

INDUCED INNOVATION AND INTERNATIONAL ENVIRONMENTAL AGREEMENTS: EVIDENCE FROM THE OZONE REGIME*

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Abstract

Can international environmental agreements help with the development of new environmentally friendly technologies? This paper provides evidence that the Montreal Protocol's restrictions on chlorofluorocarbons (CFC) triggered a substantial increase in research and innovation on alternatives to ozone-depleting molecules. I compare CFC substitute molecules to molecules that have similar uses but are unrelated to ozone depletion. After the signing of the agreement, patents on CFC substitutes increase by 400% and scientific articles by 500% compared to the control group. The findings from Montreal give hope that environmental agreements can be the trigger to developing technological solutions to the problem of climate change.

JEL Codes: Q55, O31, O33, F53.

Keywords: Induced innovation, environmental agreements, difference-in-differences, synthetic control, topic modeling.

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1 INTRODUCTION

With environmental issues threatening mankind in myriads of ways, the question of how to foster green technologies is as pertinent as never before. Governments around the world spend much effort negotiating international agreements in the hope to reduce environmental impacts. But can agreements help with the development of new environmentally friendly technologies? Previous theoretical work has made the dismal prediction that environmental agreements occur only when costs to the players are low, or in other words, when cheap technological solutions are readily available (Barrett 1994). If that is the case, agreements may do little to foster the development of new technologies.

This paper studies the Montreal Protocol’s restrictions on chlorofluorocarbons (CFCs) to show that environmental agreements can successfully induce the development of environmentally friendly technologies. In 1987, in Montreal, high-income countries decided to phase-out CFCs from industrial activities because CFCs were known to destroy the protective layer of ozone molecules in the stratosphere. Technological change unrolled rapidly, and within a decade, the production and consumption of CFCs decreased by more than 80%.¹

With the problem of ozone depletion virtually solved, the protocol is often hailed as one of the most successful environmental international agreements and remains a point of reference in discussing global environmental problems such as climate change (Barrett 1999; Sunstein 2007). Yet, despite the sizeable literature on the topic, the dynamics of innovation in the ozone crisis are still debated. For example, Richard E. Benedick, the chief U.S. negotiator at Montreal, argues the agreement triggered a vast effort in research to find CFC substitutes². Others, however, claim that CFC substitutes were already available at the time of negotiations (Heal 2016; Sunstein 2007).

In this paper, I use datasets of scientific articles and patents to study the causal impact of the Montreal protocol on innovation. I construct panel datasets at the molecule-level and use a difference-in-differences (DiD) strategy and a synthetic control method. Furthermore, I use topic

1. My calculations using UNEP data.

2. “It was evident (...) that the protocol was in fact moving industry in directions that two years earlier had been considered impossible.” (Benedick 2009, Chap.8 p.104.)

modeling algorithms on the text of patents and articles to semantically characterize the documents in which molecules are mentioned, and construct a measure of similarity between molecules.

The nature of innovation and the challenges that researchers were facing during the ozone episode guides the empirical strategy. Developing CFC substitutes did not require scientists to identify and create new chemical structures. In fact, the molecules with the highest potential to be CFC substitutes were already well-known at the time. The technological challenge lay, instead, in finding out how such molecules could be used in the many industrial processes that required CFCs, how to use them cost-effectively and at scale. This meant scientists had to learn about their thermodynamic properties, toxicity profile, and environmental acceptability. Firms had to develop new processes and formula designs to retrofit installed equipment with the CFC substitutes or to replace them altogether. As I show, these required innovations were only developed after Montreal had been signed.

To capture research efforts related to CFC substitutes, I collect all scientific articles between 1970 and 2000 published in journals indexed by ScienceDirect in disciplines such as engineering and material sciences, and all patents granted by the United States Patent and Trade Office (USPTO) between 1976 and 2000. I compile a list of 14 molecules that scientists and industry experts had identified as having the highest potential to be CFC substitutes and consider those molecules as treated by the signing of the Montreal Protocol. Unfortunately, no pre-existing classifications identify which documents relate to CFC substitutes. I, therefore, search the full text of patents and articles for mentions of any of the 14 CFC substitutes and construct a panel dataset where each observation is the number of documents mentioning at least once a molecule in a given year.

As illustrated in Figure 1, I find that only a few patents and articles on CFC substitutes were published before 1987. I also document that the trend before 1987 is flat, possibly indicating that the agreement was little anticipated. To estimate the causal effect of Montreal, I use a another group of molecules to empirically proxy the counterfactual. Specifically, I compare innovation on CFC substitutes with a control group of molecules known as hazardous air pollutants (HAPs).

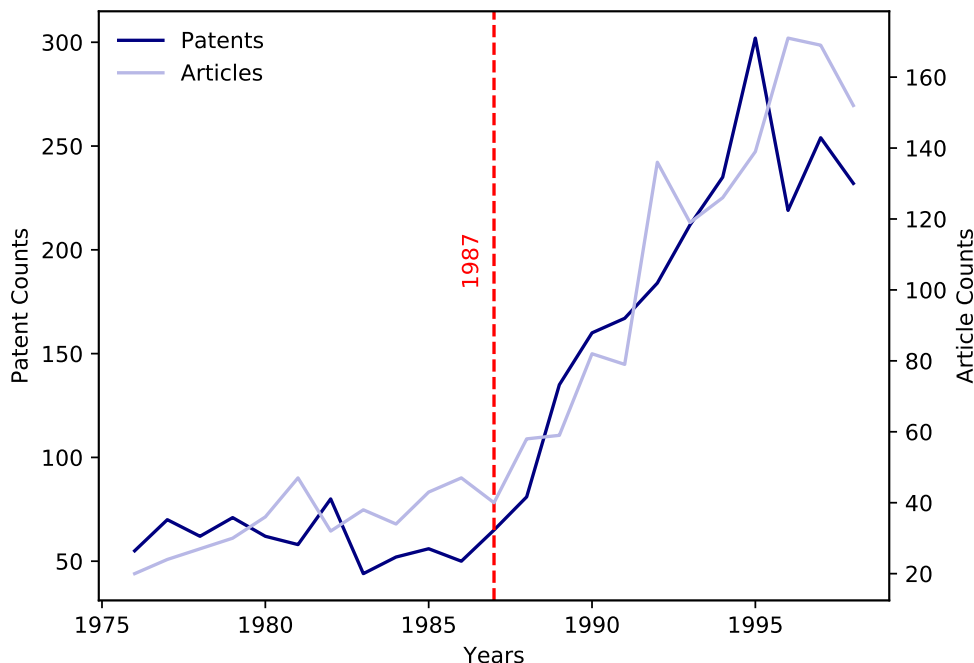


FIGURE 1
Counts of Patents and Articles Mentioning CFC Substitutes

Note: The graph plots the yearly number of patents and articles mentioning the names of any of the 14 CFC substitutes. For patents, the graph shows any patent granted between 1976 and 1999, and the year on the x-axis corresponds to the application date. For articles, the year on the x-axis corresponds to the year the article was published in the academic journal.

These molecules can serve as controls because they are unrelated to ozone or CFCs and are used in a diverse range of industrial applications, just like CFC substitutes. Importantly, pre-trends in the number of documents mentioning both sets of molecules are comparable.

To ensure that the molecules are as comparable as possible, I construct molecule-level variables that proxy for the scientific and industrial context of the molecules using a topic-modeling algorithm. These variables correspond to the proportion of specific topics present in documents. Intuitively, the topic proportions describe which words are associated with a molecule, and, therefore, capture the chemical and industrial characteristics of the molecule. The preferred DiD specification controls for topic proportions to help account for heterogeneity in chemical and industrial characteristics. Results indicate that the Montreal protocol led to a 400% increase in patenting and a 500% increase in scientific articles related to CFC substitutes (relative to the pretreatment period). This corresponds to increases of about 17 patents and 8 articles per year on average per

molecule.

The increase in the number of documents becomes statistically significant, starting in 1989 for patents and in 1990 for articles, two to three years after the signature of the agreement. This delay is similar to prior results in the literature (e.g., Popp (2002)) and can be attributed to the time required to turn research efforts into patent applications and published academic papers. The estimates are robust to a series of alternative specifications, including weighting counts by the number of occurrences of the molecule's name in the text, and weighting by the number of citations that the document received. As an alternative approach, I estimate the causal impact of the Montreal protocol using a synthetic control method (Abadie, Diamond, and Hainmueller 2010, 2015) and find consistent, yet smaller, increases of about 135% for patents and 180% for articles.

I provide further results to exclude two possible alternative hypotheses. First, I examine the claim that CFC substitutes were kept secret by key manufacturers such as DuPont until the agreement was announced. I argue that, if that had been the case, we should expect a one-time increase in patent counts in the immediate aftermaths of Montreal. Indeed, when competitors work on closely related projects, delaying patenting increases the risk that a competitor patents first. I find no spike in patenting after the signing of the agreement, but instead a progressive increase. I, therefore, conclude that there is little support for the claim.

Second, I investigate whether consumer pressure was an important driver of patenting. The saliency of the issue likely increased in the public's eyes when in March 1988, scientists causally attributed the presence of an ozone "hole" over Antarctica to CFCs. However, I find that the increase in patenting for molecules that were not used in consumer appliances is similar to the increase found for the broader sample of molecules, suggesting that consumer pressure is unlikely to drive the large increase in patenting.

At first sight, it seems hard to reconcile this result with the theory of international environmental agreements, and what the implications are for climate agreements. Theory predicts that agreements occur only when cooperation is easy to achieve, that is, when the costs of taking action are low while the benefits are high (Barrett 1994). This may well have been the case with Mon-

treal in 1987. The initial protocol was not ambitious in its reduction targets: high ambitions came with later with amendments in 1990 and 1992 that established a full ban on CFCs and added new molecules to the list of regulated ozone-depleting substances.

However low Montreal's ambitions, the agreement included trade restrictions, and threats of banning trade in any products made using CFCs. This made the agreement economically binding and provided a clear signal and powerful incentives for firms and scientists to increase work on CFC substitutes. Doing so did not just enable the implementation of the small reductions agreed-upon in 1987; it also moved the research frontier forward and improve the technologies necessary to obtain even larger reductions. Hence, by inducing firms to innovate, Montreal reduced the expected cost of further emission abatement. In turn, this made it easier for governments and industries to negotiate binding amendments with more ambitious targets.

The ozone layer's success story, therefore, is better summarized as a series of agreements that progressively ramped up ambitions in emission reductions. We may think of it as a repeated cooperation game where, at each stage, small but binding reductions force firms to innovate. This reduces expected abatement costs and leads to better cooperation outcomes in the next stage. Innovation, here, plays a critical role in enabling ambitions to ratchet up. By showing that a low-ambition but binding agreement such as the Montreal Protocol did encourage the development of technological solutions, this paper suggests such agreements are potent tools that dynamically improve the benefit-cost equation of environmental protection and may therefore also be useful to deal with current problems such as climate change.

This paper contributes to the literature on technological change and the environment (Jaffe, Newell, and Stavins 2002; Popp 2019; Popp, Newell, and Jaffe 2010). Recent studies have drawn attention to the factors inducing innovation on environmental-friendly technologies. In particular, the literature has emphasized both the role of energy price increases (Aghion, Dechezleprêtre, Hemous, et al. 2016; Popp 2002) and domestic environmental policies (Calel and Dechezleprêtre 2016; Jaffe and Palmer 1997). This paper, instead, documents that agreements for global environmental public goods can induce innovation.

In principle, like domestic policies, agreements should force firms to allocate inputs to reduce pollution, thereby inducing them to innovate (Milliman and Prince 1989; Porter and Van Der Linde 1995). Several studies investigate the effect of such agreements on pollution outcomes (Aichele and Felbermayr 2011; Finus and Tjøtta 2003; Kellenberg and Levinson 2014) but they seldom look at the impact on science and innovation. One exception is Dekker, Vollebergh, Vries, et al. (2012) who focuses on transboundary air pollution.

The paper starts by providing some background information in Section 2 and data description in Section 3. Section 4 outlines the empirical strategy, Section 5 presents the main results, and Section 6 considers alternative hypotheses and mechanisms. Finally, Section 7 discusses how the results connect to the literature on international environmental agreements and implications for how to deal with other global environmental issues such as climate change.

2 BACKGROUND

2.1 Theory and Hypotheses

The concept of *induced innovation* goes back to Hicks (1932) who stated that innovations are biased towards high priced factors to make their use more efficient or to substitute them.³ The theory was later augmented to include environmental policies. In the simplest model, environmental regulations force firms to allocate some inputs (labor or capital) to pollution reduction or restrict the choice of technologies and inputs in the production process (Milliman and Prince 1989). Environmental regulations, therefore, are typically modeled as extra costs. The theory of *induced innovation* argues that such costs induce firms to innovate in the hope of offsetting them, at least partially.⁴ The theory can easily be extended to international environmental agreements. An agreement would oblige firms to adapt their production processes only once it is translated into domestic

3. In the past two decades, the concept has reappeared under the phrase “directed technical change” (Acemoglu 1998) encompassing not just price effects, but also market size and regulatory effects.

4. The *Porter Hypothesis* goes further arguing the extra costs imposed by environmental policies can sometimes be even more than fully offset (Ambec, M. A. Cohen, Elgie, et al. 2013; Porter and Van Der Linde 1995).

law. However, the signature on its own immediately changes expectations regarding future domestic environmental policies, at least, if firms perceive the agreement as binding. Arguably, this is what happened with the Montreal Protocol.

Montreal included trade restrictions with non-parties in ozone-depleting substances and products containing those substances, and it also included the threat of banning trade in products made using ozone-depleting substances. Barrett (1999) suggested such trade measures solved the enforcement problem, and Wagner (2016) further argued they promoted full participation in the protocol, ensuring its almost-universal ratification. Hence, the trade restrictions effectively acted as a mechanism for free-rider deterrence and leakage prevention, rendering the agreement binding. The main hypothesis, therefore, is that Montreal credibly signaled firms that the continued use of CFCs would become increasingly costly, and induced them to innovate. Richard Benedick, the U.S. head negotiator at Montreal, argued that “(it) was evident (...) that the protocol was in fact moving industry in directions that two years earlier had been considered impossible” (Benedick 2009, Chap.8 p.104.). However, Benedick only refers to articles published in the *New York Times* and *Chemical and Engineering News* to support his claim.

On the other hand, an often heard narrative argues that CFC substitutes were readily available before the negotiations. Sunstein (2007) claims that “an international agreement was largely in the interest of American manufacturers, which had already initiated a transition to safe CFC-alternatives.” This view is also often expressed in media outlets. For example, *The New York Times*, on August 20, 2002, stated that “(the) agreement’s success occurred, in large part, because substitutes for the harmful chemicals were readily available (...)” Importantly, such claims are consistent with the theory of why and when agreements appear (Barrett 1994). In the case of Montreal, that theory implies that the agreement was successfully negotiated because the costs of doing so were low relative to benefits.

This paper relies on quantitative analysis to disentangle these different hypotheses. Section 7 will further discuss how to reconcile the empirical results with the theory of international environmental agreements.

2.2 Events That Led to Montreal

The story of the ozone crisis began in 1974 when two chemists laid out the theoretical possibility that CFCs broke down ozone molecules in the stratosphere (Molina and Rowland 1974). The harmful effects of a thinner ozone layer were not well understood, but it was clear that more UV light would cause more skin cancers, eye cataracts, and, likely, lower productivity in fishery and agriculture (Miller and Mintzer 1986).

In the late 1970s, the issue began to take prominence in the media and policy circles. A few countries and firms unilaterally decided to take action. In August 1977, the U.S. Congress wrote into law a CFC ban on aerosols by 1978,⁵ and firms such as DuPont removed CFCs from their spray products because they worried about their public image. In essence, these pre-Montreal domestic regulations and corporate decisions were zero-cost unilateral moves. They targeted a particular industrial application of CFCs for which cheap substitutes existed.⁶⁷ They did not require a significant research effort, and the low levels in patent and article count between 1970 and 1987 in Figure 1 indicates that neither aerosol regulations nor consumer pressure seemed to have stimulated science and innovation on the 14 CFC substitutes I consider.⁸

At the beginning of the 1980s, the issue stopped being a priority. Uncertainties in the science of atmospheric ozone seemed irreducible, and the year 1981 saw the election of a strongly anti-regulatory American administration. In Europe as well, many governments persisted in opposing environmental regulations that would harm manufacturers. Edward A. Parson highlights that, although some manufacturers initially started research on potential substitutes in the late 1970s, these efforts quickly came to an end around 1981 (Parson 2003, Chap.3 p.53 and Chap.7 p.173). Parson argues that manufacturers stopped these R&D programs because they had determined that CFC substitutes would cost around two to five times more than CFCs, and it made no sense to continue developing these substitutes with little sign of regulations underway.

5. Similarly, in 1978, Canada, Switzerland and Scandinavian countries all banned CFC aerosols. Germany called for a European Community-wide ban, but without success.

6. Physical substitutes included roll-on devices; chemical substitutes included alkanes.

7. In 1980, the EPA proposed to freeze other uses beyond aerosols but U.S. industry blocked the initiative.

8. These 14 CFC substitutes were targeting foams, refrigeration and solvent applications of CFC.

Benedick emphasizes the complexity of the negotiations and the great uncertainty of the negotiations' outcome. He further argues that some exceptional turns of events unlocked the situation. Unexpectedly, Reagan overruled his administration and approved the agreement. Benedick hints at Reagan's life experiences weighing heavily on his decision as the U.S. President had skin cancer removed twice in the past. On the European side, the most prominent opponent to CFC regulation, the United Kingdom, left the European Community Presidency, leaving Germany, Denmark, and Belgium, firm proponents, as the head negotiators. This account of the negotiations' success does indeed indicate that the agreement largely occurred independently from the state of R&D activities on CFC substitutes.

2.3 Which Molecules Were “Treated”?

CFCs have a particular molecular structure: they contain only carbon, chlorine, and fluorine atoms. Such chemical structure is the crucial reason for their attractive thermodynamics properties: they are unusually stable, nonflammable, nontoxic, and noncorrosive. In a word, they were ideal for manufacturing many consumer goods.⁹ Best of all, they were cheap to produce, and so they became broadly used in many different industries such as foams, refrigeration and air-conditioning, aerosols, fire protection, and solvents. CFCs are great refrigerants because they vaporize at low temperatures and are very energy-efficient coolants. As aerosols, they were used in cosmetics, household products, pharmaceuticals, and cleaners. Finally, their nonreactive property made them key products for cleaning microchips and telecommunication equipment.

Strategies for reducing CFCs included physical substitutes (like pump-action sprays instead of aerosol sprays) or recycling. However, the most critical applications (e.g., air-conditioning units) needed chemical substitutes. Importantly, the intricate relationship between molecular structure and industrial properties implied that there was not an infinite number of possible substitutes: good candidates would present similar molecular structure but where hydrogen atoms replace chlorine

9. Initially, CFCs somewhat embodied the miracle of modern chemistry. They were first commercially used in 1928 as cooling fluids for refrigerators, and were specifically designed to substitute other dangerous refrigerants that were either toxic or inflammable (Parson 2003).

atoms. For example, and as detailed in Figure 2, when a hydrogen atom substitutes a chlorine atom in CFC-12, we get HCFC-22, or when, instead, a methyl group substitutes a chlorine atom, we obtain HCFC-142b. Here “HCFC” stands for hydro-chlorofluorocarbons. When hydrogens substitute all the chlorine atoms, the compounds are known as hydro-fluorocarbons (HFCs). For example, when hydrogens replace the two chlorine atoms in CFC-12, we get HFC-32

It was public knowledge, therefore, that the quest for CFCs substitutes lay in the realm of HCFCs and HFCs. These molecules had been known for a long time, at least on paper and in the lab.¹⁰ Developing CFC substitutes, therefore, was not so much about “new-to-the-world” compounds, but instead “new-to-the-industry” compounds. The key technological challenges lay in making large-scale production cost-efficient, redesigning processes and equipment already installed, and learning about environmental acceptability and human toxicity.

To conduct the empirical analysis, I construct a list of potential substitutes using historical records using several reports published after Montreal regarding the atmospheric chemistry of several potential substitutes. Specifically, the list of potential substitutes includes the twelve molecules studied in the AFEAS (Alternative Fluorocarbon Environmental Acceptability Study), a report issued in December 1988 investigating the atmospheric dynamics of twelve potential CFC substitutes. Importantly, the report did not cover aspects of the molecules related to industrial activities, but merely how the molecules may interact with human health and the environment once released in the atmosphere. I also include two other possible CFC substitutes mentioned in Benedick (2009) and Parson (2003).¹¹

10. The first-ever granted patents related to HCFCs and HFCs typically go back to the 1930s; at the time, chemists were experimenting with halogenation processes and heat transfers. For example, in 1934, a patent is claimed for a “method of producing refrigeration which comprises evaporating in the vicinity of a body to be cooled and subsequently condensing CH₂ClF.” US Patent 1,968,049. CH₂ClF is a.k.a. HCFC-22.

11. HFC-245fa and HFC-365mfc are mentioned as possible substitutes in foams. Online Appendix Table ?? shows the name and additional information about all molecules considered in the analysis.

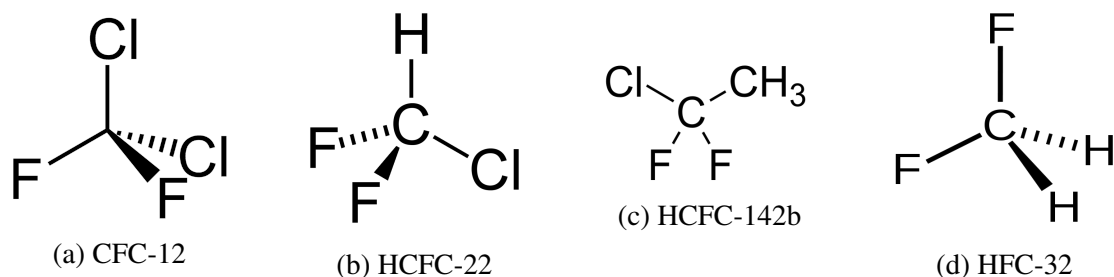


FIGURE 2

Molecular Structure of CFCs, HCFCs and HFCs

Note: CFC stands for chlorofluorocarbon, i.e., a molecule entirely made of carbon, chlorine, and fluorine atoms. When a hydrogen atom substitutes a chlorine atom in CFC-12, we get HCFC-22, or when, instead, a methyl group substitutes a chlorine atom, we obtain HCFC-142b. Here “HCFC” stands for hydro-chlorofluorocarbons. When hydrogens substitute all the chlorine atoms, the compounds are known as hydro-fluorocarbons (HFCs). For example, when hydrogens replace the two chlorine atoms in CFC-12, we get HFC-32.

3 DATA DESCRIPTION

3.1 Patents

In the chemical industry, patenting is an essential way of protecting competitive advantage from new products and processes (Sampat 2018). Since chemicals can often easily be “reverse engineered,” secrecy offers a limited mode of appropriation and strong incentives exist to use patenting either to protect inventions from being copied or to prevent competitors from patenting related inventions (W. M. Cohen, Nelson, and Walsh 2000).¹² I, therefore, follow prior literature in using patent counts as a proxy for innovation.¹³ Furthermore, I collect the texts contained in the abstract and summary description of USPTO patent grants published between 1976 and 2000¹⁴. The cleaning procedure involves a series of standard steps that are detailed in the Online Appendix ??.

Patents contain the names, addresses, and affiliations of inventors and assignees, which I categorize by type (e.g., business, education, or government). To associate patents to specific countries, I use the country of the assignee. When patents have no assignee but only inventors, I use the country of

12. See for example Moser (2012) for an examination of how the publication of the periodic table in 1869 made chemicals easier to reverse engineer and led chemical inventors to shift from secrecy to patents in the mid-nineteenth century.

13. Examples and reviews include Hall and Jaffe (2012), Henderson, Jaffe, and Trajtenberg (1998), Popp (2005), and Williams (2013, 2017).

14. The full-text patent data is available at bulkdata.uspto.gov/. It represents a total of 2,605,925 patents.

the inventor. More details about how the meta-data is cleaned, matched, and classified by type are provided in the Online Appendix ???. I use the OECD Citations database File to obtain data on the number of forward citations received by each patent.¹⁵ Finally, I sort patents by application date (as opposed to the date when they are granted).

3.2 Articles

The development of appropriate CFC substitutes required a better understanding of the fundamental thermodynamic properties of the proposed molecules, as well as how they would interact with humans and the environment. Following prior literature, I use counts of scientific articles as a proxy for increases in such knowledge.¹⁶ I collect scientific articles published between 1970 and 2000 in journals indexed by ScienceDirect, which hosts articles from about 2,500 academic journals published by Elsevier. The sample provides excellent coverage of journals in fields related to engineering and physical sciences and allows to characterize trends in the emergence of scientific knowledge related to CFCs substitutes. I used ScienceDirect’s API to download the full-text of articles in journals from the following disciplines: chemistry, chemical engineering, engineering, environmental science, materials science, and physics and astronomy.¹⁷ After a series of cleaning procedures described in Online Appendix ??, I obtain a total number of 1,811,301 articles. For data on affiliations and citation counts, I query the Scopus search API, and use the Global Research Identifier Database¹⁸ to classify authors’ affiliations (e.g., education or company).

3.3 Searching for Molecule Names

Chemical compounds often go by several names; for example, HCFC-22 has 39 other possible names such as chlorodifluoromethane or algeon 22. I develop an automatic script to collect all pos-

15. OECD, Citations database, February 2019

16. Examples and reviews include Azoulay, Graff Zivin, and J. Wang (2010), Pierre Azoulay, Fons-Rosen, and Zivin (2019), Iaria, Schwarz, and Waldinger (2018), Redner (2005), Thompson and Fox-Kean (2005), and D. Wang, Song, and Barabási (2013).

17. Journals are listed by disciplines on Elsevier’s website: <https://www.elsevier.com/solutions/sciencedirect/content/journal-title-lists>.

18. <https://www.grid.ac/>

sible names on SciFinder, a database of chemical information maintained by the American Chemical Society and search through the text of patents and articles for any occurrence of these names.¹⁹ I proceed similarly to identify the patents and articles that mention any of the 171 HAPs. In total, I find 3270 patents and 1926 articles mentioning at least one CFC substitute. The search procedure may lead to measurement error with over-detection if patents and articles mention molecules despite these same molecules not being the core subject of the document. However, there is no reason to believe that over-detection will be higher for CFC substitutes than for the control molecules; it should therefore not introduce any particular bias. I nonetheless run robustness checks using counts weighted by the number of occurrences of molecules in Section 5.2.

3.4 Descriptive Statistics on Documents Mentioning Substitutes

Tables 1, 2 and 3 illustrate the types of patents and articles that mention CFC substitutes. The most common patent codes are related to chemical compounds containing halogen atoms, and the most cited patents correspond to innovations for the pharmaceutical sector. The most cited articles focus on physical characteristics or new synthesis routes. Furthermore, the average patent is granted to a for-profit organization in the United States. More than 96% of patents are granted to for-profit organizations, while educational and public sector organizations share the rest. European assignees represent around 25% of patents, Japanese around 12%.²⁰

4 EMPIRICAL STRATEGY

4.1 A Sharp Post-1987 Increase

In this section, I examine the temporal trends in the yearly count of documents about CFC substitutes. As Figure 1 illustrates, the number of patents and articles increases after the signature

19. I look for any English name listed in SciFinder but I do not look for chemical symbols. The articles' text is usually the output of optical character recognition, and chemical symbols and formulae are too often rendered with mistakes. A full list of all the possible names of CFC substitutes is shown in Online Appendix Table ??.

20. Online Appendix Table ?? displays summary statistics about countries and affiliations of patent assignees and authors of articles.

TABLE 1
Five Most Common Patent Codes for Patents Mentioning CFC Substitutes

ICL	Count	Description
C07C	357	Acyclic or carbocyclic compounds
C08J	156	General processes of compounding
C09K	147	Materials for applications not otherwise provided for
C08G	84	Compounds of unknown constitution
C10M	73	Lubricating compositions

Note: The table displays the most frequent codes associated with patents mentioning CFC substitutes. As expected, most codes belong to the C class ("Chemistry, Metallurgy"). The subclasses "C07" and "C08" refer to the preparation (e.g., purification, separation, or stabilization) of organic compounds. As such, they encompass any patent related to compounds containing carbon and halogen atoms (e.g., C07C 19/00: Acyclic saturated compounds containing halogen atoms). To limit noise, the sample used to generate the table contains only documents with at least three occurrences of CFC substitutes.

TABLE 2
Titles of the Five Most Cited Patents Mentioning CFC Substitutes

Nbr Cit	Year	Assignee	Title
104	1995	Glaxo Group Limited, UK	Aerosol formulations containing P134a and salbutamol
103	1995	Glaxo Group Limited, UK	Aerosol formulations containing P134a and particulate medica- ments
101	1995	Glaxo Group Limited, UK	Aerosol formulations containing propellant 134a and fluticasone
97	1995	Riker Laboratories, Inc., USA	Medicinal aerosol formulations

Note: The table displays the titles of the most cited patents mentioning CFC substitutes. Patent citation patterns vary significantly across industries. The fact that the most cited patents here all relate to pharmaceuticals applications (e.g., aerosol formulation of a drug) may only be indicative of that sector's higher patenting output or tendency to cite more. To limit noise, the sample used to generate the table contains only documents with at least three occurrences of CFC substitutes.

TABLE 3
Titles of the Five Most Cited Articles Mentioning CFC Substitutes

Nbr Cit	Year	Title	Journal	Affiliation 1st author
509	1992	Organic peroxy radicals: Kinetics, spec- troscopy and tropospheric chemistry	Atmospheric Envi- ronment Part A	Academia (DE, UK, FR)
419	1982	Evaporative heat transfer, pressure drop and critical heat flux in a small vertical tube with R-113	International Journal of Heat and Mass Transfer	GE Global Research (USA)
401	1992	Environmental catalysis	Applied Catalysis B: Environmental	Air Products & Chem. Inc (USA)
346	1993	Synthesis of chiral and bioactive fluoroor- ganic compounds	Tetrahedron	Academia (IT)
333	1996	Methods for the synthesis of gem- difluoromethylene compounds	Tetrahedron	James Black Foundation (UK)

Note: The table displays the titles of the most cited articles mentioning CFC substitutes. As expected, articles focus on the chemical and physical characteristics of CFC substitutes (e.g., "kinetics" or "evaporative heat transfer") as well as on synthesis routes. To limit noise, the sample used to generate the table contains only documents with at least three occurrences of CFC substitutes.

of Montreal in 1987.²¹ I quantitatively investigate these temporal patterns with first-difference specifications. Equation 1, below, models a mean shift while Equation 2 models a trend-break.

$$\text{Count}_{mt} = \alpha + \beta_0 \times \lambda_{post1987} + \lambda_m + \varepsilon_{mt} \quad (1)$$

$$\text{Count}_{mt} = \alpha + \beta_1 \times Y \times \lambda_{post1987} + \beta_2 \times Y + \lambda_m + \varepsilon_{mt} \quad (2)$$

$\text{Count}_{m,t}$ is the number of documents in year t mentioning molecule m ; $\lambda_{post1987}$ is a dummy variable that equals one when $t > 1987$; λ_m are molecule fixed effects; Y is a continuous variable indicating the number of years relative to 1987. The main hypothesis is that β_0 and β_1 are both positive for CFC substitutes, implying significant increases in research and patenting activities relating to CFC substitutes after 1987 once Montreal passed.

Table 4 presents the results for these specifications. The sample here consists of the 14 different CFC substitutes for which I track the number of patents and articles throughout the years. I run separate regressions for patents and articles, and bootstrap standard errors. Model 1 confirms that there is a significant and positive mean shift after 1987 in the number of patents and articles mentioning CFC substitutes. The coefficients indicate almost 30 additional patents and around 13 additional articles for the average CFC substitute every year after 1987. This corresponds to a 551% increase (594% increase) in the number of patents (articles) for the years 1987-2000 relative to the years 1975-1986. Model 2 shows that the change can also be modeled as a trend break. The coefficient for “Years” indicates that there is a small positive underlying trend for articles.

The post-1987 increase, however, may be driven by factors other than Montreal (e.g., policies or macroeconomic conditions fostering academic and industrial research in the 1990s). To further investigate whether the post-1987 increase can be causally attributed to the protocol, I use a set of molecules known as HAPs as a comparison group.

21. Online Appendix Figure ?? plots time-series similar to Figure 1, but each CFC substitutes separately. The post-1987 increase is present for most substitutes.

TABLE 4
First Differences Results

	(1) Patents	(2) Patents	(3) Articles	(4) Articles
Post 1987	29.510*** (2.113)	6.097** (2.632)	13.022*** (1.072)	2.113 (1.581)
Post 1987 x Years		3.955*** (0.439)		1.442*** (0.284)
Years		-0.027 (0.246)		0.156** (0.063)
Molecule FE	Yes	Yes	Yes	Yes
Bootstrapped	Yes	Yes	Yes	Yes
R-squared	0.639	0.736	0.577	0.630
Observations	322	322	406	406

Standard errors in parentheses

Years are relative to 1987.

Time-series: (1976-1998) for patents; (1970-1998) for articles

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: The Table presents the regression results for first-difference specifications. Model 1 and 3 confirm that there is a significant and positive mean shift after 1987 in the number of patents and articles mentioning CFC substitutes. Model 2 and 4 indicate that the change can also be modeled as a trend break. The coefficient for ‘Years’ indicates that there is a small but statistically significant positive underlying trend for articles.

4.2 Hazardous Air Pollutants as a Comparison Group

HAPs is an umbrella term for molecules categorized as *hazardous air pollutants* and became monitored under the 1990 Clean Air Act due to human health concerns including cancer, asthma, congenital disabilities, reproductive effects, and neurodevelopmental effects, as well as adverse ecological impacts. Examples include benzene, chromium, or formaldehyde.²² HAPs are an appropriate comparison group for CFC substitutes for two reasons. First, their industrial applications are very similar. Figure 3 shows that patents about CFC substitutes and HAPs fall into similar top-level codes. Online Appendix Figure ?? further shows that they also display similar second-level patent codes. Second, HAPs are unrelated to ozone depletion and are therefore not affected by the Montreal Protocol.²³ Going further still, one would like to ensure that the HAPs chosen are as similar as possible to CFC substitutes in terms of chemical, physical, and industrial properties. To

22. The full list of HAPs is displayed in Online Appendix Table ??.

23. Three HAPs (chlorine, methylenechloride, trichloroethylene) were suggested as possible CFC substitutes, but I exclude them from the sample. I use the EPA SNAPs website to obtain the list of compounds or devices suggested by firms to the EPA as possible alternatives to CFCs.

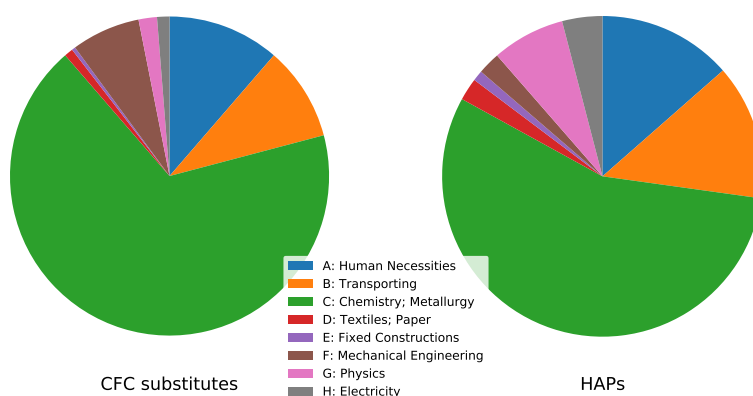


FIGURE 3

Top Level Patent Codes for CFC Substitutes and HAPs

Note: The figure shows that, overall, patents mentioning CFC substitutes and HAPs fall into similar top-level codes. HAPs are a group of 171 molecules that have no relationship to ozone and that are used for diverse industrial applications. The figure indicates the two groups of molecules present remarkable similarities, which motivates the use of HAPs as control molecules to estimate the causal effect of the post-Montreal regime. The patent codes are from the international patent classification.

do so, I leverage topic modeling algorithms, as explained in the next subsection.

One concern is that other policies may have impacted research and innovation related to HAPs during the same period of analysis. In particular, in 1990, an amendment to the Clean Air Act required the EPA to promulgate regulations establishing emission standards for large sources of HAPs. However, the EPA published the initial promulgation schedule in 1993 only, and so, in practice, HAPs are not impacted by this policy change until later in the period that I consider.²⁴ I nonetheless take a conservative approach and limit my analysis to the time-period until 1992 for patents and 1995 for articles. The additional three-year period for articles is to account for further delays between submission and publication of scientific articles.²⁵

24. The EPA published the initial list of "source categories" in 1992 (i.e. the list of industries and production processes targeted by the regulations), and in 1993, the promulgation schedule specified by which year sectors were expected to comply with the emission standards for each category or subcategory of major sources and area sources of HAPs. This was known as the National Emission Standards for Hazardous Air Pollutant (NESHAP), and most sectors were asked to comply by 1997 or 2000.

25. This problem does not arise for patents since the data provides the *application* date of patents.

4.3 Topic Modeling

I use a Latent Dirichlet Allocation (LDA) algorithm to model which *topics* are present in the documents (Blei 2012; Blei and Lafferty 2009). In this context, a topic means a distribution over words and a document a distribution over topics. The *number* of topics is a parameter chosen by the experimenter. I run several LDA models, each with different number of topics, and compute their coherence score (Röder, Both, and Hinneburg 2015).²⁶ For each corpus, I choose the lowest number of topics that offers the highest coherence score, which is 20 for patents and 15 for articles.²⁷

I use the trained topic models to generate document-level variables called topic proportions. These variables take values between 0 and 1 and indicate to what extent a topic is present in a document. Said differently, the model uses the words appearing in a document to infer the proportion of each topic in that document. Furthermore, I aggregate topic proportions at the molecule level. To do so, I calculate weighted means where the weights are proportional to the number of times a document mentions a molecule.²⁸

The molecule-level topic proportions describe quantitatively what the documents with molecule *i* talk about. They help, therefore, describe and measure the molecule’s chemical and industrial characteristics. Figure 4 displays a series of scatterplots illustrating the variation in topic proportions across molecules. Some HAPs have values of topic proportions that stand out as outliers, indicating that they present semantic contexts that are very different from the one of CFC substitutes. This, in essence, illustrates why topic proportions are useful: they allow to control for differences across molecules.

Table 5 illustrates the words the topics contain.²⁹ The documents are highly technical, and topics can be challenging to interpret. For example, for patents, the most likely word in Topic 1 is “polymer” (with probability 0.61). Then come “catalyst” and “carbon.” A trained chemist may

26. Online Appendix Figure ?? shows that coherence increases with the number of topics up to a certain point.

27. I train the algorithm, not on the entire corpus, but on the subset of documents that contain at least one mention of a molecule

28. Online Appendix Figure ?? summarizes these steps.

29. Online Appendix Table ?? and ?? provides the full list of words and topics.

TABLE 5
Top Five Words in Selected Topics

(a) Patents			(b) Articles		
	Words	Probability		Words	Probability
Topic 1	polymer	0.0161	Topic 1	compound	0.0162
	catalyst	0.0123		extract	0.0072
	carbon	0.0095		structure	0.0068
	weight	0.0094		product	0.0061
	atom	0.0087		methyl	0.0056
Topic 2	metal	0.0084	Topic 2	surface	0.0155
	membrane	0.0082		material	0.0096
	solution	0.0071		layer	0.0086
	particle	0.0067		film	0.0075
	surface	0.0065		process	0.0062
Topic 3	formula	0.0118	Topic 3	laser	0.0129
	carbon	0.0092		signal	0.0102
	atom	0.0088		sample	0.0097
	substitute	0.0086		pulse	0.0092
	amine	0.0077		radical	0.0081
Topic 4	agent	0.0147	Topic 4	gifhttps	0.0351
	composition	0.0112		thumbnail	0.0282
	active	0.0064		downsample	0.0270
	weight	0.0062		smlhttps	0.0190
	water	0.0052		stripin	0.0175

Note: The tables present the three most likely words in the first four topics generated by the LDA algorithm. The highly technical nature of the documents is apparent here. It is possible to associate labels to some of the topics, but not to all. Some topics also appear to contain many filler words (e.g., topic 4 in both patents and articles). Full topics are shown in Online Appendix ??.

suggest to label Topic 1 “Catalysts on polymer substrates.”³⁰

30. Catalysts are molecules (typically “metals”, word 7 in topic 1) used to start and maintain chemical reactions. They are often made more effective by being “attached” to a polymer substrate. Hence, the production of such catalysts often involves a “polymerization” process (word 6 in topic 1) where free “radicals” (word 13 in topic 1) ensure the addition of new monomers to the polymer chain.

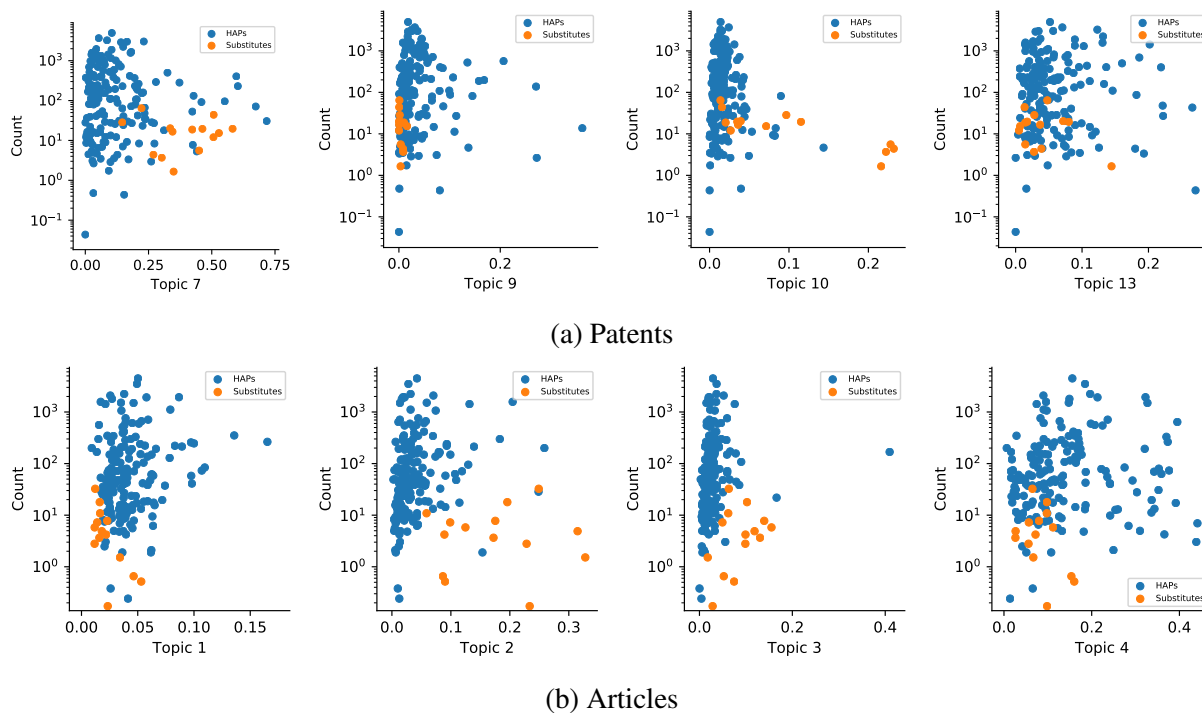


FIGURE 4

Topics Proportions and Counts for Selected Topics.

Note: The figures plot the average topic proportion for every molecule for a selected number of topics against the average count over the years of documents mentioning each molecule. Topic proportions are averaged over all documents mentioning the given molecule published (across all years in the sample). In particular, the graphs indicate that the semantic contexts of HAPs can vary far from those of CFC substitutes. Using topic proportions in the DiD and synthetic control methods therefore provides a way of controlling for variation in how different molecules are mentioned in the text of documents.

5 RESULTS

5.1 Difference-in-Differences

Although HAPs are related to industrial activities similar to those of CFC substitutes, some HAPs will be more similar to CFC substitutes than others. In particular, as Figure 5 illustrates,³¹ some have much higher counts than the average CFC substitute. In what follows, I adopt a strategy where only HAPs with similar counts are included in the control group. I use two criteria. First, I only include in the control group HAPs that have an average pre-period count of the same order of magnitude than the pre-period average count of CFC substitutes (i.e., not higher than ten times). Second, I rank all remaining HAPs according to how close their pre-trend is to that of the average CFC substitute. I then keep the 28 HAPs with closest slope. I choose the number of HAPs to be 28 so to construct a control group that is twice as large as the treated group. Figure 6 shows that pre-trends for the treated and control groups appear parallel.

I estimate the following two DiD models: a mean shift specification (Equation 3) and a trend-break specification (Equation 4)

$$Count_{mt} = \alpha + \beta_0 \cdot D_m \cdot Post_t + \lambda_t + \lambda_m + \gamma_t \cdot X_{mt} + \epsilon_{mt} \quad (3)$$

$$Count_{mt} = \alpha + \beta_1 \cdot Y \cdot Post_t \cdot D_m + \beta_2 \cdot Y \cdot Post_t + \beta_3 \cdot Y + \lambda_t + \lambda_m + \gamma_t \cdot X_{mt} + \epsilon_{mt} \quad (4)$$

$Count_{m,t}$ stands for the number of documents mentioning molecule m in year t ; $Post_t$ equals one when $t > 1987$; D_m equals one if the molecule belongs to the treated group; Y is a continuous variable indicating the number of years relative to 1987; λ_m are molecule fixed effects; λ_t are year fixed effects; X_{mt} is a vector of topic proportions. β_0 identifies the DiD estimate. The primary hypothesis is that β_0 and β_1 are positive. Furthermore, Online Appendix Table ?? displays balance tables for topic proportions and highlights that, for most topics, proportions are significantly different across the two groups. They may, therefore, capture relevant variation.

31. A similar graph can be found for articles in Online Appendix Figure ??

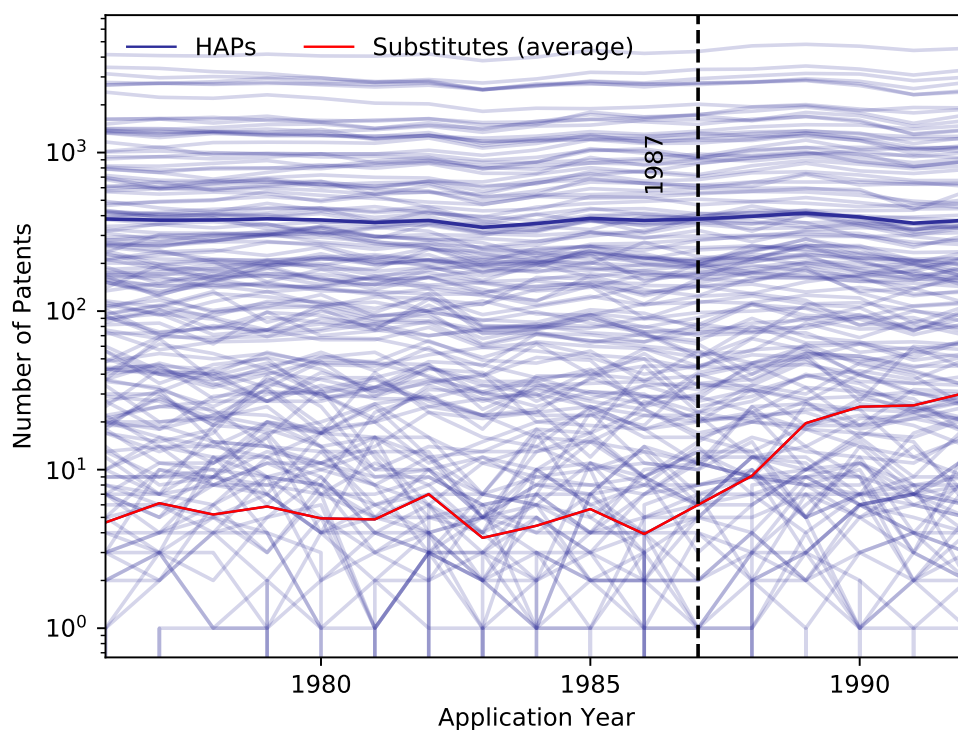


FIGURE 5

Patent Counts for Each HAP and for the Average CFC Substitute

Note: The graph shows patent counts for each HAP (thin lines), for HAPs on average (thick line labeled “HAPs”) and for CFC substitutes on average. The graph illustrates that many HAPs have counts much higher than the average CFC substitute and may, therefore, not be appropriate as comparison units.

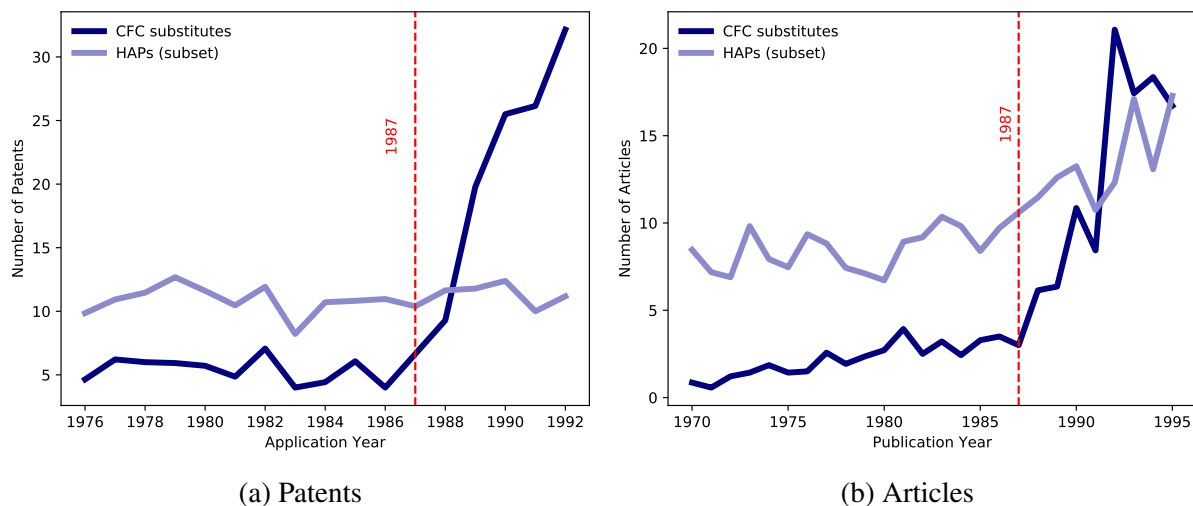


FIGURE 6

Pre-Trends in Counts of Documents Mentioning CFC Substitutes and HAPs

Note: The graphs display the pre-trends for the treated group (CFC substitutes) and the control group constructed using a subset of the HAP molecules that have counts and pre-trends closest to the average CFC substitutes.

TABLE 6
Difference-in-Differences Results

	(1) Patents	(2) Patents	(3) Patents	(4) Patents	(5) Articles	(6) Articles	(7) Articles	(8) Articles
Post 1987 x Substitutes	16.543*** (1.740)	21.124*** (2.056)	0.455 (2.681)	3.443 (2.494)	7.581*** (1.118)	12.634*** (1.689)	-0.273 (1.625)	1.437 (2.485)
Post 1987 x Substitutes x Years			5.235*** (1.005)	5.773*** (0.825)			1.825*** (0.379)	2.057*** (0.500)
Substitutes x Years			0.045 (0.117)	-0.004 (0.133)			-0.027 (0.078)	0.109 (0.159)
Years			-0.073 (0.063)	-0.086 (0.066)			0.183*** (0.029)	0.212*** (0.042)
Post 1987			1.182* (0.647)	1.205 (0.760)			0.968** (0.449)	0.913* (0.515)
Year FE	Yes	Yes	No	No	Yes	Yes	No	No
Molecule FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	No	Yes	No	Yes	No	Yes	No	Yes
Bootstrapped	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.841	0.859	0.854	0.875	0.634	0.640	0.634	0.638
Observations	714	595	714	595	1092	846	1092	846

Standard errors in parentheses

Years are relative to 1987.

Time-series: (1976-1992) for patents; (1970-1995) for articles

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The dependent variable is best suited to be modeled as count data using a Zero-Inflated Negative Binomial model.³² Since results do not differ much from the simpler specification with counts in levels, I report the latter as the main specification for ease of interpretation and provide results with a Zero-Inflated Negative Binomial model as robustness checks in Online Appendix Table ?? .

Table 6 displays the main results. Model 1 and 5 correspond to the differences-in-differences specification without any controls. The binary variable “Post 1987 x Substitutes” equals 1 for observations belonging to the group CFC substitutes after 1987. Model 2 and 6 control for topic proportions and is the preferred specification. For patents, the coefficient is large and statistically significant: it corresponds to an additional 21 patents on average per year per substitute from 1988 to 1992. Since there are 14 CFC substitutes in the sample, this implies 294 additional patents a

32. A Zero-Inflated Negative Binomial model is more appropriate than Poisson here because the data is zero-inflated and over-dispersed (as can be seen in Online Appendix Figure ??).

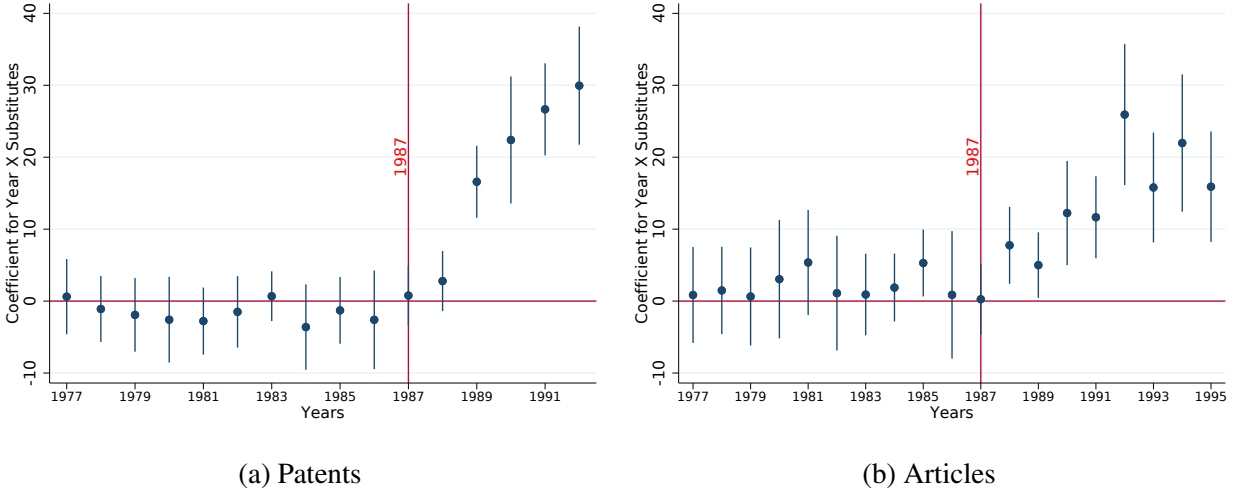


FIGURE 7

Difference-in-Differences Treatment Effects by Year Controlling for Topic Proportions

Note: For patents, the treatment effect is statistically significant, starting in 1989 and keeps increasing with time. For articles, the treatment effect is significantly different from zero from 1990 onwards.

year for CFC substitutes in aggregate, and it is equivalent to almost a 400% increase relative to the pre-period mean number of patents (which equals 5.4).

The coefficient for articles is also large and significant: it corresponds to an additional 13 articles on average per year per substitute from 1988 to 1995. Since there are 14 CFC substitutes in the sample, this implies 182 additional patents a year for CFC substitutes in aggregate, and it is equivalent to a 576% increase relative to the pre-period mean number of patents (which equals 2.19). Model 3, 4, 7, and 8 present trend-break specifications and confirm that the data can be modeled as a trend break too. The number of patents mentioning CFC substitutes increases with the years after 1987 by 5.8 patents more than the control group. Similarly, the number of articles mentioning CFC substitutes increases with the years after 1987 by two articles more than the control group.

Figure 7 displays the year-by-year coefficients corresponding to Model 2. We note that, for patents, the treatment effect is statistically significant, starting in 1989 and keep increasing with time. We should expect a delay between the moment firms and inventors decide to redirect their efforts towards CFC substitutes and the moment when they are ready to apply for a patent. However, the time required to obtain any technology worth patentable can vary broadly from technology to

technology, even within the same technological field. We can expect some patents to be “low-hanging fruits,” i.e., inventions requiring just a few months of R&D work before applying for a patent. Hence, it may not be surprising to observe a significant treatment effect as early as two years after Montreal. Others have documented similarly fast treatment effects. In the context of energy patenting, Popp (2002) estimates that the mean lag between a change in energy prices and patenting on energy-saving technologies occurs in 3.71 years.

For articles, the treatment effect is significantly different from zero from 1990 onwards (see Panel b in Figure 7). Since the data only contains the publication date of articles (as opposed to submission date), the lag between treatment and its effect also accounts for processing and reviewing time at academic journals (which, in chemistry and engineering, takes around nine months on average (Björk and Solomon 2013)).

Using HAPs to construct a counterfactual, the treatment effect captures the overall effect of the Protocol’s signature, the country-by-country ratifications,³³ and the amendments to the Protocol that happened in 1990 and 1992 (in London and Copenhagen respectively). It also includes, therefore, the implementation of these international treaties into domestic regulations. In the US, for example, this was done through the Clean Air Act amendment of 1990. The counterfactual, therefore, represents a world without any of those interventions, i.e., a world with limited unilateral actions. The inherent challenges of any global public good problem provide a good case for arguing that a world with limited unilateral actions is an appropriate counterfactual. The absence of costly unilateral actions before 1987 is further testimony to those challenges.³⁴

5.2 Robustness Checks

I run additional DiD specifications controlling for lags of counts. A typical model of science and innovation is one with positive knowledge externalities: patents or articles lead to more patents and articles as scientists and inventors build on previous work. Controlling for lagged count allows

33. The USA ratified in April 1988; European countries in December 1988.

34. The aerosol bans in the 70s and 80s were not costly because physical and chemical substitutes existed; for example, roll-on deodorants instead of spray deodorants.

capturing such a cumulative mechanism. Model 2 in Table 7 confirms that the treatment variable remains statistically significant in both patents and articles. Model 3 shows that results are robust to considering, as an alternative outcome variable, counts weighted by the number of forward citations each document receives. Citations can be interpreted as the publication’s degree of influence (or “quality”). Panel a and c in Figure 8 show that pre-trends in citation weighted counts look similar across CFC substitutes and HAPs for both patents and articles.

Similarly, Model 4 shows that the results are robust to considering patent and article counts weighted by the number of times the molecule appeared in each document (molecule “occurrence”). Panel b and d in Figure 8 show that pre-trends in occurrence-weighted counts look similar across CFC substitutes and HAPs in patents. For articles, a small pre-trend indicates that, when articles contain the name of CFC substitutes, they tend to mention these substitutes more often over the years. I provide more details about trends in counts for different thresholds of occurrences in Figure ??.

5.3 Synthetic Control Method

5.3.1 Implementation

The DiD strategy implemented above assumes that the counts of patents and articles for each molecule are independent. However, a single document typically mentions several CFC substitutes; almost 40% of patents mention more than one molecule.³⁵ An alternative strategy is to add up the observed counts of the 14 CFC substitutes and consider them as one single treated unit (what I refer to as the “aggregate CFC substitute”). To illustrate, Figure 9 plots the number of patents mentioning each CFC substitute, and the thick line corresponds to the number of patents mentioning any of the 14 CFC substitutes.

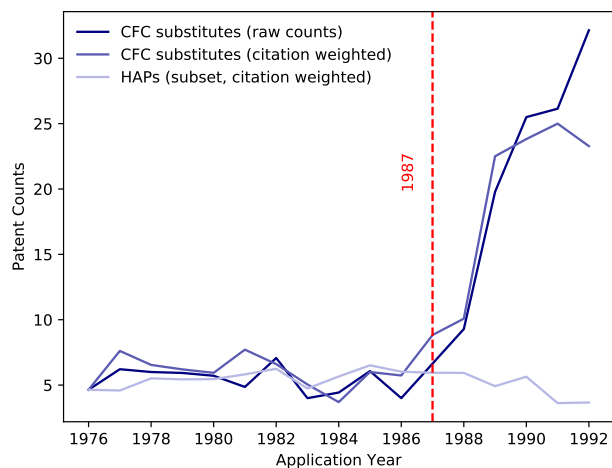
To obtain an estimate of the treatment effect on the “aggregate CFC substitute,” I implement a Synthetic Control Method and constructs a counterfactual molecule that mimics the evolution

35. Out of 3270 patents mentioning CFC substitutes, 1234 mention more than one CFC substitutes. The DiD considers 5999 observations when, in reality, there are only 3270. For articles, out of 998, 226 mention more than one CFC substitutes. Hence the DiD considers 1266 observations when, in reality, there are only 998.

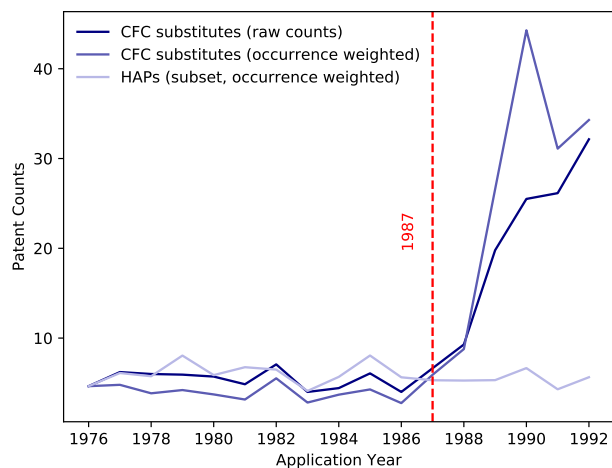
TABLE 7
Difference-in-Differences Robustness Checks

(a) Patents					
	(1) Count	(2) Count	(3) Cit	(4) Occ	(5) Cit-Occ
Post 1987 x Substitutes	21.124*** (2.056)	12.999*** (1.706)	29.849*** (3.376)	33.454*** (3.786)	44.910*** (6.697)
Count (lag 1)		0.385*** (0.074)			
Count (lag 2)		0.265*** (0.072)			
Year FE	Yes	Yes	Yes	Yes	Yes
Molecule FE	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	Yes	Yes	Yes	Yes	Yes
Bootstrapped	Yes	Yes	Yes	Yes	Yes
R-squared	0.859	0.897	0.784	0.702	0.664
Observations	595	528	595	595	595
Time span: 1976 to 1992					
(b) Articles					
	(1) Count	(2) Count	(3) Cit	(4) Occ	(5) Cit-Occ
Post 1987 x Substitutes	12.634*** (1.689)	5.098*** (1.250)	12.216*** (3.383)	17.619*** (2.708)	18.110*** (4.430)
Count (lag 1)		0.341*** (0.054)			
Count (lag 2)		0.340*** (0.076)			
Year FE	Yes	Yes	Yes	Yes	Yes
Molecule FE	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	Yes	Yes	Yes	Yes	Yes
Bootstrapped	Yes	Yes	Yes	Yes	Yes
R-squared	0.640	0.751	0.342	0.490	0.373
Observations	846	790	846	846	846
Time span: 1970 to 1995					

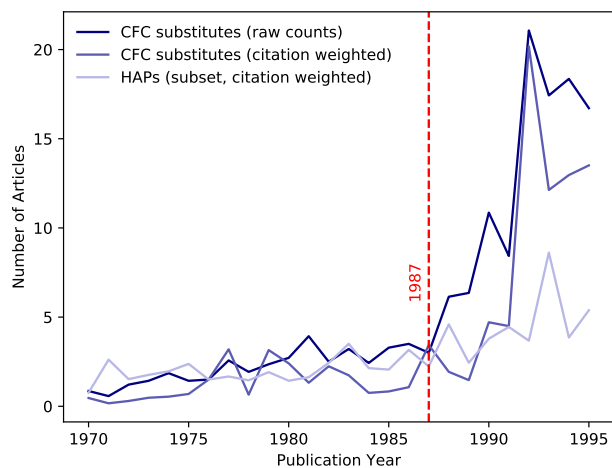
Note: The tables present the regression results for robustness checks for the difference-in-differences. The specifications use different outcome variables. Column 1 and 2 use counts; column 3 uses citation-weighted counts; column 4 uses occurrences-weighted counts, and column 5 uses counts weighted by both citation and occurrences.



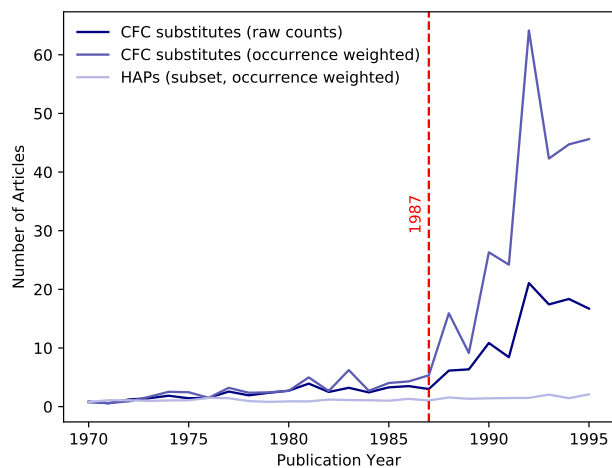
(a) Patent Citation Weighted Counts



(b) Patent Occurrence Weighted Counts



(c) Article Citation Weighted Counts



(d) Article Occurrence Weighted Counts

FIGURE 8

Time Series of Citation- and Occurrence-Weighted Counts

Note: Time-series are scaled to make them equal in the first year of the sample. The graphs indicate that the post-1987 gap between CFC substitutes and HAPs persists even when counts are weighted by the number of citations or by the number of times molecules appear in the text.

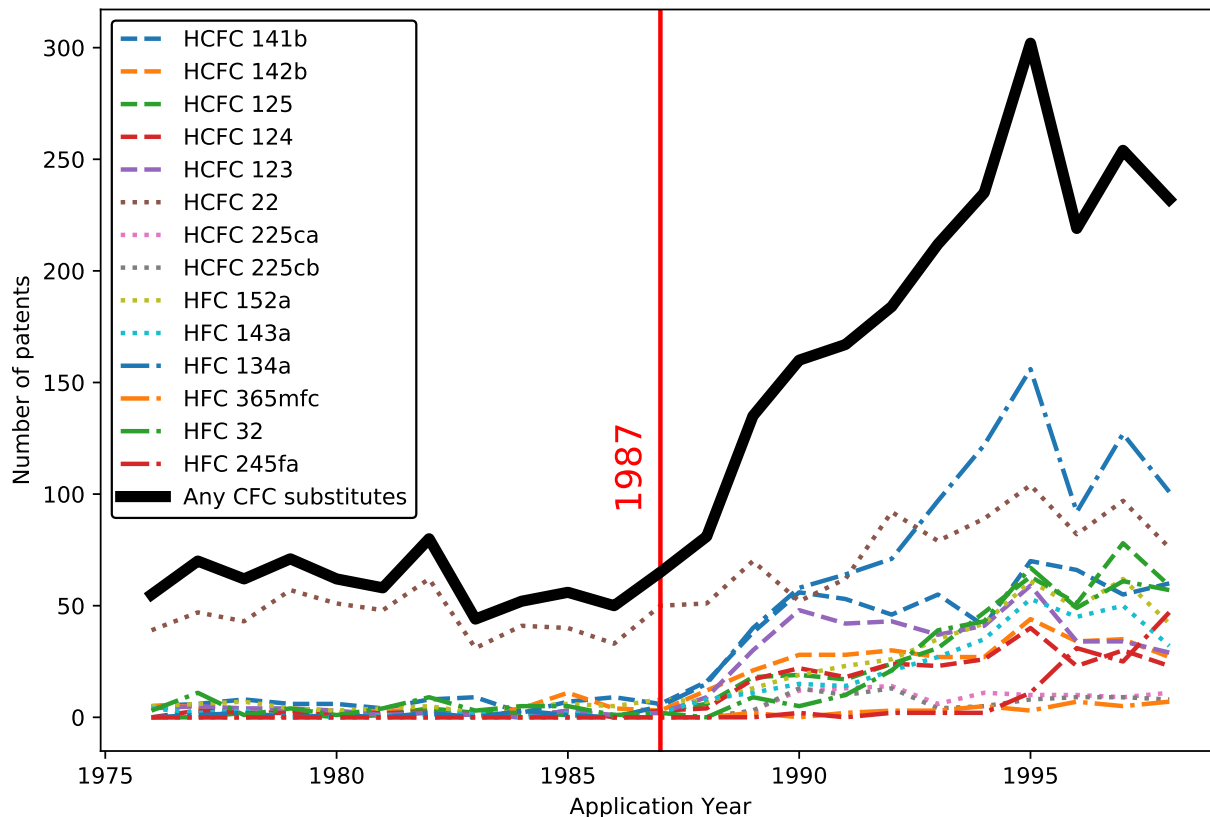


FIGURE 9

Patent Counts for Each CFC Substitute and for the “Aggregate” CFC Substitute

Note: The graph illustrates the difference between considering the 14 molecules independently and considering them as one treated molecule. Since the names of different CFC substitutes often appear simultaneously in the same documents, the time series of CFC substitutes are not independent of each other. The thick line called “Any CFC substitutes” corresponds to the number of patents mentioning any of the 14 CFC substitutes. It is equivalent to considering the 14 compounds as one and only one molecule. I implement the synthetic control method on this “aggregated CFC substitute.” Online Appendix Figure ?? displays a similar graph for articles.

of CFC substitutes in aggregate. The synthetic control method emerged as a way to evaluate the effects of interventions that affect aggregate quantities (Abadie, Diamond, and Hainmueller 2010, 2015; Abadie and Gardeazabal 2003; Athey and Imbens 2017). Many interventions are in fact implemented at an aggregate level and impact a small number of large entities, such as cities, school districts, or states. I enlarge the application of SCM to a new kind of aggregate entity: field of scientific and engineering inquiry.

The synthetic control method consists of using a weighted average of a set of control units with the weights chosen so that the weighted average is similar to the treated unit regarding covariates

and outcome in the pretreatment periods.³⁶ The outcome is the number of patents (or articles) that mention any of the 14 molecules. The synthetic control is constructed by fitting the values of counts in the pretreatment period and the topic proportions. The treatment year is the first year in which the treatment becomes active: this is defined as 1988 since Montreal was agreed in 1987. To be conservative, I use data only up to 1985 to fit the synthetic control. Topic proportions are averaged over the entire pre-1985 period, while the outcome, count, is not.

As explained by Abadie, Diamond, and Hainmueller (2015), reducing the size of the donor pool can limit the risk of over-fitting and the risk of interpolation biases. Following their advice, I use a smaller donor pool containing only the thirty HAPs closest to the treated unit in terms of counts.³⁷ For inference, I follow the non-parametric approach method suggested by Abadie, Diamond, and Hainmueller (2010) and Abadie, Diamond, and Hainmueller (2015). The approach is akin to implementing placebo tests wherein each unit in the control group is assumed to have received the treatment in the year 1987. The “true” treatment effect can then be compared to the distribution of placebo treatment effects. A p-value is calculated as the fraction of placebo effects that are greater than or equal to the effect estimated for the “true” treated unit. As suggested by Abadie, Diamond, and Hainmueller (2010), I compute the ratios of post-RMSPE over pre-RMSPE and examine where the treated unit lies in the distribution of those ratios.³⁸

5.3.2 Results

Figure 10 graphically displays the results of the synthetic control method for CFC substitutes. The graphs on the left-hand side represent the raw effect, which is the observed time series of the treated group along with the time series of the constructed synthetic control. Graphs on the right-hand side show the placebo tests to evaluate the significance of the results; the black lines represent the effect on the treated group relative to the control group, while each gray line is a placebo test performed

36. Online Appendix ?? provides more details on the theoretical foundations for the synthetic control method.

37. I also check that there is no risk of extrapolation. See Online Appendix Table ??

38. The pre-RMSPE measures lack of fit between the path of the outcome variable for any particular unit and its synthetic counterpart: the pre-RMSPE of unit i is defined as $(\frac{1}{T_0} \sum_{t=1}^{T_0} (Y_{it} - \sum_{j=2}^{J+1} w_j^* Y_{jt}))^{1/2}$ where T_0 is the number of pretreatment periods. A post-RMSPE can be similarly defined for periods going from $T_0 + 1$ to the end of time-series available.

on a unit drawn from the donor pool. The treatment effect on CFC substitutes appears significant for both patents and articles. We note that the black line rises above most other lines, mostly as of 1989. This indicates that, as in the DiD, the treatment effect is statistically significant, starting in 1989. For articles, the treatment effect is statistically significant, starting in 1992.

Graphically, the treatment effect corresponds to the area between the two curves on the left-hand side graphs. Numerically, it corresponds to 84 (resp. 49) additional patents (resp. articles) per year on average between 1988 and 1992 (resp. 1995). This roughly corresponds to 135% and 177% increases in patents and articles. To examine more closely the constructed control unit, Figure 8 provides information regarding the main HAPs that compose it.³⁹ We note that the synthetic control picked up HAPs that have broad industrial applications (not unlike CFC substitutes). In particular, we find industrial applications (e.g., coatings or solvents) similar to CFC substitutes.

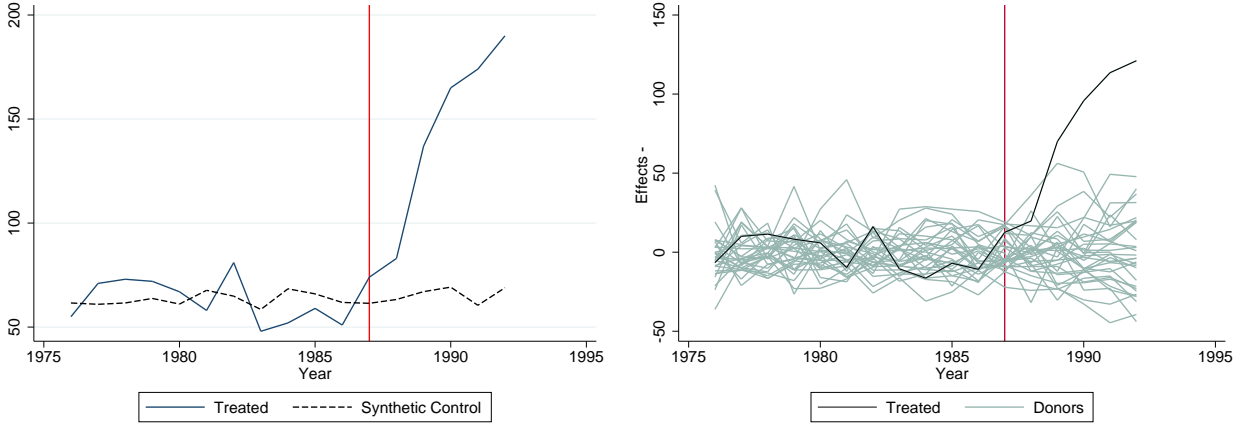
6 MECHANISMS AND ALTERNATIVE HYPOTHESES

6.1 Mechanisms

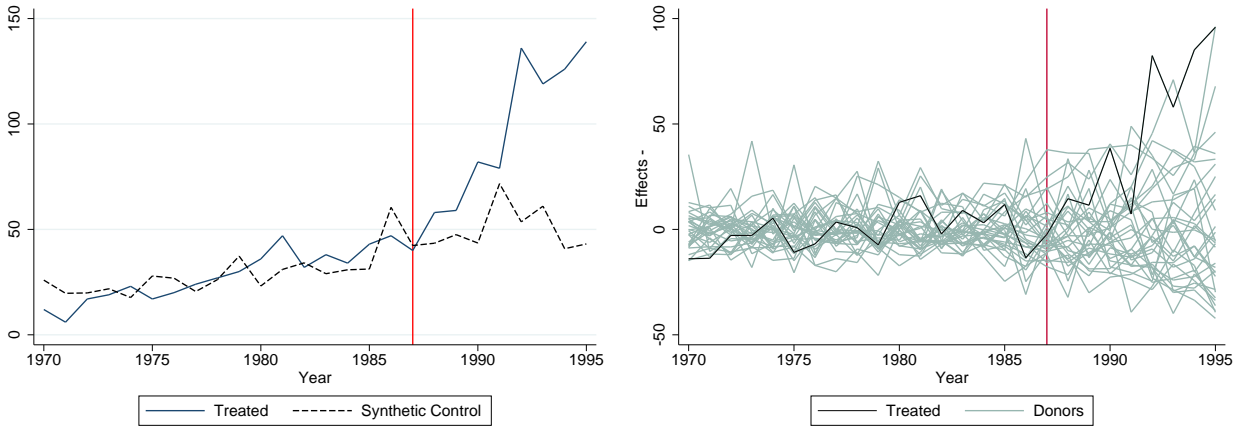
In this section, I provide more descriptive details about the increase in research and innovation fostered by Montreal. First, Figure 11 shows that the increase in the number of patents mentioning CFCs applies to all countries; we note a substantial increase for patents with assignees located in Japan and the UK. Online Append Table ?? provides more detailed summary statistics. We note that US-based private sector firms are the entities patenting the vast majority of CFC substitutes, both before and after Montreal. Finally, Figure 12 illustrates that the most frequent patent codes are generally the same before and after 1987. At the same time, many codes with low or no frequency before 1987 become important after 1987.⁴⁰

39. Additionally, Table ?? displays the value of each variable's contribution to the synthetic control.

40. C08G: Macromolecular compounds obtained otherwise than by reactions only involving carbon-to-carbon unsaturated bonds, C10M: Lubricating compositions; Use of chemical substances either alone or as lubricating ingredients in a lubricating composition, C23G: Cleaning or de-greasing of metallic material by chemical methods other than electrolysis, C11D: Detergent compositions; Use of single substances as detergents; Soap or soap-making; Resin soaps; Recovery of glycerol.



(a) Patents: Raw Effect (left) and Placebo Tests (right)



(b) Articles: Raw Effect (left) and Placebo Tests (right)

FIGURE 10

Synthetic Control Method Graphs for CFC Substitutes

Note: The treatment effect on CFC substitutes appears significant for both patents and articles. We note that the black line rises above most other lines, mostly as of 1989. This indicates that similarly, as in the DiD, the treatment effect is statistically significant, starting in 1989. For articles, the treatment effect is statistically significant, starting in 1992.

TABLE 8
HAPs Contributing to the Synthetic Control

(a) Patents

HAPs	Weight	Description
Calcium cyanamide	0.327	Used as a fertilizer, defoliant, herbicide, fungicide, and pesticide; in the manufacture and refining of iron; and in the manufacture of calcium cyanide, melamine, and dicyandiamide.
Polychlorinated biphenyls	0.206	Group of chemicals characterized by non-flammability, stability, high boiling point and electrical insulating properties. Hundreds industrial applications: electrical and heat transfer, paints, plastics.
Methyl bromide	0.140	Used as a fumigant in soil to control fungi, nematodes, and weeds; inspace fumigation of food commodities (e.g., grains); and in storage facilities (such as mills, warehouses, vaults, ships, and freight cars) to control insects and rodents.
Benzidine	0.116	Production of dyes, especially azo dyes in the leather, textile, and paper industries
o-Xylenes	0.103	Used in the production of ethylbenzene, as solvents in products such as paints andcoatings, and are blended into gasoline.

(b) Articles

HAPs	Weight	Description
Bromoform	0.503	Used as a fluid for mineral ore separation, as a laboratory reagent and in the electronics industry in quality assurance programs. Was used as a solvent for waxes, greases, and oils, as an ingredient in fire-resistant chemicals and in fluid gauges. Also used as an intermediate in chemical synthesis, as a sedative and cough suppression agent.
1,4-Dichlorobenzene	0.332	Used mainly as a fumigant for the control of moths, molds and mildews, and as a space deodorant for toilets and refuse containers. Also used as an intermediate in the production of other chemicals, in the control of tree-boring insects, and in the control of mold in tobacco seeds.
Trifluralin	0.165	Herbicide. Mostly used on cotton, soybeans and some fruits and vegetables

Note: The tables describe the HAPs entering the synthetic control for the synthetic control method specification. The information displayed in the "Description" column was collected from the EPA website.

The post-Montreal burst of innovations on CFC substitutes is also not driven by a few firms that would have been historically patenting on CFC substitutes since the 1970s. Figure 13a displays the yearly number of unique assignees with patents mentioning CFC substitutes and HAPs. It indicates that the post-Montreal patenting world features many more firms. Figure 13 displays the yearly number of assignees that are "new", meaning they appear for the first time in the data with a patent mentioning CFC substitutes and HAPs. The figure confirms that, after 1987, many firms with no prior experience on CFC substitutes begin patenting.

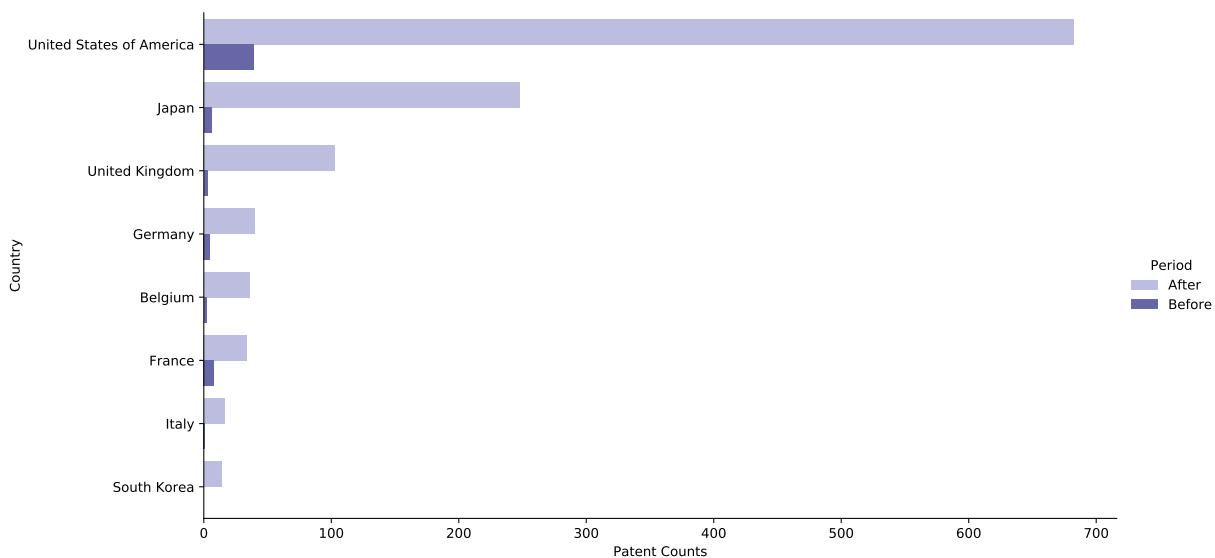


FIGURE 11
Patent Counts by Country Before and After 1987

6.2 Were CFC Substitutes Kept "Secret"?

In this section, I further examine whether firms may have initiated the transition to CFC substitutes before the signature of the Montreal Protocol, without patenting but instead keeping their technologies as trade secrets. At the end of the 1970s, a few firms announced some R&D investments into CFC substitutes. Although the same firms, soon after, announced the termination of those same R&D programs, it has been suggested that they developed key technologies which they kept secret.

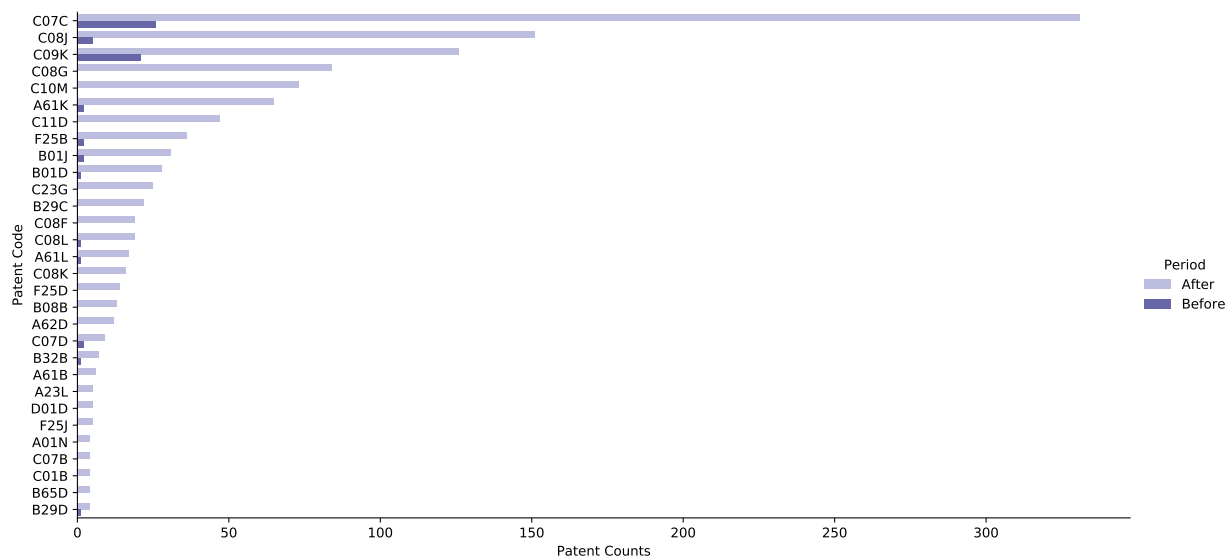


FIGURE 12

Most Frequent Codes for Patents Mentioning CFC Substitutes Before and After 1987

Note: The figure illustrates the differences between the most frequent codes for patents before and after 1987. The most frequent patent codes before 1987 tend to be the most frequent after 1987. At the same time, some codes with low to zero frequency before 1987 become important after 1987 (e.g., C08G, C10M, C23G or C11D). Only patents with at least 3 molecule occurrences are kept in the sample.

Here, I argue that, if that had been the case, we should expect a one-time increase in patent counts in the immediate aftermaths of Montreal. Indeed, when competitors work on closely related projects, delaying patenting increases the risk that a competitor patents first. If, until Montreal, firms were with the impression that policy pressure was low, they may have elected not to patent. However, once the protocol is signed, they have tangible incentives to patent any old technologies that they may have previously developed as fast as possible to outrun possible competitors.

Figure 14 plots the number of patents mentioning CFC substitutes month by month in the two years that followed Montreal. On the first graph, we note the absence of a patenting peak after 1987. On the second graph, I present trends for assignees that never patented on CFC substitutes before 1987 and those who did. If the R&D carried out before Montreal was a key driver to the post-Montreal increase in patenting, we would observe significant differences in patenting trends between firms with and firms without prior patenting experience on CFC substitutes. Although a gap seems to build up over time, trends look mostly similar.

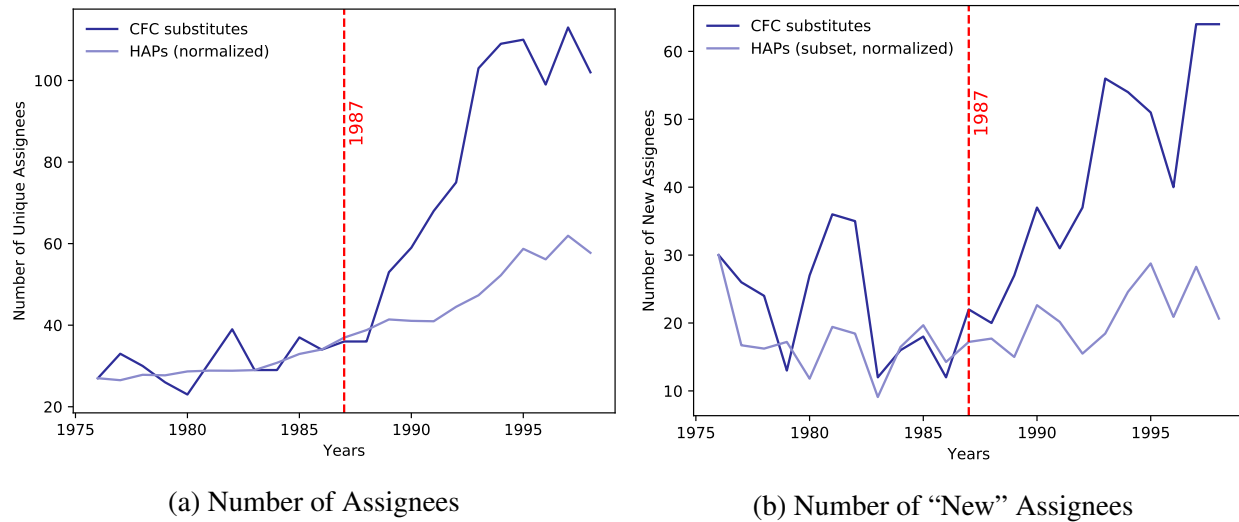


FIGURE 13

Number of Patent Assignees Over Time

Note: Figure 13a displays the number of assignees that patent on CFC substitutes or HAPs in any given year. Figure 13b displays the number of assignees that are "new" (i.e., they apply for a patent on CFC substitutes or HAPs for the first time). The figure shows that, after 1987, many firms with no prior experience on CFC substitutes begin patenting. To limit noise, the sample used to generate the table contains only documents with at least three occurrences of CFC substitutes.

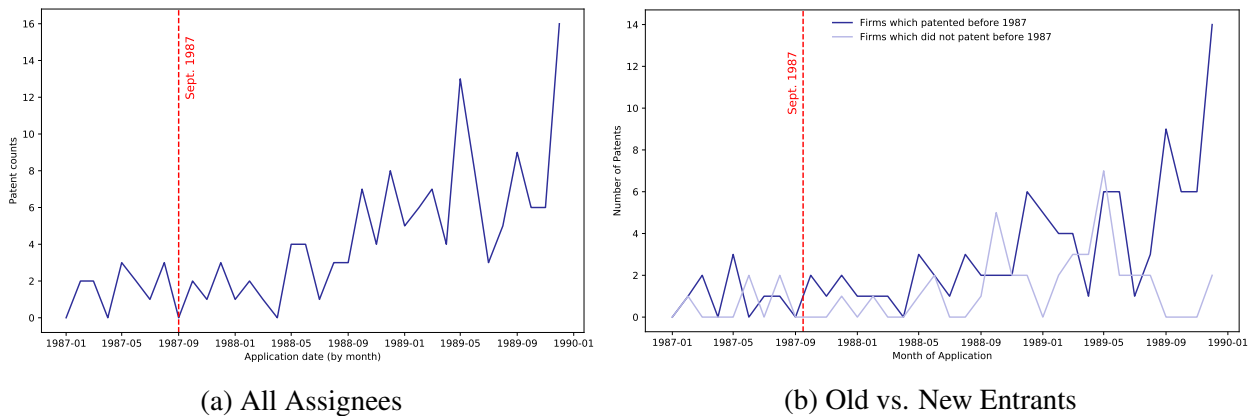


FIGURE 14

Monthly Counts for Patents Mentioning CFC Substitutes

Note: The graphs show the monthly trends in count of patents mentioning CFC substitutes. Panel 14b shows the monthly count of patents mentioning CFC substitutes for firms that patented on CFC substitutes before 1987 vs. those who did not. The period "Before 1987" includes the year 1987. To limit noise, the sample used to generate the table contains only documents with at least three occurrences of CFC substitutes.

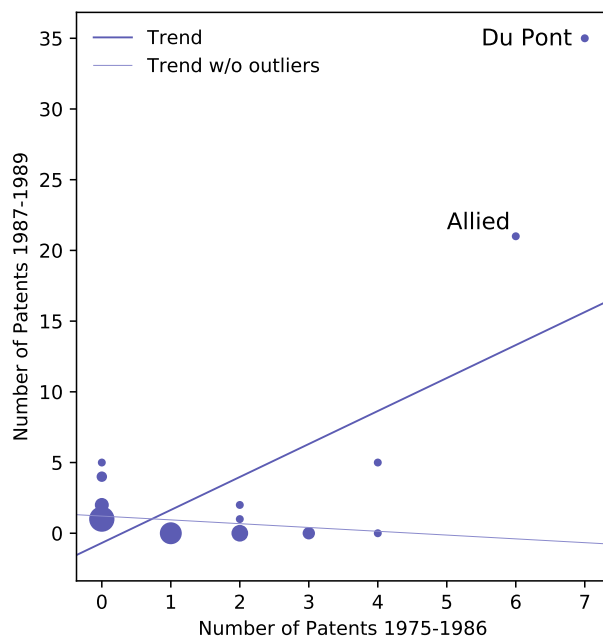


FIGURE 15
Patenting Before 1987 as a Predictor to Patenting After 1987

Note: The size of the dot is proportional to the number of firms. To limit noise, the sample used to generate the table contains only documents with at least three occurrences of CFC substitutes. The scatter plot shows, for each firm in the sample, patent counts between 1975 and 1986 on the x-axis, and patent counts in the two years that followed Montreal on the y-axis. We see that two outlier firms drive to a positive trend: DuPont and Allied. Excluding those, there are no clear correlations between patenting before 1987 and patenting in the immediate aftermaths of Montreal.

Figure 15 illustrates the possible key role of a few manufacturers: the scatter plot shows, for each firm in the sample, the number of patents between 1975 and 1986 on the x-axis and the number of patents in the two years that followed Montreal on the y-axis. We see that two outlier firms (DuPont and Allied) drive the positive correlation. Excluding those, there are no clear correlations between patenting before 1987 and patenting in the immediate aftermaths of Montreal. This plot, however, motivates a more detailed investigation in the behavior of DuPont and Allied.

Figure 16a shows that most patents granted to DuPont and Allied were applied for after 1989, and in particular, Figure 16b shows that there is no sudden peak patenting right after Montreal. Instead, we observe a gradual ramping up of patenting activity. Figure 16c illustrates that the patents from DuPont and Allied which received the highest number of citations, mostly originate from 1989 to 1991. Figure 16d indicates, however, that, in the weeks that followed Montreal, both DuPont and Allied applied for patents that would go on receiving a high number of citations. This

seems to indicate that DuPont and Allied likely had a first-mover advantage on some technologies. However, the magnitude of the ramping up in patenting activity that follows from 1990 onwards supports the claim that most of the innovative activity started after Montreal.⁴¹

6.3 Was Consumer Pressure a Potential Driver?

The science of ozone made much progress during the 1980s. In particular, in 1985, scientists detected an extensive depletion of ozone over Antarctica (the “hole”), and importantly, they were able to causally attribute it to CFCs in March 1988 (the “discovery”). The image of the Earth seen from space with a massive hole (artificially colored in blue for the occasion) became world-famous and moved public opinion. The perceived benefits of phasing-out CFCs certainly increased and made the issue more salient in the eyes of the public. To what extent, then, did consumer pressure drive innovation in the aftermaths of Montreal?

There exist very few empirical analyses suggesting that consumer pressure is effective (Lyon and Maxwell 2002; Popp, Hafner, and Johnstone 2011), and they all deal with local pollutants such as toxic chemical emissions. We could reasonably expect consumer pressure to be less effective for a global air pollutant such as ozone. As profit-maximizing entities, firms would have few incentives to incur R&D costs without the guarantee of a large market, and without the guarantee that their foreign and domestic competitors do the same. To investigate the role of consumer pressure for innovation on CFC substitutes, I leverage the fact that not every molecule or application was exposed to consumers. Restricting the analysis to substitutes unexposed to consumers allows setting aside the possible influence of public opinion.

I use data available on the EPA SNAPs website to identify which CFC substitutes were not exposed to consumers. The EPA website lists a total of 1001 requests corresponding to a given

41. Another way of examining the effect of the international agreement on DuPont would be to look at DuPont’s stock market valuation. Unfortunately, although in 1986 DuPont produced CFCs for about half of the US market, it represented only 2.2% of DuPont revenues (1.8% in 1984 and 1.7% in 1985), 2% of corporate assets and 0.9% of DuPont’s employees (Reinhardt and Vietor 1989). It is therefore unlikely that financial markets would capture much impact. Additionally, it would be difficult to attribute any movement to the regulation of CFCs only and not to other parts of DuPont’s business (especially since DuPont was facing other public relations issues related to medical implants of which it supplied the raw material).

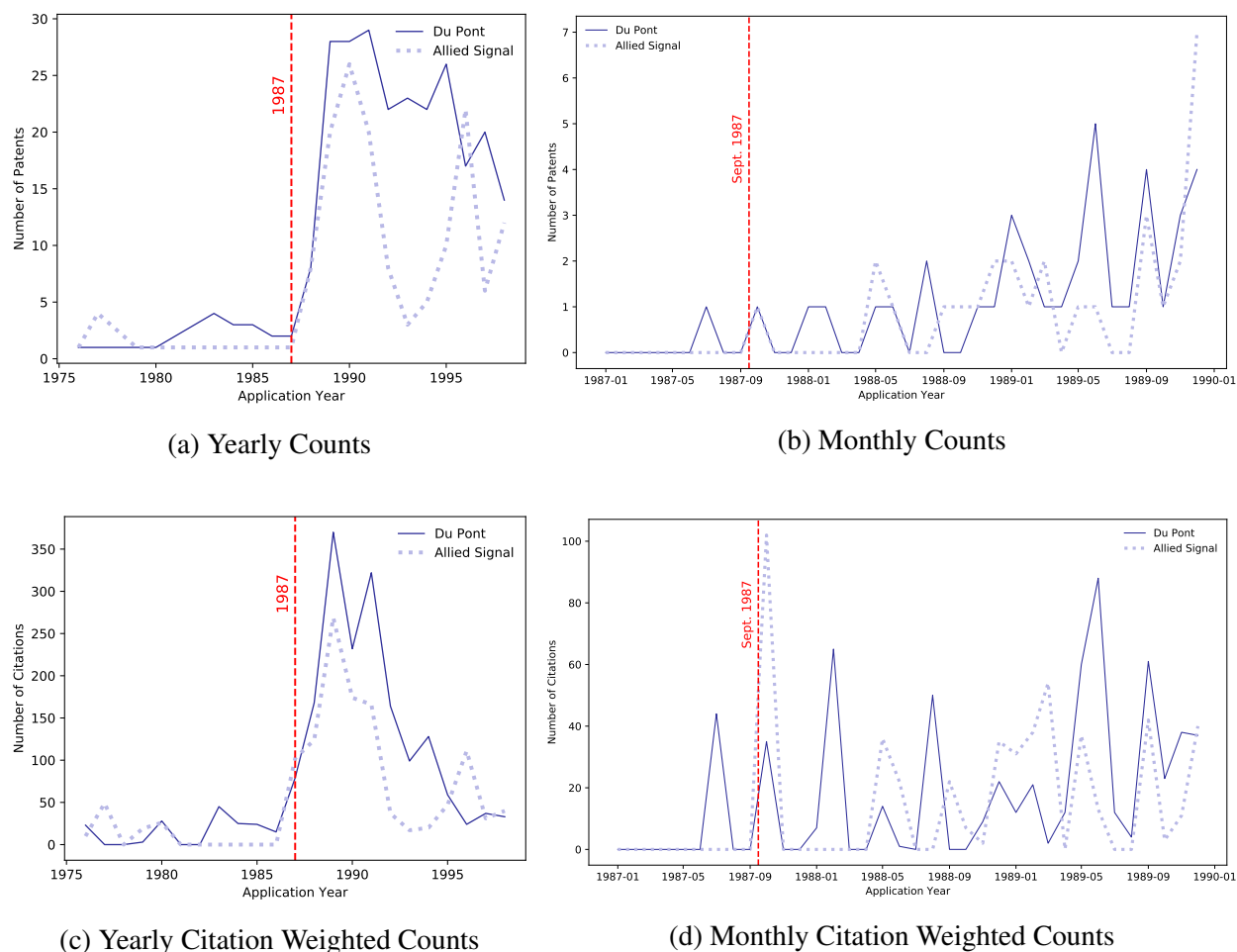


FIGURE 16

Patent Counts for DuPont and Allied

Note: Figure 16a shows that most patents granted to DuPont and Allied were applied for after 1989. Figure 16b shows that there is no sudden peak patenting right after Montreal. Instead, we observe a gradual ramping up of patenting activity. Figure 16c illustrates that the patents granted to DuPont and Allied, which received the highest number of citations, mostly originate from 1989 to 1991. Figure 16d indicates, however, that, in the weeks that followed Montreal, both DuPont and Allied applied for patents that would go on receiving a high number of citations. Only patents with at least three occurrences of a molecule are retained in the sample.

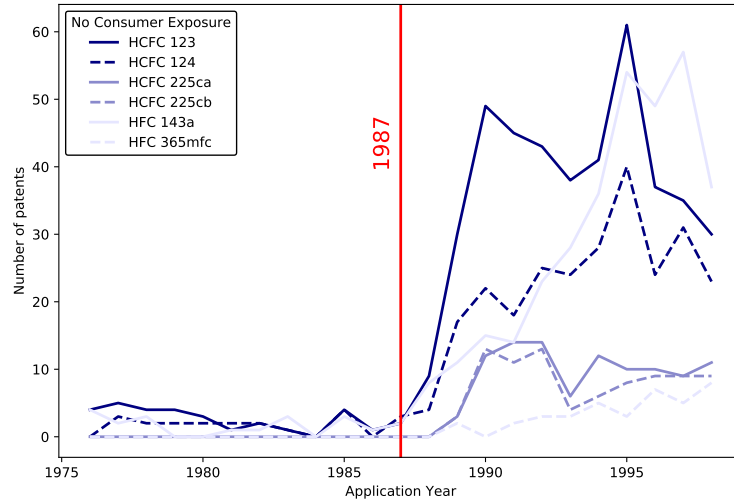


FIGURE 17

Patent Counts for CFC Substitutes not Exposed to Consumers

Note: The plot shows the temporal evolution of the number of patents mentioning CFC substitutes that were arguable not exposed to consumers. We observe that, for almost all of them, the number of patents increases sharply after 1987. This is indicative that consumer pressure and public opinion did not play an essential role in driving innovation in the aftermath of the Montreal protocol.

substance for a given application. As part of the implementation of the Montreal protocol, the EPA was in charge of controlling which substitutes firms could use. To this end, any firm using or producing substitutes had to request an authorization for a specific substance-application pairs. An example is HCFC-225cb for Electronics Cleaning. I manually classify applications as either consumer exposed, not consumer exposed, or undetermined. In doing so, I identify 6 CFC substitutes that are not consumer exposed. The typical applications requested for these CFC substitutes are all related to industrial activities invisible to consumers: e.g., centrifugal chillers, foam blowing agents for rigid polyurethane, or precision cleaning.

Figure 17 displays the time-series of the number of patents mentioning CFC substitutes that were arguable not exposed to consumers. We observe that, for almost all of them, the number of patents increases sharply after 1987. This is indicative that consumer pressure and public opinion did not play an essential role in driving innovation in the aftermath of the Montreal protocol.

7 DISCUSSION AND CONCLUDING REMARKS

Tackling environmental problems often relies on developing and diffusing new technologies. It is, therefore, important to better understand the drivers of technological change. In this paper, I document that the Montreal Protocol, and its following amendments, led to the development of CFCs substitutes. This empirical evidence goes against the often-heard narrative that alternatives technologies were readily available before the treaty. Sociologist Reiner Grundmann once characterized that narrative as “the most pervasive and most widespread myth surrounding the Montreal Protocol” (Grundmann 1998).⁴² And indeed, the treatment effect estimated in this paper tells a story where almost all of the science and innovation on CFC substitutes was triggered by the post-Montreal regime.

The signature of Montreal induced firms and researchers to orient their R&D effort towards CFC substitutes. It had the immediate effect of modifying expectations about future prices and created a worldwide demand for substitutes. As a result, it incentivized profit-seeking firms to bring CFC substitutes to market at the cheapest possible cost. As explained, CFC substitutes did exist on paper for a long time, but the challenge was to make them cost-effective for many industrial applications. Patenting, here, can be interpreted as efforts to lower down such costs, the typical reason why firms patent in response to environmental policies. Researchers publishing in peer-reviewed journals also redirected scientists’ work towards CFC substitutes, possibly due to a shift in their research priorities at a time where both government and industry required more information about the molecules.

The role of the Montreal Protocol in solving the crisis has been intensely discussed. In a seminal article, Barrett (1994) developed a theory of international environmental agreements which highlighted that Montreal was successfully negotiated because it was cheap to do so. Murdoch and Sandler (1997) also argued that some countries, and in particular the USA, accepted to sign Montreal because the costs of doing so were low. They highlighted the existence of a cost-and-

42. Benedick traces the origin of the “myth” to the fierce opposition between Americans and Europeans during the Concorde controversy (Benedick 2009, p. 33).

benefit analysis issued by the EPA in 1987, concluding that the estimated benefits (cancers avoided) overwhelmed the estimated costs on the industry.

The idea that the Montreal agreement was “cheap” has often been rephrased as the idea that substitutes existed. However, it is more exact to state the claim in terms of what, at the time, industries and governments expected to be technologically feasible. A crucial but typically understated fact is that the targets in Montreal were not ambitious. Indeed, the agreement was not successful in its attempt to negotiate a full ban (which the industry actively lobbied against). Instead, it settled for modest emission reduction targets. Hence, we shall not be surprised that the expected compliance costs calculated at the time by the EPA were low.

The real success should be seen in the later amendments: London in 1990 and Copenhagen in 1992. More ambitious reduction targets were then agreed (deepening), while other molecules were added to the list of regulated compounds (widening). An interesting question to ask, therefore, is why countries agreed to widen and deepen the protocol. To this, the results in this paper can contribute a novel answer. On the one hand, Montreal was not ambitious, but, on the other, it set up a credible enforcement mechanism which, critically, changed firms’ expectations about CFCs. Hence, the agreement induced innovation. In doing so, it contributed to lowering down the perceived costs associated with a full phase-out.

Hence, the success story of Montreal is better summarized as a repeated cooperation game with ratcheting up ambitions and where innovation plays the critical role of enabling factor. It is a case of the theory of international environmental agreements and the theory of induced innovation walking hand in hand. At each stage, binding reductions force firms to innovate and develop technologies to comply. With realized innovations, expectations for further innovation increase, and the expected costs of abatement decrease. More aggressive reductions then appear affordable, and governments and industries become willing to increase ambition and bind themselves to it.

When solutions to environmental problems are plagued with technological uncertainties or high price tags, decision-makers are tempted to wait for proven cheap technologies, and then negotiate an agreement. By showing that agreements can encourage the development of green technolo-

gies, this paper suggests they should be negotiated as early as possible if we hope to solve global environmental problems.

SUPPLEMENTARY MATERIAL

The Online Appendix for this article can be found at eugeniedugoua.com/papers/Dugoua_Innovation_Montreal_SOM.pdf.

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