; (ii) the relation between the dependent variables of a spatial unit and both the dependent and explanatory variables of contiguous spatial units (known as spillovers), embodied in the coefficients δ_1–δ_n and representing the *spatial effects*. In particular, δ_1 represents the spatial autocorrelation of the dependent variable on contiguous spatial units. We estimate equation [6] using spatial Durbin models.

4. Results

4.1. Descriptive statistics

Before presenting the results of the regression analysis, we briefly comment some descriptive evidence. Fig. 1 reports the average emissions per capita for EU regions, while Fig. 2 reports the average number of green patents per capita; these are the two dependent variables of our models, as we will explain in the next section. Both averages are computed over the period of observation. While high levels of emission can be observed for many regions, only few regions have high levels of green patents per capita. The regions with the highest average AP values span from Spain, through the Northern Italy, to some Poland, Bulgarian and Romanian regions (Fig. 1).

Regions with high levels of average green patents per capita are few and concentrated in a small number of countries. Most high patenting regions are in Sweden, Denmark, Belgium and Netherland, as well as in Southern UK (Fig. 2).

From a first cursory look, regions with the highest levels of emissions do not tend to overlap with those with the most intensive production of green patents; notable exceptions are Ile-de-France and Finland regions. On the one hand, this evidence suggests that there appears to be no causal link from pollution to green patents generation, and that some other factors, as GCV participation, are at play. On the other hand, the same evidence suggests that there is a considerable number of regions that would particularly benefit from getting access to more green knowledge.

The spatial concentration of the two variables suggests that spillover

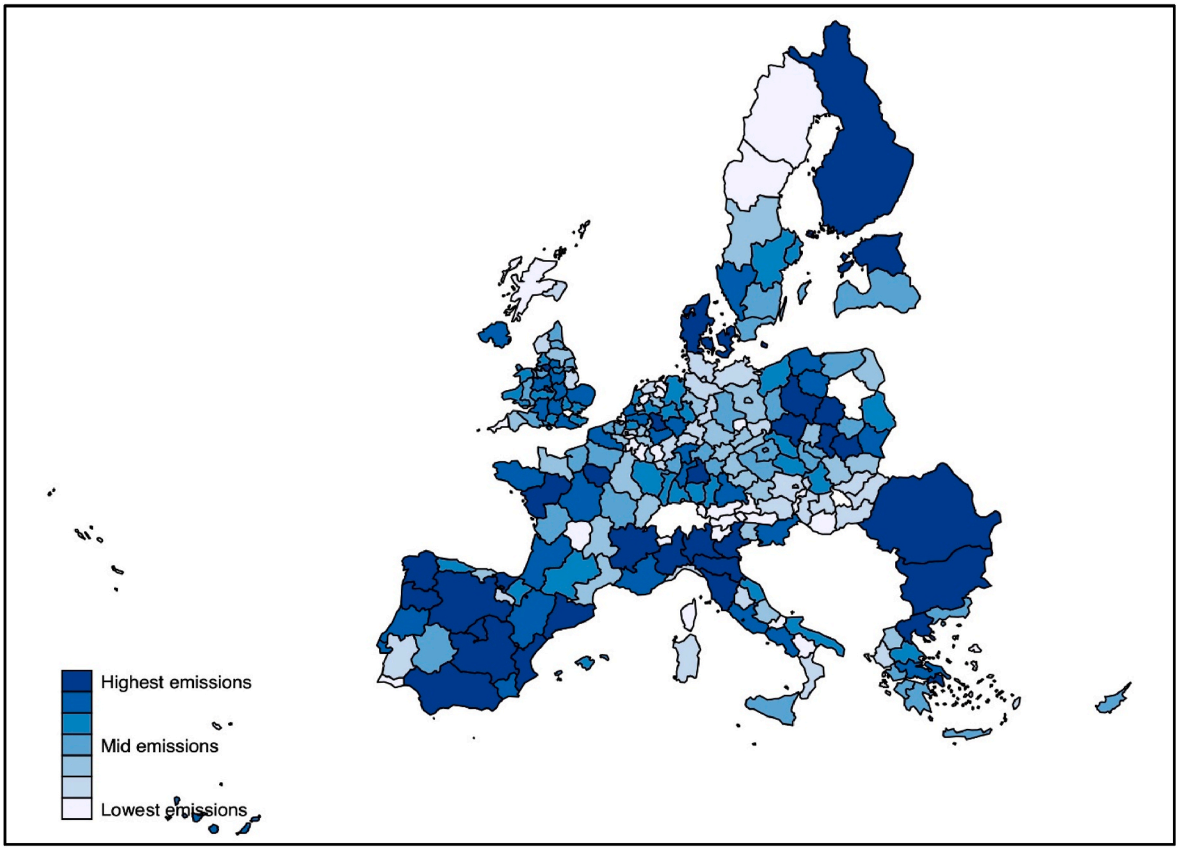

Fig. 1. Air pollutants emission per capita, EU regions (average for 2000–10).
Source: elaboration by the authors. The regions are grouped into 7 categories: darker shades of blue indicate more emissions of AP, while lighter shades represent regions with lower emissions.

mechanisms can be at work. Therefore, in the regression analysis, after having presented ordinary least square regressions with regional fixed effect, we will also use a spatial approach. Moreover, the descriptive statistics of the variables reported in the online appendix (Table A3) show that variability derives mainly from between region differences rather than within regions, suggesting the existence of a high degree of inertia in the observed phenomena.

4.2. *Regression analysis*

In this section we present the results of the econometric models illustrated above. In Table 1 we report the results of the fixed effect estimations. Model 1 shows the results for the measure of overall participation into GVCs (*GVCs index*). The coefficient related to GVCs is not statistically significant in the AP estimation while it is positive and statistically significant in the green patent regression. In other words, GVCs participation is not associated with lower pollutants emissions, providing a negative answer to our first research question, but it is positively associated with the development of green patents. GVC connections of EU regions seems to favour the transfer of knowledge relevant to develop green technologies. Interestingly, all things being equal, a higher specialization in manufacturing activities (Manufacturing RCA) is not only associated with higher levels of NOx and SOx emissions per capita but also with lower levels of green patents. EU regions with relatively higher shares of manufacturing value-added tend to show a lower capacity to develop environmentally friendly technologies, despite needing them more. As expected, higher degrees of education are positively associated to green patents and negatively to AP.

At the bottom of Table 1 we present the coefficients of direct, indirect and total effects of GVCs on AP. As we mentioned in the methodological section, the direct effect of GVCs is the coefficient resulting from the AP regression (AP pop), while to retrieve the indirect effect we multiply the GVCs coefficient in the green patent regression (GreenPat pop) by the green patent coefficient in the AP regression. The sum of the direct and indirect effect provides the total effect of GVCs on AP. In the case of GVCs participation, the values reported at the bottom of the table replicate the main results: only the indirect effect matters. In other words, GVC participation of EU regions is associated to lower levels of NOx and SOx emissions thanks to an enhanced capacity of developing green technologies. The answer to our third research question is that green technologies do not only moderate but are the only channel linking GVC participation to lower pollutant emissions.

Models 2 and 3 disaggregate GVCs participation into its backward and forward components. The results associated to the two forms of participation greatly differ. Higher values of backward participation (i.e., importing inputs for own exports) are associated with lower emissions and a higher number of green patents per capita. Moreover, the indirect effects are much more important than the direct ones (elasticity of 0.32 vs. 0.18). Differently, forward participation (i.e., performing production activities for other areas' exports) is not statistically related to green patents and positively and significantly related to AP. In other words, a higher forward participation is associated with higher levels of pollutant emissions, a result that might be peculiar to the EU industrial structure.

These findings suggest that the link between GVC participation and pollutant emissions might depend on the specific way a place is integrated into GVCs. Backward participation is both directly and indirectly linked to lower levels of emissions, while the positive relation between forward participation and emissions is in line with the arguments of pollution shifted to suppliers of intermediate products (the PHH

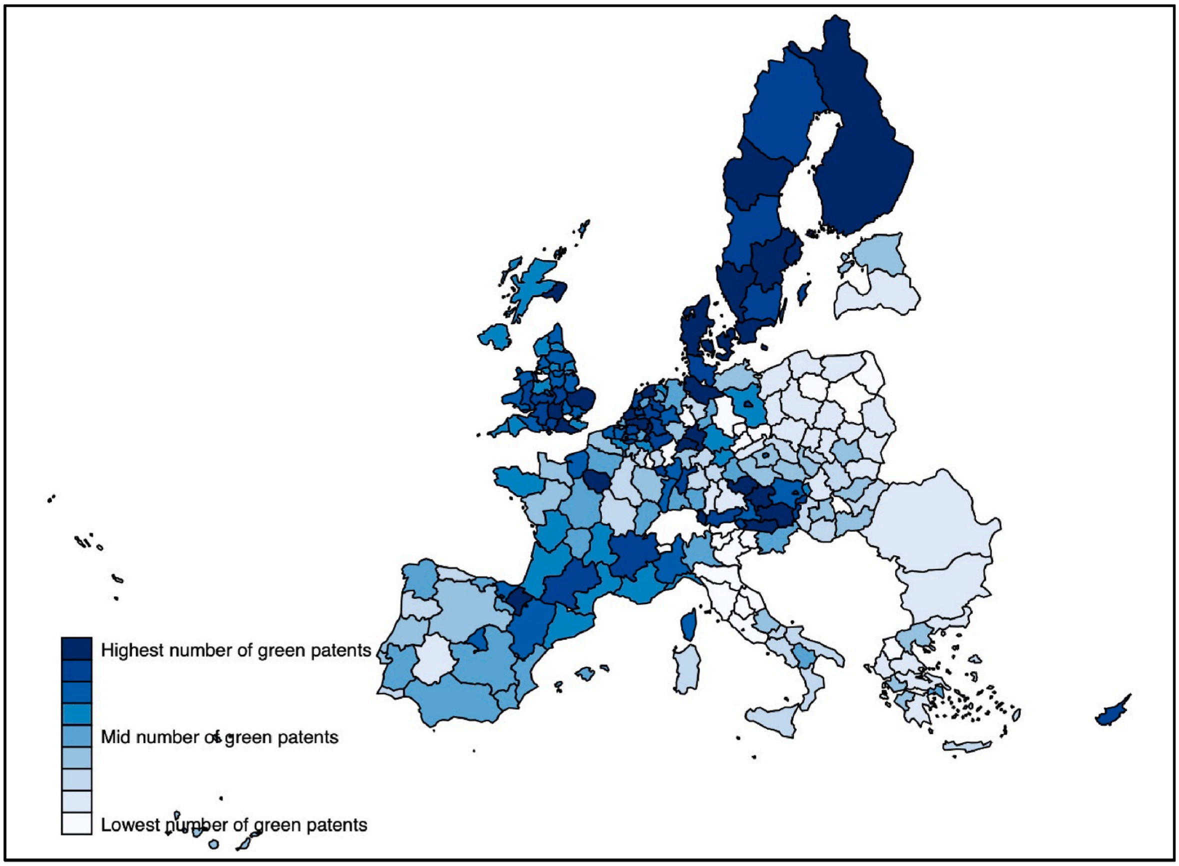

Fig. 2. Green patents per capita of EU regions, average for 2000-10
Source: elaboration by the authors. The regions are grouped into 9 categories: darker shades of blue indicate more green patents, while lighter shades represent regions with fewer green patents.

hypothesis).

In Table 2 we report the results of the spatial regression estimates; the table is organized slightly differently from Table 1 in that it reports the results for green patents in the left hand-side panel and for AP in the right hand-side one. The results corresponding to the tests for spatial correlations of the model residuals are reported at the bottom of the table (Wald test) and suggest that we can reject the hypothesis that residuals are spatially uncorrelated; in Table 2 we report only the autoregessive part of the model, that is, the spatial autocorrelation of the dependent variable.

The results of the spatial regressions only partly confirm the results discussed above. Indeed, the coefficient of our measure of GVC participation in the AP regression is also in this case not statistically significant. In other words, when considering spillovers effects, it is only the backward participation that is positively related with lower levels of AP at the regional level. Interestingly, all the coefficients of the spatial part of the regressions are in line with the main ones, hinting that regional spillover effects between regions work in a manner that is similar of regional own characteristics. For example, by increasing the quality of the workforce through education not only a region improves its environmental footprint but contributes also to improvements in neighbouring regions. The autocorrelation of green patents is higher than that of AP, suggesting that knowledge spillovers are stronger than "pollution spillovers" (see Table A3 in the online appendix for the additional results from the spatial regression).

Finally, in the online appendix (Table A5) we report the results of the fixed effect estimation for AP without including green patents among the explanatory variables. This allows us to assess the results of our two-equation model by comparing them with a specification where the role of green patents in mitigating pollution emissions is not considered.

The estimated coefficients for the three GVCs indicators are very close to the total effects reported at the bottom of Table 1, and the relationship between GVC participation turns out to be statistically significant. In other words, the estimation of the relationship between GVCs and air pollution is upward biased (in absolute value) if the indirect effect deriving from a higher green patenting were not considered. Not considering the role played by green knowledge would provide statistical (and cognitive) evidence on the relationship between GVC participation and pollutants emissions that is erroneously magnified.

5. Concluding remarks

Although the EU's support to climate policies has been strengthened in the last "multiannual financial framework" (2021–2027), still little attention is paid to the role of GVCs in influencing the environment in different territories. GVCs do not offer all regions the same opportunities for environmental upgrading. Some regions can leverage their integration in GVCs to receive useful knowledge for the development of green technologies, in addition to the well-known practice of 'pollution haven', i.e. delocalizing most polluting activities in third areas to reduce emissions. For other regions, the benefits are often limited or even negative. So far, the literature has hardly considered and quantified the relationship between GVCs and the environment at the subnational level (Colozza and Pietrobelli, 2023).

This paper provides new evidence on the relationship between global value chains, green technologies and the emission of air pollutants at the regional level. In the empirical analysis we make use of an original database on pollution emissions and participation into GVCs for EU NUTS-2 regions covering the decade in the aftermath of the adoption of the Gothenburg protocol, which set emissions ceilings for sulphur oxides

Table 2
Air pollution, green patents and GVC in EU regions, spatial regression with fixed effects.

	Dependent variable: Green Patents per capita			Dependent variable: AP per capita		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
GVCs index	0.782***			0.0217		
	(0.234)			(0.0726)		
Backward GVCs		0.769***			−0.0899*	
		(0.160)			(0.0461)	
Forward GVCs			−0.440**			0.350***
			(0.192)			(0.0566)
Green Patents per capita				−0.063***	−0.063***	−0.060***
				(0.00497)	(0.00486)	(0.00488)
Patents per capita	0.238***	0.232***	0.248***			
	(0.0250)	(0.0250)	(0.0245)			
Education rate	0.353***	0.353***	0.316***	−0.123***	−0.123***	−0.121***
	(0.0336)	(0.0336)	(0.0334)	(0.0103)	(0.0103)	(0.00990)
Manufacturing RCA (ISP)	−0.432***	−0.432***	−0.468***	0.639***	0.624***	0.684***
	(0.148)	(0.148)	(0.144)	(0.0653)	(0.0632)	(0.0599)
Spatial autocorrelation of dep variable	0.768***	0.759***	0.796***	0.510***	0.518***	0.436***
	(0.0231)	(0.0234)	(0.0208)	(0.0790)	(0.0726)	(0.0790)
Spatial autocorrelation errors	−0.413***	−0.408***	−0.465***	0.700***	0.689***	0.763***
	(0.0640)	(0.0636)	(0.0627)	(0.0736)	(0.0698)	(0.0581)
Constant	0.480***	0.480***	0.477***	0.111***	0.111***	0.110***
	(0.00783)	(0.00780)	(0.00781)	(0.00174)	(0.00173)	(0.00174)
Observations	2497	2497	2497	2497	2497	2497
Number of groups	227	227	227	227	227	227
DVvar	Contiguity	Contiguity	Contiguity	Contiguity	Contiguity	Contiguity
Errorlag	Contiguity	Contiguity	Contiguity	Contiguity	Contiguity	Contiguity
Wald test	1642.95***	1551.57***	2095.99***	1883.46***	1840.47***	2180.37***
Fixed Effects	Regions	Regions	Regions	Regions	Regions	Regions

Note: Robust standard errors in parentheses; ***: $p < 0.01$; **: $p < 0.05$, *: $p < 0.1$. All variables are in logarithms (except Manufacturing RCA) and lagged by one year.

(Sox) and nitrogen oxides (NOx).

Our findings confirm and complement previous literature, notably the positive role of GVCs in enhancing green patents (Wang et al., 2021), and of green technologies in contributing to the reduction of pollution emissions (Costantini et al., 2017). In addition, we explicitly consider green patents as mediator in the GVC-pollution relationship and obtain evidence that a large part of the linkages between GVCs and the environment occurs through an enhanced capacity to develop green technologies. Moreover, we disentangle the role of different types of integration into GVCs (i.e. backward vs. forward) and show that the general positive relationship between GVCs and lower emissions at the regional level is due to backward participation.

EU regions more integrated through backward linkages show lower levels of air pollution, while forward participation is associated with higher levels of pollution. This finding does not allow us to reject the "Pollution Haven" hypothesis. However, we propose the hypothesis of a "Technological Heaven", which is related to the higher capacity to develop green technologies for regions participating in GVCs, particularly through backward linkages. In sum, the relationship between GVCs and the environment appears to be specific to the way regions participate in GVCs. Our results also show that the combined effect of GVCs and green technologies on polluting emissions is not bounded to a specific region but may trigger relevant spillovers on other neighbouring regions. Thus, GVCs participation may have not only a local positive effect on emissions, but also favour neighbouring regions through knowledge spillovers.

The contribution and implications of our research are manyfold. First, we provide novel evidence on how GVC participation influences the environmental performance of EU regions, showing the differential role of GVC through backward linkages. Second, we show that only backward participation in GVCs enhances the development of green technologies. We acknowledge that our results can be peculiar to advanced industrial areas like the EU regions, and that the GVC-pollution relationship may be different for more factor-based economies. Third, we produce additional evidence on the ongoing debate on the "Pollution Haven" (Duan et al., 2021), arguing that backward linkages may play a dual role favouring the development of green technologies (a "Technological Heaven"). In sum, the contribution of GVCs to the overall polluting emissions will depend on whether the haven or the heaven effects prevail.

Despite drawing from the years in the aftermath of the Gothenburg protocol, our results provide compelling evidence on the current evolution of GVCs. Recent crises and the rise of geopolitical stands are contributing to a reconfiguration of GVCs that can have climate related implications. Moreover, recent climate actions, such as the EU Directive on corporate sustainability requiring companies to establish due diligence procedures of their actions on the environment, can have non-trivial repercussions on third economies. Our findings suggest that understanding the impact that current developments in GVCs may have on the production and transfer of green technologies is essential to help reducing global emissions.

CRediT authorship contribution statement

Federico Colozza: Writing – original draft, Writing – review & editing, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carlo Pietrobelli:** Writing – original draft, Writing – review & editing, Validation, Supervision, Investigation, Conceptualization. **Antonio Vezzani:** Writing – original draft, Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

The authors thank three anonymous referees, Francesco Crespi and the participants at GDS, Rossi-Doria, SIEPI and IFAD conferences for the useful comments on the preliminary version of this work. Funding from Roma Tre University and SVIMEZ for the Post-Doc contract of Federico Colozza is gratefully acknowledged. The usual disclaimer applies.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141180.

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