

Directed Technological Change and International Environmental Agreements: Quantitative Evidence from the Montreal Protocol*

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Abstract

Can international environmental agreements help direct technological change? An extensive literature has shown that domestic environmental policies foster the development of green technologies. But it is unclear whether international agreements can do the same. Rather, they might occur only when readily available technological solutions facilitate cooperation. I provide the first empirical evidence that the Montreal Protocol, and its following amendments to protect the ozone layer, triggered a large increase in research and innovation on alternatives to ozone-depleting molecules. To do this, I use the full text of patents and scientific articles to construct new panel data of the yearly number of published documents mentioning these molecules. I first implement a difference-in-differences strategy using hazardous air pollutants as control units. I then leverage a synthetic control method to obtain more appropriate comparison units. To construct synthetic controls, I measure the similarity between molecules by applying machine learning techniques to the documents' text. The latter method estimates that the post-Montreal regime caused a 170% increase in patents and a 190% increase in articles mentioning substitutes to ozone-depleting substances; the difference-in-differences strategy yields comparable estimates. These results challenge the view that agreements foster technological diffusion without affecting much of the dynamics of innovation. Agreements can thus encourage the development of green technologies, which importantly suggests they should be negotiated as early as possible if we hope to solve global environmental problems such as climate change.

JEL Classification: O31, O33, Q55, Q58, F53

Keywords: international agreements, Montreal Protocol, ozone, CFCs, synthetic control, topic modeling, environment, innovation.

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1 Introduction

Technological change is a keystone for addressing many environmental problems. A large literature has developed to better understand the drivers of environmental-friendly innovation, and many studies show that domestic environmental policies can foster green innovation (Jaffe, Newell, and Stavins 2002; Popp, Newell, and Jaffe 2010). But, environmental degradation often runs across national borders. In this context, individual governments usually lack incentives to create domestic policies, and international cooperation becomes necessary. I thus ask: Can international agreements, like domestic regulations, foster innovation on environmental-friendly technologies? Noncooperative game theory suggests that agreements only occur when costs to the players are low, i.e., when little innovation is needed to solve the problem at stake. This view implies that agreements foster little innovation and instead simply enable the diffusion of technologies already developed before the international agreement. This paper shows, on the contrary, that such agreements can induce innovation. To make this argument, I provide empirical evidence from the *Montreal Protocol on Substances that Deplete the Ozone Layer* and its following amendments.

The ozone layer in earth's atmosphere protects humans and ecosystems from the harmful effects of ultraviolet solar radiation. In the 1970s, scientists discovered that chlorofluorocarbons (CFCs) could catalyze the rapid destruction of ozone in the stratosphere (Molina and Rowland 1974) which would lead to increased rates of skin cancer (European Commission 2007; UNEP 2012). Following years of political and scientific discussion, high-income countries reached a major agreement in 1987 in Montreal: industries would phase out CFCs by meeting a set of binding reduction targets (UNEP 2016). Technological change unrolled rapidly: within a decade, the production and consumption of CFCs decreased by more than 80%¹. The protocol is still hailed as the most successful environmental international agreement and remains a point of reference in modern environmental history.

The dynamics of innovation in the ozone crisis, however, are still debated. Some claim the agreement triggered a vast effort in research to find CFC substitutes (Benedick 2009). Others emphasize that a key feature of the ozone crisis was the availability of CFC substitutes at the

¹My calculations using UNEP data

time of negotiations (Heal 2016; Sunstein 2007). In this paper, using a novel molecule-level panel dataset, I present the first quantitative evidence that the Montreal Protocol induced innovation on CFC substitutes. I analyze these unique data using both a difference-in-differences strategy and a synthetic control method (SCM). And to construct synthetic controls, I innovatively apply machine learning methods to semantically match documents and measure similarity between molecules.

I collected all scientific articles published in journals indexed by Science Direct between 1970 and 2000 in the disciplines of engineering and physical sciences, and all patents granted by the United States Patent and Trade Office (USPTO) between 1976 and 2000. Unfortunately, no pre-existing article or patent classifications allow me to easily identify which documents relate to CFC substitutes. Hence, using historical records, I compile a list of 14 molecules known in 1988 to be potential CFC substitutes; I consider those molecules as treated by the Montreal Protocol. Since molecules usually have many different names, I develop an automatic script to collect all possible names from SciFinder, a database of chemical information. I then search the full text of patents and articles for mentions of any of these molecule names and construct a panel dataset where each observation is the number of documents mentioning a given molecule at least once in a given year.

I begin by estimating the difference between the number of documents mentioning CFC substitutes before and after 1987. But to account for potential underlying trends and to estimate the causal effect of Montreal, mentions of CFC substitutes should be compared to a control group. To this end, I use 171 hazardous air pollutants (HAPs). These molecules can serve as controls because they are unrelated to ozone or to CFCs and, just like CFC substitutes, are used in a diverse range of industrial applications. Additionally, trends prior to 1987 ("pre-trends") in the number of documents mentioning both sets of molecules are comparable. To implement a difference-in-differences design, I use as controls the 40 HAPs whose log count pre-trends are closest to the average log count pre-trend of CFC substitutes. This estimate indicates that Montreal led to an increase of about 415% and 95% in the number of patents and articles, respectively. This corresponds to average annual increases of about 300 patents and 47 articles from 1987 to 2000.

These estimates can be improved by using control units driven by structural processes that are as similar as possible to those driving CFC substitutes. HAPs are a diverse group of molecules

with a broad range of document counts and industrial applications. Thus, a better control group than the one afforded by a difference-in-differences design would contain only the HAPs most similar to CFC substitutes. To achieve this, I use a synthetic control method (SCM) (Abadie, Diamond, and Hainmueller 2010, 2015); specifically I construct a control unit by using a weighted average of control molecules. The method chooses the weights so that the synthetic control unit reproduces most closely the log count path of the outcome variable in the pre-treatment periods. I also use weights chosen so that the synthetic control resembles the treated unit along some covariates. Ideally, such covariates would reflect the structural processes driving the observed document counts. To this end, I apply machine techniques to text analysis to construct variables that proxy the scientific and industrial context of the molecules.

With this method, the average treatment effect indicates the Montreal protocol lead to an increase of about 170% in the number of patents mentioning the CFC substitutes, corresponding to about 113 additional patents per year over the study time period after 1987. This yields a lower estimate than the difference-in-differences strategy, indicating that the control constructed in SCM provides a more conservative comparison. For articles, on the other hand, results are similar to the difference-in-differences. I find an average treatment effect close to a 190% increase in the number of articles, which corresponds to about 43 additional articles per year after 1987. To assess the statistical significance of these results, I follow the placebo tests method suggested by Abadie, Diamond, and Hainmueller (2010, 2015). I find treatment effects are significant at the 99% level. In addition, the increase in the number of documents mentioning CFC substitutes becomes statistically significant as from 1990, three years after the agreement was signed. This lag might correspond to the time it organizationally and professionally takes to redirect research towards CFC substitutes and to have patents and articles published (Popp 2002).

I test the robustness of these findings by varying empirical elements of the analysis and obtain similar results. In particular, since interpolation biases and overfitting can be problematic with SCM procedures, I restrict the donor pool to the 20 HAPs that fit most closely CFC substitutes in the pre-treatment period. Also, since business firms might have anticipated the success of Montreal and begun research initiatives before 1987, I run an SCM redefining the treatment year as 1985

instead of 1987. I find similar results as before. Last, I also examine whether Montreal impacted the science and innovation of CFCs, the pollutants that were phased out from industrial activities. I replicate the methodology described above, and find no effect of Montreal on the number of articles and patents mentioning CFCs. Likely, the agreement sent a strong signal that CFCs were molecules of the past, and reduced incentives to create new technologies based on them. On the other hand, Montreal certainly created incentives to develop technologies for recycling CFCs or for using them more efficiently. These two opposing forces might explain why the data indicates that Montreal had no impact on the overall magnitude of research on CFCs.

This paper contributes to the literature on directed technological change in the context of environmental issues (Acemoglu 2002; Jaffe, Newell, and Stavins 2002; Popp 2010). Many papers have explored the relationship between domestic environmental regulations and innovation (e.g., Aghion et al. (2016), Calel and Dechezleprêtre (2016), and Jaffe and Palmer (1997)), but few investigate the causal effect of international agreements. In particular, while scholars have thoroughly investigated the diplomatic and game theoretic aspects of the ozone crisis (Barrett 2003; Benedick 2009; Parson 2003), no quantitative analysis of the dynamics of innovation has been carried out. This is despite the economics, science, and politics of ozone serving as an anchor point for our understanding and beliefs about the role of diplomacy, agreements, and technologies in solving environmental issues, especially climate change (Barrett 1999; Sunstein 2007). When technological solutions remain plagued with uncertainties or high price tags, decision-makers are incentivized to adopt a "wait-and-see" strategy: wait for proven new technologies, then negotiate an agreement. This paper, however, provides an argument for negotiating ambitious agreements as early as possible, as it shows agreements can be part of the process of delivering cheaper environmental-friendly technologies.

The following section 2 summarizes the literature on directed technological change and its relationship to the environment, provides further information on the ozone crisis and the Montreal Protocol, and discusses the various factors driving patenting and publication of peer-reviewed articles in this context. I describe the data in section 3 and the methodologies and empirical strategies in section 4. I then present the main results in section 5, and conclude in section 6.

2 Directed Technological Change and the Ozone Layer

2.1 Directed Technological Change and the Environment

The concept of directed technological change goes back to 1936 when Hicks defined ‘induced’ innovations as the type of innovations that result from a change in relative factor prices². The *induced innovation hypothesis* stated that innovations would be biased towards high priced factors in order to make their use more efficient or to substitute them. In the past two decades, the concept has reappeared under the phrase ‘directed technical change’³ and encompasses not just price effects but also market size and regulatory effects. The phrase’s popularity took off after Daron Acemoglu’s 1998 model showing that an increase in skilled labor force can induce skill-biased technological change through a market size effect that fosters the development of innovations complementary to the abundant factor, in that case, skills (Acemoglu 1998). In another paper, Acemoglu (2002) presents a model where the direction of technological change is influenced by both scarce factors (through prices) and abundant factors (through market size).

The relationship between technological change and the environment has drawn more and more interest, particularly since the 1990s. On one hand, technical change affects the intensity of environmental impacts. On the other hand, there was the growing recognition that environmental policies created new types of incentives and constraints possibly affecting technical change. In fact, we can think of environmental regulations as modifying the shadow prices of environmental inputs which, as the induced innovation hypothesis suggests, induces innovation in non-polluting directions. This is specifically discussed by Newell, Jaffe, and Stavins (1999) who generalized the concept of induced innovation to include inducement by regulations. In the environmental context, the direction of innovation is particularly important. The usual technology policy (e.g. public funding for research and development activities or intellectual property regimes) attempts to deal with knowledge market failures by fostering the rate of innovation and diffusion of new

²‘We must put on one side those inventions which are the result of a change in the relative prices of the factors; let us call these "induced" inventions. The rest we may call "autonomous" inventions.’

³The phrases ‘directed technical change’ and ‘directed technological change’ are in practice often used interchangeably. They are however distinct. The first one encompasses the second since technological changes are types of technical change. Other types of change such as institutional or organizational usually fit under technical but not technological change.

technologies but in a direction-blind way. As a result, a large literature has developed at the intersection of environmental and technology policy to better understand how and to what extent technical change could be directed.

Three main articles review in depth the key questions at stake as well as the theoretical and empirical contributions (Jaffe, Newell, and Stavins 2002; Popp 2010; Popp, Newell, and Jaffe 2010). For a while, the debate focused on Porter's hypothesis (Ambec et al. 2013; Porter 1991; Porter and Van Der Linde 1995a,b). Michael Porter in 1991 argued that, in the long-term, environmental regulations fostered business competitiveness by forcing firms to innovate, even though in the short term regulations meant additional costs for businesses. The verification of the hypothesis in empirical research was to be mixed and seemed sector specific. The focus then turned to empirical investigations of the effect of environmental regulations on patenting activities as well as R&D spendings and there is overall strong evidence that regulations have an important influence on environmental-friendly innovations (Popp 2005; Vollebergh 2007).

A series of empirical papers in the 1990s focused on water and air pollution and found that expenditures on pollution abatement correlate with R&D spending (Jaffe and Palmer 1997) and with patenting related to environmental technologies (Brunnermeier and Cohen 2003; Johnstone et al. 2012; Lanjouw and Mody 1996). Popp (2006a) finds significant increases in patents pertaining to sulfur dioxide and nitrogen oxides emissions reduction in response to the passage of environmental regulations in the United States, Japan, and Germany. More recently, scholars have studied the impact of climate policy on innovation-related alternative energies and energy efficiency (Brunel 2015; Johnstone, Haščič, and Popp 2010; Nesta, Vona, and Nicolli 2014). Particularly, Caelal and Dechezleprêtre (2016) show that the European Union Emissions Trading System increased patenting related to low-carbon technologies by about 10%, while not crowding out other technologies. These results, however, imply that the EU ETS accounts for only about 1% of the increase in European low-carbon patenting compared to a counterfactual scenario. In this paper, I propose to examine the case of the ozone layer to investigate to what extent the international agreement signed in Montreal might have contributed to direct the research and development effort. Below I narrate a short history of the ozone issue and discusses the role of technology. I will in the last

part of this section discuss the potential processes unleashed by the signature of the protocol.

2.2 Ozone Regulations and Diplomacy

The story of the ozone crisis began in 1974 when two scientists published an article in which they laid out the theoretical possibility that ozone molecules could be broken down in the stratosphere by chlorofluorocarbons (Molina and Rowland 1974). Even though the potentially harmful effects of a thinner ozone layer were not well studied, it was clear that more UV light would cause more skin cancers, eye cataracts and likely a loss in the productivity of fisheries and agriculture (Miller and Mintzer 1986).

Chlorofluorocarbons (CFCs), the main molecules responsible for depleting ozone, had become important molecules for industrial activities due to their chemical properties: they are unusually stable, nonflammable, nontoxic and noncorrosive. This makes them ideal molecules for manufacturing many consumer goods. Best of all for industry, they were cheap to produce. The use of CFCs spread almost equally over five different sectors: foams, refrigeration and air-conditioning⁴, aerosols⁵, fire protection and solvents⁶. Experts valued the entire market for CFCs to a small amount⁷; but because they were essential to production of many high-value goods such as electronics or air-conditioning units, finding substitutes became a critical economic matter. In 1988 in the United States, \$28 billion of goods and services were produced with CFCs, using \$135 billion worth of capital equipment (Parson 2003).

In some countries, consumer pressure built up quickly towards the end of the 1970s; the U.S. and Canada for example banned CFCs from aerosol products in 1978⁸. The U.S. led the diplomatic effort to obtain an international agreement, and would eventually face a series of setbacks and successes⁹. Uncertainties in the science of atmospheric ozone seemed irreducible for a while, the year 1981 saw the election of a strongly anti-regulatory administration in the

⁴They vaporize at low temperature and are very energy-efficient coolants.

⁵They were used as propellants in cosmetics, household products, pharmaceuticals and cleaners.

⁶Their nonreactive property was key for cleaning microchips and telecommunication equipment

⁷\$2 billion worldwide according to Parson (2003)

⁸It was technologically easy to replace CFCs in aerosols. This explains why on figure A3, the portion of USA uses that is in aerosol is very small.

⁹The appendix features a timeline of key events related to ozone diplomacy.

U.S. and European governments persisted in refusing to harm their domestic manufacturers with international regulations.

However, in September 1987, industrialized countries agreed to a binding agreement regulating the production and use of CFCs. The approach was flexible with a series of phase-out dates, as opposed to banning altogether the molecules. These phase-out schedules were further consolidated and extended to other molecules in the years that followed¹⁰. The London amendment, signed in 1990, regulated new chemicals such as carbon tetrachloride and methyl chloroform. In 1995, the parties successfully negotiated phase-out targets for lower income countries, which were until then exempted from any regulation. The agreement proved to be a staggering success. Most ODS concentrations peaked by 2014 and most ODS are well on track to become a problem of the past¹¹.

The exact events around the negotiations are narrated by Richard E. Benedick, former U.S. ambassador and chief negotiator to the Montreal Protocol, in a book called “Ozone Diplomacy” (Benedick 2009). Benedick emphasizes the complexity of the negotiations and the great uncertainty, until the last minute, of the negotiations’ outcome. But some exceptional turns of events seemed to unlock the situation. Reagan overruled his own administration and approved the agreement. The U.S. President had a skin cancer removed twice in the past, and Benedick hints that Reagan’s life experiences weighed heavily on his decision. On the European side, the biggest opponent to the regulation of CFCs, the U.K., left the European Community Presidency, leaving Germany, Denmark, and Belgium, firm proponents, as the head negotiators.

Even if countries finally agreed on a treaty, one may raise the question of its actual effectiveness. Looking back on environmental history, we cannot avoid the comparison of the Montreal Protocol with the Kyoto Protocol¹²: the former is a paradigm of success, the latter a paradigm of failure. Scholars such as Scott Barrett greatly contributed to understanding Montreal’s effectiveness at reducing emissions by analyzing the incentive structure of the Protocol using game theory (Barrett 1999). As Barrett suggests, a distinctive aspect of the Montreal Protocol was to solve the enforcement problem. Saying that CFCs cannot be produced or used anymore is one thing. But

¹⁰Figure A4 in the appendix shows the various phase-out schedules.

¹¹Figure A2 in the appendix displays the actual and projected atmospheric concentrations of several ODS.

¹²The Kyoto Protocol was agreed in 1997 and attempted to reduce greenhouse gases emissions to limit climate change.

what consequences would there be if a country decided not to comply? Montreal included trade restrictions with non-parties in ozone depleting substances, as well as in products containing those substances. It also included the threat of banning trade in products made using ozone depleting substances. These trade restrictions effectively acted as a mechanism for free-rider deterrence and leakage prevention. This contrasts with treaties trying to reduce greenhouse gases emissions to limit climate change, Kyoto or even the more recent Paris agreement, which do not include enforcement mechanisms.

2.3 The Role of Technology in Ozone Diplomacy

Perspectives on the role of innovation are mixed. Some like Richard Benedick argued that the agreement triggered a vast effort in research to find CFC substitutes and that qualitative evidence abounds on the dynamics of the innovation process under the Montreal Protocol. In his book, he asserts that ‘(it) was evident (...) that the protocol was in fact moving industry in directions that two years earlier had been considered impossible.’ But others have taken a different stance, highlighting instead that some CFC substitutes already existed, which in turn made it easier for countries to agree on a binding and constraining treaty. Sunstein (2007) stresses that the situation on the eve of the signature of Montreal was not a prisoner’s dilemma. He claims that ‘an international agreement was largely in the interest of American manufacturers, which had already initiated a transition to safe CFC-alternatives’. In a recent book examining the most urgent environmental issues of our time, environmental economist Geoffrey Heal discusses the failure of the Kyoto Protocol in comparison to the success of Montreal: ‘However, there are big differences between ozone depletion and climate change. We have not yet seen the equivalent of DuPont’s discovery of an alternative to CFCs, which would be the discovery by oil and coal companies of a greenhouse-gas-free energy source capable of meeting world energy demand at current energy costs.’ (Heal 2016, p68). This view was also spread by some media outlets. Here is an excerpt from an article published in *The New York Times* on August 20, 2002: ‘The agreement’s success occurred, in large part, because substitutes for the harmful chemicals were readily available (...)’.

However, according to sociologist Reiner Grundmann, the idea that CFC substitutes were

known to some firms, and in particular to DuPont, is ‘the most pervasive and most widespread myth surrounding the Montreal Protocol’(Grundmann 1998). Both Grundmann and Benedick trace the origin of this ‘myth’ to the fierce opposition between Americans and Europeans. The British and the French, in particular, had suspicions about the real intents of U.S. industry. They believed environmental issues were a disguise for commercial interests, that American firms had some secret CFC substitutes, and that they would use international regulations to gain market shares. An element that helps better understand this accusation is the Concorde controversy from 1974 (Benedick 2009, p. 33). When the French and the British had hoped to conquer the world with supersonic jets, Americans denied them the authorization to land the aircraft on U.S. soil, protesting that the pollution emitted by the plane’s engine was a serious threat to the ozone layer. These claims were dismissed later on as it was shown that the atmospheric reactions would not occur at the Concorde flying altitudes. This incident certainly left an aftertaste of distrust for Europeans.

A more subtle argument can be made however that, even without secret CFC substitutes, it was still in the interest of U.S. firms to create a global market for CFC substitutes. These new substitutes would require R&D investments and the patenting of new synthesis and process routes. Patents, in turn, would mean that these molecules could be sold with a higher profit margin. In this scenario, firms that are better at R&D have a competitive advantage. Under consumer pressure, some American firms had started some research programs about CFC substitutes, and even if these programs were prematurely stopped with no substitutes fully developed, these firms likely retained more inside knowledge about the effort required and a better idea of what the way forward would be under international regulations. This would have conferred some degree of competitive advantage they could leverage to gain market shares.

There is no question that if emission reductions were successful, it was thanks to CFC substitutes becoming available. Goods that contained or required ODS for their production continued to be commercialized and no air capture system of ODS was ever designed. The more interesting question is when these CFC substitutes were developed and whether the agreement triggered the bulk of the effort to find CFC substitutes. Some works have focused specifically on the technolog-

ical story behind the Montreal Protocol (Glynn 2002; Gonzalez, Taddonio, and Sherman 2015; Le Prestre, Reid, and Morehouse Jr 1998; Miller and Mintzer 1986; Parson 2003; Taddonio, Sarma, and Andersen 2012) as well as the reaction of the business community (**Reinhardt.Vietor1989a**; Falkner 2005; Mulder 2005; Reinhardt and Vietor 1989; Smith 1998). However, a comprehensive quantitative analysis of the scientific landscape has never been pursued.

For example, Benedick refers to articles published in the New York Times and in Chemical and Engineering News (Benedick 2009, Chap.8 p.104.) when he asserts that the agreement triggered a vast research effort. On the other hand, Edward A. Parson, in ‘Protecting the ozone layer: science and strategy’, narrates the various waves of research efforts to develop CFC substitutes, both before and after the signature of the Montreal Protocol (Parson 2003, Chap.3 p.53 and Chap.7 p.173). He highlights that some manufacturers initially started research on potential substitutes in the late 1970s¹³, but this effort quickly came to an end around 1981. According to Parson, manufacturers would have stopped these R&D programs because they had determined that CFC substitutes would cost around 2 to 5 times more than CFCs, and it made no sense to continue developing these substitutes with little sign of regulations under way. And given the context of the early 1980s (uncertainties in the science and the election of Reagan) regulations appeared unlikely¹⁴. As a result, in 1986, on the eve of the negotiations, technological uncertainties loomed large. Little was known about the toxicity and environmental acceptability of the potential CFC substitutes, how they could be processed at a large scale, and whether they would require a redesign of the processes and equipment in the various industries that used CFCs as inputs. Parson goes on to explain how a continuous flow of innovations starting in 1987 was really the key to solving the problem. He does not, however, analyze temporal trends and only provides several examples of patents granted to Dupont at different point in time¹⁵. However focusing on specific occurrences of patenting does not inform about general trends and a broader study would contribute to understanding the dynamics of innovation during the ozone crisis.

¹³In 1979 for example DuPont announced \$10 million of research effort.

¹⁴This is also what Benedick relates: Du Pont announced in 1986 that it believed it could develop substitutes in about five years but that ‘neither the marketplace nor regulatory policy ... has provided the needed incentives’ to justify the required investments

¹⁵For example Figure A30 and A31 in the appendix show two examples of patents granted to Du Pont; one was granted in 1982, i.e., before Montreal was signed. The second was granted in 1998.

2.4 Empirical Indicators of Technological Change

The process of technological change is often described as a sequence of distinct activities: basic research, applied research, development, commercialization, and diffusion (Greenhalgh and Rogers 2010, figure 1.1). But economists prefer to distinguish two main phases, each characterized by specific market failures. First, the invention and innovation phase is characterized by positive externalities because of the public good aspect of knowledge (non-rival and non-excludable). Second, the diffusion and adoption phase is characterized by problems of dynamic increasing returns (learning by doing, learning by using, network externalities). To strengthen the incentives to generate innovations, modern economies have adopted regimes of intellectual property rights where inventors are granted exclusive rights through patents. The publication of a patent, as a result, is a testimony to the successful process of research and development and can be considered as a proxy for technological change in general, and of innovation in particular.

Patent data has been broadly used in empirical research in the past two decades (Hall and Jaffe 2012; Henderson, Jaffe, and Trajtenberg 1998). Popp (2005) review key learnings from using such data in the context of environmental models. A strand of the literature also actively investigates patenting patterns examining citing-to-cited relationships (Kay et al. 2014). For example, Popp (2006b) finds that the probability that new energy patents be cited decreases over time; this implies that the quality of knowledge available for inventors to build upon also decreases. I follow this literature by using patent counts as a proxy of innovation. However because there does not exist a specific patent classification for innovations related to ozone-depleting substances, I develop a strategy to identify which patents belong to such category.

If obtaining a patent represents a goal for profit-seeking inventors, the phases of basic and applied research focus more specifically on the production and dissemination of knowledge that innovators often build upon to bring about new technologies. Through the publication of scientific articles, researchers can hope to make others aware of their contribution and disseminate the knowledge they generated. A large literature has focused on the study of science, or as it is often called scientometrics. It was born out of Derek J. de Solla Price’s contributions to a quantitative understanding of the growth of science (De Solla Price 1965; De Solla Price 1986). More recently,

scholars have analyzed the distribution of citations to understand differences between papers with low or high citations (Iaria and Waldinger 2015; Redner 2004; Thompson and Fox-Kean 2005; Wang, Song, and Barabási 2013). Part of the literature has also focused on the links between science and innovation by relating patents and scientific articles (Trajtenberg, Henderson, and Jaffe 1997). In this paper, I build on both literatures on patents and scientific articles to better examine the story of technological during the ozone crisis.

2.5 Drivers of Innovation in the Case of Ozone Depletion

As I intend to investigate the patterns of research and patenting on CFC substitutes, it is useful to review possible mechanisms driving the publication of patents and scientific articles. I treat separately mechanisms that apply to firms developing patentable technologies and mechanisms that apply to researchers intending to publish in peer-reviewed journals.

2.5.1 Factors Driving Patenting.

Consumer Pressure. Consumers' environmental values can modify their preference curve leading them to choose greener products or products from companies with higher standards of environmental stewardship. Businesses, therefore, have all the more incentives to innovate in greener technologies when consumer awareness of environmental issues is high. There is some evidence that this mechanism took place at the beginning of the ozone story. Some manufacturers unilaterally decided to remove CFC from their spray products even in the absence of any threat of regulations but mostly because they worried about their public image. The innovations rolled out under these auspices were especially cheap for the producers, and it is unlikely that they required a significant research effort. For example, it consisted in substituting spray with roll-on deodorants.

National Environmental Regulations. I discussed earlier in the paper how national regulations can be effective ways to redirect research activities towards environmentally-friendly technologies. The primary mechanism here follows the induced innovation hypothesis: for example, a ban on CFCs is akin to setting an infinitively high price of CFCs, and this acts as a strong incentive to find CFC substitutes. Indeed, once a ban is enforced, firms have no choice but to

stop producing and commercializing the product and must innovate to maintain profits. Hence, environmental regulations implicitly modify the prices of some inputs, and direct innovation efforts towards technologies that substitute them or use them more efficiently.

In the case of ozone, the domestic regulations that were passed and implemented before the signature of the Montreal Protocol only targeted specific industrial applications of CFCs: aerosols. In August 1977, the U.S. Congress amended the Clean Air Act with the Stratospheric Ozone Protection amendment writing into law a CFC ban on aerosols by 1978. Similarly, in 1978, Canada, Switzerland and Scandinavian countries all banned CFC aerosols. On continental Europe, Germany called for a European Community-wide ban without success. In 1980, the EPA proposed to freeze other uses beyond aerosols but U.S. industry blocked the initiative. Aerosol bans might have created some incentives to invest in research programs, but since the bans targeted a fraction of the market for CFCs only and since some physical substitutes, such as roll-on devices, were easy to deploy, I believe these incentives to be quite weak.

International Environmental Agreements. The signature of international agreements might not immediately change the prices of polluting products, but they can effectively modify the expectations about future prices. The hypothesis is that the signature of Montreal acted as a strong signal to the business community that prices were going to change and modified expectations regarding where future profits lay, i.e. in CFC substitutes. Of course, one might formulate the opposite hypothesis, that is, Montreal was not a strong signal and that, instead, the change in expectations and the redirection of research towards CFC substitutes took place more progressively throughout the 1980s. We shall add that the response to an international agreement should be greater if many countries participate in that agreement. A global market means more profit-making opportunities for firms about to incur the sunk costs of research and development.

Anticipation of Regulations and Agreements. Another path through which expectations change is when firms anticipate regulations or agreements. Even in the absence of regulations, industrial actors are induced to pursue development if the likelihood of regulations in the near future is high. They pursue development as a risk management strategy, investing in preliminary research to pave the way forward in case regulations were to come through. There is some evidence

that as the ozone crisis took prominence in the media and regulators' minds in the late 1970s, firms initiated some R&D projects regarding CFC substitutes. However, as mentioned before, those projects were canceled by the early 1980s. Interestingly, in some cases, anticipating can confer a first mover advantage. By undertaking early-on research activities, firms might be able to develop patentable cleaner technologies before competitors. They will then find themselves with a strategic advantage when regulations are passed and could even decide to lobby in favor of environmental regulations for that reason (Puller 2006). If we believe that anticipation of CFC regulations was strong, we should not expect the signature of Montreal to be a strong signal, and therefore, we should not expect to be able to model the patterns of patent publications as a two-regime model with before Montreal and after Montreal phases. Instead, there should be a progressive and continuous increase in patents and articles.

2.5.2 Factors Driving the Publication of Peer-Reviewed Articles.

The mechanisms driving the publications of peer-reviewed articles are less straight-forward since they might involve a combination of personal and professional motives.

Ethical Motivations. Environmental values drive some research effort on CFC substitutes by influencing researchers when they decide what research questions to tackle next.

Signaling and focal point. The international agreement to phase-out ODS acts as a strong signal making ozone-related research the focal point of publication outlets, thereby inducing researchers to redirect their research towards such topics. The discovery in 1985 of a dramatic loss of ozone over Antarctica and the confirmation in 1988 that CFCs were causing it might also have served as a strong focal point for environment-conscious scholars.

Directed research funding. The choice of which scientific research to conduct is also heavily influenced by governmental organizations funding research, such as the National Science Foundation, when research grants are dedicated to a specific topic such as ozone depletion. Besides, following the Montreal Protocol, industrial actors participated in cooperative research efforts (known as AFEAS and PAFT) for research topics that were not patentable and which related to environmental safety and human toxicity of potential CFC substitutes.

Even before an agreement is reached, we can, therefore, expect some level of research and development because ethical motivations might drive researchers and firms, or because firms might anticipate the possibility of an agreement and decide to invest in finding CFC substitutes just in case. The innovation flowing from this initial research effort will facilitate an agreement (if expected costs seem manageable), or deter an agreement (if the level of technological change needed to solve the problem seems greater than the benefits of doing so). But the signature of a binding agreement triggers the other mechanisms and should, therefore, enhance the research and development effort.

3 Data

3.1 Patents

I downloaded the full-text of all U.S. patent grants from 1976 to 2000 from the U.S.P.T.O. repository (a total of 2,605,925 patents). I use the texts contained in the abstract and summary description of the invention. Contrary to articles, the text data for patents require less pre-processing and cleaning steps because all documents and all sentences in documents are in English. Besides, contrary to articles, typos or random series of letters and digits are very rare.

3.2 Articles

I downloaded the full-text of scholarly articles published between 1970 and 2000 and indexed by ScienceDirect using Elsevier web interface¹⁶. I only selected journals categorized as belonging to the following disciplines: chemistry, chemical engineering, engineering, environmental science, materials science, and physics and astronomy. I first collected ISSN numbers of such journals from Elsevier's website¹⁷. For each ISSN, I use ScienceDirect to obtain 1) the DOI¹⁸ for any article published in that journal between 1970 and 2000 and 2) the full text of articles for the

¹⁶<http://dev.elsevier.com/>

¹⁷<https://www.elsevier.com/solutions/sciencedirect/content/journal-title-lists>

¹⁸A DOI, or Digital Object Identifier, is a sequence of digits and letters that uniquely identifies an academic article.

DOIs returned. Full text data was successfully downloaded for 1,843,684 articles, out of a total of 2,307,345 DOIs initially returned by the API¹⁹. After a series of cleaning procedures, I obtain a total number of articles of 1,811,301. I use Google’s CLD2 library in Python to detect every document’s language and drop articles that are detected as not English. The cleaning procedure involved a series of standard steps such as replacing English contractions with their non-shortened forms or converting non-ASCII characters into their closest ascii equivalents. Details are provided in the Appendix. Besides, because the translation of English articles in other language is often contained in the full text, I dropped any sentence containing less than 80% of tokens recognized by a standard English dictionary²⁰.

3.3 Molecule Groups

I primarily focus on a group on molecules that were known to be potential CFC substitutes. Since there is no pre-existing categories or classification of such molecules, I construct a list using historical records. After Montreal, manufacturers from the US, Europe, and Japan received authorization from antitrust officials to organize cooperation, at least on the science for which patenting was not possible. They launched two working groups to study the feasibility of various alternatives. The PAFT (Program for Alternative Fluorocarbon Toxicity Testing), created in January 1988, worked on assessing the toxicity of five possible alternatives. The AFEAS (Alternative Fluorocarbon Environmental Acceptability Study), created in December 1988, investigated the atmospheric dynamics of twelve potential CFC substitutes. I use these twelve molecules to form a first group. I also include in this group two other possible CFC substitutes mentioned in Benedick (2009) and Parson (2003)²¹. Table 1 shows the name and additional information about these molecules.

I then search through every document to identify which mention any of these molecules. Being able to search the full text of the documents is an advantage here since relying on abstracts only could lead to many false negatives. Chemical compounds, however, are often given several names; for example, HCFC-22 has 39 other possible names such as chlorodifluoromethane or algeon 22.

¹⁹This implies that Elsevier listed 463,661 DOIs for which the full text was not available. This might be due, for example, to entire journals dropping out of Elsevier Science Direct’s collection.

²⁰I used SpaCy’s English dictionary in Python.

²¹HFC-245fa and HFC-365mfc are mentioned as possible substitutes in foams.

To capture all the occurrences of a mention of a molecule, I develop an automatic script to collect all possible names for a given molecule through SciFinder, a database of chemical information maintained by the American Chemical Society. I then search through all patents and articles to identify which documents mention any of these molecule names. When a document contains the name of only one of the molecules, the document is assigned to that molecule’s group. But if a document mentions several molecules belonging to different groups, which group should this document be assigned to? Under what i call the *weak* rule, a document is assigned to group X if a molecule of group X is mentioned in the document, regardless of whether molecules from other groups are also mentioned. I develop an alternative rule as a robustness check.

In a similar fashion, I identify which patents and articles mention a group of molecules that are not related to ozone depletion: the 171 molecules categorized as Hazardous Air Pollutants (HAPs). I explain in the next section how these molecules are useful for my methodology. The full list of HAP molecules that I consider is displayed in the appendix.

3.4 Meta-data

To collect article meta-data, I queried the Scopus search API²². I leveraged the Global Research Identifier Database²³ (GRID) to classify authors’ affiliations as education, company, government, facility, non-profit, health care. For patents, UPSTO data contains names and addresses of inventors and assignees. I use the country of the assignee, and when the patent has no assignee, I use the country of the inventor. More details about how the meta-data is cleaned, matched and classified by type is provided in the appendix.

²²Because of quota limitations, I queried meta-data only for articles mentioning only CFC substitutes, Annex A or B compounds.

²³<https://www.grid.ac/>

4 Methodology and Empirical Strategies

4.1 HAPs as a Comparison Group

A simple approach to study patterns in patents and articles is to observe the yearly count of documents about CFC substitutes and test whether there is a change of patterns before and after the date of the signature of the agreement. Figure 1 plots the yearly number of articles or patents mentioning the names of given CFC substitutes. We note a clear increase for most CFC substitutes in the 1990s. Equations 1 and 2 present an econometric specification of simple differences with, respectively, a mean shift and a trend-break to detect a change happening in 1987 onwards. $LogCount_{m,t}$ is the log number of documents in year t about molecule m ; $\lambda_{post1987}$ is a dummy variable that equals one when $t > 1987$; λ_m are molecule fixed effects; $Years$ is a continuous variable indicating the number of years relative to 1987. Here, I suggest to use counts in log, instead of level, as the outcome variable since it will likely provide a better linear fit over time. Indeed we can think of scientific production as exponentially growing over time.

$$LogCount_{m,t} = \alpha + \beta_0 * \lambda_{post1987} + \lambda_m + \epsilon_{m,t} \quad (1)$$

$$LogCount_{m,t} = \alpha + \beta_1 * Years * \lambda_{post1987} + \beta_2 * Years + \lambda_m + \epsilon_{m,t} \quad (2)$$

The main hypothesis is that β_0 and β_1 are both positive for CFC substitutes, implying a significant increase in research and patenting activities relating to CFC substitutes after 1987 once Montreal passed. But because this is only a simple temporal difference, such an increase could also be due to other underlying trends not specific to ozone negotiations. For example, it might be possible that some other reforms or the economic context fostered more academic and industrial research in the 1990s. Hence, we need to find a group of molecules that could serve as a control group; the challenge consists in finding molecules that are very similar to the treated molecules, while, at the same time, remaining different enough to ensure that they are not affected by the treatment. Specifically, a good control group should contain molecules whose undergo similar influences as CFC substitutes apart from the one of the Montreal Protocol. One way of choosing such molecules

is such that they present similar pre-treatment trend in the outcome variable *LogCount* but also such that they are as close as possible to the treated molecules chemically, physically and regarding industrial applications. Such molecules can potentially be found in the large pool of HAPs.

HAPs have no connection to ozone but they are often related to industrial activities. They became monitored under the Clean Air Act due to human health concerns including cancer, asthma, birth defects, reproductive effects, and neurodevelopmental effects, as well as adverse ecological impacts. Examples include benzene, chromium or formaldehyde. The full list of the molecules included in the different treatment groups is displayed in the appendix. Figure 2 illustrates why HAPs are a good choice as control molecules: overall patents about CFC substitutes and HAPs fall into similar top-level codes. I will first explain how I implement a difference-in-differences design using HAPs as a control group. I will then show how we can improve on the identification strategy by implementing a synthetic control method.

Table 2 displays summary statistics for some of the variables available in the meta-data of patents and articles for CFC substitutes and HAPs. We note that more than 70% of articles have at least one author affiliated with an organization belonging to the higher education sector. In addition, for-profit organizations constitute more than 96% of patent assignees. The other most common types are education, government, and facility. The majority of patent assignees come from the United States, while about 20 to 30% come from Europe and 10 to 20% from Japan.

4.2 Difference-in-Differences Approach

One commonly used approach consists in implementing a difference-in-differences (DD) design. In my case, I construct a control group using HAP molecules that present similar pre-trends to the pre-trend of the average substitute. This method excludes from the control group HAPs with drastically different trends. On Figure 3, I plot the yearly mean counts of documents mentioning CFC substitutes and HAPs to gauge similarity in the pre-trends. When using the whole sample of HAPS (that is 171 HAPs molecules), pre-trends look similar. However, a close observation reveals that, in patents, pre-trends for CFC substitutes are slightly up, while maybe the one for HAPs goes slightly down. In articles, HAPs have a clear upward trend before 1987 while CFC substitutes

seem somewhat flatter. Hence, similarity in pre-trends can be improved by selecting a subset of HAPs with pre-trend closest, in terms of log count, to the average CFC substitutes. Specifically, if N_t is the number of molecules in the treated group, I construct the control group as the $3 \times N_t$ HAPs whose pre-trend is closest to the average trend of the treated group.

I estimate the difference-in-differences model with a mean shift specification (Equation 3) and a trend-break specification (Equation 4). $LogCount_{m,g,t}$ is the log number of documents with molecule m belonging to molecule group g , in year t ; $Post_t$ equals one when $t > 1987$; D_m equals one if the molecule belongs to the treated group; λ_m are molecule fixed effects; λ_t are year fixed effects; $Years$ is a continuous variable indicating the number of years relative to 1987. β_0 identifies the diff-in-diff estimate.

$$LogCount_{m,g,t} = \alpha + \beta_0 \cdot D_m \cdot Post_t + \lambda_t + \lambda_m + \epsilon_{m,g,t} \quad (3)$$

$$LogCount_{m,g,t} = \alpha + \beta_1 \cdot Years \cdot Post_t \cdot D_m + \beta_2 \cdot Years \cdot Post_t + \beta_3 \cdot Years + \lambda_t + \lambda_m + \epsilon_{m,g,t} \quad (4)$$

The primary hypothesis is that β_0 and β_1 are positive for the group of CFC substitutes. Significant coefficients would imply that the research and development activities underwent important changes after 1987 relative to the counterfactual. If there is no significance, this might suggest that the research effort was redirected towards CFC substitutes in a progressive fashion and that the signature of the treaty was not a determining signal in the dynamics of innovation.

The magnitude of the treatment effects estimated with a DD strategy inherently relies on the choice of the control group. It is possible to improve those estimates by choosing the molecules that are included in the control group more precisely. Within the group of HAPS, there is vast heterogeneity. Some HAP molecules are mentioned very frequently while others more rarely. Some of the HAPs might also be very different chemically, physically and from an industrial point of view. An improvement on using all HAPs in the control group is therefore to use only the HAPs that are driven by structural processes most similar to those driving CFC substitutes. The selection

of comparison units is crucial in such study: if there are too different from the treated unit, any difference in outcome post treatment can be attributed to initial differences and the resulting estimate would be biased. For this reason, I implement a synthetic control method.

Furthermore, DD strategies are designed to estimate average effects over a population from which we sample a large enough number of units exposed and units nonexposed to treatment. Considering the overall population of potential CFC substitutes, I have sampled 14 of them; the reported standard errors in the DD regressions then will reflect uncertainties about the aggregate data. This is problematic because the greatest uncertainty lies in the choice of the control group, and not in the aggregate quantities. In fact, here, the aggregate quantity can be thought of as observed: adding up the observed counts of the 14 CFC substitutes, and considering them as one single treated unit. This makes sense because I am most interested in examining whether the aggregate count of these 14 substitutes has gone up compared to a control group rather than estimating an average effect of a supposed population of CFC substitutes. SCM was specifically developed to evaluate the effects of large aggregate interventions when the treatment affects an aggregate quantity. Many interventions are in fact implemented at an aggregate level and have an impact on 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.

Figure 4 plots the number of patents (in log) mentioning CFC substitutes. The thick line called "Substitutes (aggregated)" 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 substitute because my objective is to estimate the effect of Montreal on research and innovation on any of the substitutes rather than on one specific substitute. Figure 5 shows patent counts in log for each HAP and for the aggregated CFC substitutes. The thick HAP line corresponds to the mean counts for HAPs. The thinner lines correspond to the trends for each individual HAP. We see that HAPs are a diverse group of molecules. The graph illustrates the high heterogeneity within the group of HAPs, and in particular that many HAPs have log counts much higher than the aggregated CFC substitutes. The advantage of the SCM is to construct a comparison unit that will be most similar to CFC

substitutes.

4.3 Constructing Synthetic Controls

The synthetic control method has risen as a way to use better comparisons to obtain estimates of causal effects (Abadie, Diamond, and Hainmueller 2010, 2015; Abadie and Gardeazabal 2003; Athey and Imbens 2016). Indeed, it is a data-driven procedure to construct suitable comparison groups, and thus avoid subjective decisions regarding which units are or not part of the control group. The process is particularly useful for studying the effect of an event that takes place at an aggregate level, and that affects aggregate entities. Here, the aggregate entities of interest are scientific objects: a group of molecules that were potential substitutes to CFC. In this exercise, I consider these molecules in aggregate, that is, I bundle the 14 CFC substitutes together and consider them as one treated unit instead of 14 different treated units. The challenge consists now in finding a good control unit to estimate the effect of the intervention.

The key idea of SCM consists in 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 pre-treatment periods. For example, suppose we had 3 HAPs as control units with weights μ_a for asbestos, μ_b for benzene, and μ_c for catechol. Then the weights are chosen such that $\mu_a \times Y_{at} + \mu_b \times Y_{bt} + \mu_c \times Y_{ct}$ is close to Y_{St} (where S stands for substitutes) for periods t before the treatment takes place. Here, Y is the log count of articles mentioning the molecule, but additional covariates can be used. The advantages of SCM relies on the opportunity to create a synthetic unit that shares as much as possible the characteristics of the treated unit. In my case, I would hope to construct a synthetic unit that not only reproduces the path of counts in pre-treatment periods, but that also resembles the treated molecules regarding chemical, physical and possibly industrial characteristics. To this aim, I attempt to proxy such characteristics with topic proportions derived from topic modeling of the documents' text. I explain this further in details in the next section.

Here, I briefly summarize the theoretical underpinnings of the SCM. Suppose there are $J+1$ molecules, J molecules as potential controls and one, denoted with the subscript 1, that is treated.

The treatment effect can be written as $\alpha_{it} = Y_{it}^T - Y_{it}^N$, where Y_{it}^N is the number of document mentioning molecule i in year t if no intervention, and Y_{it}^T the number of documents mentioning molecule i in year t if intervention. Here the quantity we need to estimate is Y_{it}^N . Abadie, Diamond, and Hainmueller (2010) show that a weighted average of the control units can approximate the counterfactual Y_{it}^N , that is:

$$Y_{1,t}^N \rightarrow \sum_{j=2}^{J+1} w_j^* Y_{jt} \text{ with } w^* \text{ s.t. } \sum_{j=2}^{J+1} w_j^* Y_{jt} = Y_{1,t} \text{ and } \sum w_j^* Z_j = Z_1$$

To understand why this is the case, Equation 5 presents the underlying factor model. δ_t is an unknown common factor w constant loadings across units; θ_t is a vector of unknown parameters; Z_i a vector of observed covariates (not affected by intervention); λ_t unobserved common factors; μ_i a vector of unknown factor loadings and ϵ_{it} unobserved transitory shocks with zero mean. Note that this model generalizes the difference-in-differences model which imposes that λ_t be constant for all t . Hence, the unobserved confounders are constant in time and can be eliminated by taking time difference. Here, the SCM allows the effects of confounding unobserved characteristics to vary with time; taking time differences would not get us rid of μ_i .

$$Y_{it}^N = \delta_t + \theta_t Z_i + \lambda_t \mu_i + \epsilon_{it} \quad (5)$$

A synthetic control such that $\sum_{j=2}^{J+1} w_j^* Z_j = Z_1$ and $\sum w_j^* \mu_j = \mu_1$ would be unbiased estimator of Y_{1t}^N . In other words, fitting Z_1 and $Y_{11} \dots Y_{1T_0}$ is a way of undirectly fitting μ_1 , the unobserved factor loadings. As a result, it is important to restrict the donor pool to units with outcomes that are thought to be driven by the same structural process as for unit representing the case of interest and that were not subject to structural shocks to the outcome variable during the sample period.

It is critical to ensure that the synthetic control closely matches the treated unit in the pre-treatment periods. If that was not the case, the synthetic control unlikely provides a good proxy of a counterfactual since it is not even a good proxy of the treated unit before treatment. Following Abadie, Diamond, and Hainmueller (ibid.), I examine the Root Mean Square Prediction Error for periods before treatment (pre-RMSPE)²⁴ to verify whether the discrepancies between the synthetic

²⁴The pre-RMSPE measures lack of fit between the path of the outcome variable for any particular unit and

control and the treated unit are large and thus whether the SCM is appropriately implemented.

4.4 Extracting Topic Proportions from Documents

I use topic modeling, a machine learning method for text analysis, to generate covariates that describe the semantics surrounding molecules and therefore proxying some chemically and industrial characteristics. I then use these covariates in the SCM. Specifically, I use Latent Dirichlet Allocation (LDA), a method of probabilistic topic modeling for text (Blei 2012; Blei and Lafferty 2006, 2009; Roberts, Stewart, and Nielsen 2016; Roberts, Stewart, and Tingley 2014). In this method, the experimenter chooses the number of topics, and after training the algorithm on a corpus, the model can return the topic distribution for each document. Put differently, using the words that appear in a given document; the LDA model infers what proportion of each topic a document contains. Intuitively, the topic proportions describe quantitatively what an article talks about, and we can, therefore, think of it as a proxy of the physical, chemical and industrial characteristics of a molecule. I train the algorithm, not on the entire corpus, but on the subset of documents that contain at least one mention of a molecule: this represents a total of 382,599 patents and 382,005 articles. The LDA model is trained choosing five topics. Table 3 displays the top three words in the five topics generated by the LDA model on the corpus of patents²⁵.

I then aggregate the topic proportions of the documents at the molecule level by calculating a weighted mean topic proportion with weights proportional to the number of times an article mentions a molecule. As a result, articles with many mentions of a molecule contribute more to the aggregated topic proportion. I also test the robustness of my results to taking a simple non-weighted mean. Figure 6 summarizes these various steps with a simple example of three documents, two molecules, and two topics.

Finally, I use these topic proportions together with the outcome variable (log count) as covariates in the synthetic control method. Hence, the algorithm will construct a synthetic control that not only reproduces the path of log count in pre-treatment periods but that also mimics the values

its synthetic counterpart: the pre-RMSPE of unit 1 is defined as $(\frac{1}{T_0} \sum_{t=1}^{T_0} (Y_{1t} - \sum_{j=2}^{J+1} w_j^* Y_{jt}))^{1/2}$ where T_0 is the number of pre-treatment periods. A post-RMSPE can be similarly defined for periods going from $T_0 + 1$ to the end of time-series available.

²⁵The appendix features the lists of top 20 words for patents and articles.

of the different topic proportions. Figure 7 displays the correlation heat map between the topic proportions and counts in patents and articles. We note that the topic proportions are only weak predictors of the variable count. Hence, in the SCM optimization, they should have a small contribution in constructing the synthetic control because the SCM algorithm assigns bigger weights to variables that are better predictors. Figure 8, however, illustrates why topic proportions are still useful. The graphs display scatter plots of topic proportions and log count. We see that some HAPs have values of topic proportions that stand out as outliers. This indicates that those HAPs present a semantic context that is likely very different from the one of CFC substitutes. Hence topic proportions ensure that such HAPs are not used in constructing a synthetic control.

4.5 Implementing SCM

I implement the SCM using log count as the main outcome variable²⁶. As explained before, I consider the 14 CFC substitutes as one treated molecule. The outcome variable is therefore the log number of patents or articles that mention any of the 14 molecules.

The synthetic control is constructed by fitting the values of log counts in the pre-treatment periods and the topic proportions. I run specifications using the weighted means and the non-weighted means of topic proportions. When choosing weights for the donor units to create the synthetic control, the SCM algorithm imposes that the weights sum to 1 and that they be nonnegative. These constraints avoid any risk of extrapolation. However, when the treated unit presents values for covariates that are either the smallest or the largest in the distribution of the donors, it becomes difficult to approximate it. To verify that the donor pool remains adequate, Table 4 presents summary statistics for CFC substitutes and the small pool of HAPs in the case of counts derived from the weak rule. It is reassuring to see that the range of values displayed by the HAPs always contains the value for CFC substitutes. Hence, here, the constraints that weights must sum to 1 and be non-negative does not seem to be an issue.

Finally, I use the 171 HAPs as units in the donor pool. However, as explained by Abadie, Diamond, and Hainmueller (2015), reducing the size of the donor pool can limit the risk of over-

²⁶I also run specifications with count in levels as robustness checks.

fitting as well as the risk of interpolation biases. Following their advice, I use a smaller donor pool containing only the HAPs that are close to the treated unit in the space of covariates and outcome. I choose the twenty HAPs with lowest pre-RMPSE, that is the twenty HAPs that are closest to the treated unit in terms of topic proportions and count. In what follows, I call this group of HAPs the "smaller" donor pool. I refer to the "whole sample" of HAPs when the donor pool includes the 171 HAPs.

In all the SCM specifications, 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 from 1970 until 1985 only to fit the synthetic control. As discussed in the background section, the agreement at Montreal came as an unexpected success of international diplomacy; this implies that there would have been little anticipation on behalf of scientists and engineers. I nonetheless implement a robustness check accounting for the possibility that some anticipation took place starting in 1984. To this end, I re-define the treatment year as 1985 and use data only up to 1983 to construct the synthetic control. Hence, the synthetic control is constructed to match only innovation efforts up to 1983. If some additional efforts, due to anticipation, were already present in 1984, they would now be detected as the difference between the synthetic control and the treated unit.

For inference, I follow the method suggested by Abadie, Diamond, and Hainmueller (2010) and Abadie, Diamond, and Hainmueller (2015). The exercise consists in applying the SCM procedure to every potential control in my sample. This allows me to assess whether the effect estimated for the unit treated is large relative to the effect estimated for a molecule chosen at random. This is akin to implementing placebo tests wherein each unit in the control group is assumed to have received the treatment at the year 1987. A synthetic control is then constructed for each placebo, and we observe what would have been the hypothetical treatment effect for this "falsely" treated unit. This creates a distribution of placebo effects, and we can evaluate the effect for the "true" treated unit vis-a-vis to where it falls in this distribution.

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), it is useful to compute the ratios of post-RMSPE over pre-RMSPE and examine where in the distribution of those ratios, the treated unit lies. For example, if the treated unit is second largest ratio among a donor pool of 50 units, then the p-value can be computed as $\frac{2}{50} = 0.04$, and the treatment effect would be significant at the 5% level²⁷. The p-value can be interpreted as the probability of obtaining an estimate at least as large as the one obtained for the ‘true’ treated unit. Hence the inference is mostly limited to assessing whether the treated effect is large compared to the distribution of the placebos.

To illustrate, how p-values are calculated, Figure 9 displays the distribution of post-RMPSE over pre-RMPSE for the case of log count, weighted means of topic proportions and the whole sample of HAPs, for the corpus of patents. The figure shows that the ratio for CFC substitutes is greater than all of the 168 other units. Hence the p-value, in this case, is 1/168.

5 Results

5.1 Difference-in-Differences for CFC Substitutes

Table 5 display summary statistics in patents and articles for the CFC substitutes and the subset of HAPs selected into the DD control group. I formed this group such that it contains only the 50 HAPs with pre-trends most similar to the average substitute. Since the control group was constructed based on pre-trends similarity and not on count levels, the average numbers of documents are very different across the two groups. We note however that topic proportions are comparable.

Table 6 displays the regression tables for the simple first time differences. Model 1 confirms that there is a significant and positive mean shift after 1987 in the number of patents and articles mentioning CFC substitutes. Model 2 shows that the change can also be modeled as a trend break. The coefficient for ‘Years’ indicates that there is a positive underlying trend for articles but not for patents. Table 7 displays the difference-in-differences results. Model 1 corresponds to

²⁷The treatment effect’s p-value for the treated unit is therefore defined as: $p_1 = \frac{\sum_{j=2}^{J+1} 1\{ratio_1 \geq ratio_j\}}{J}$, where $ratio_j = \frac{post-RMPSE_j}{pre-RMSPE_j}$ and subscript 1 refers to the treated unit.

the main differences-in-differences specification. It includes year and molecule fixed effects. The binary variable ‘Post 1987 x Substitutes’ equals 1 for observations belonging to the group CFC substitutes and after 1987. For patents, the coefficient is smaller than the coefficient in the simple difference, but remains significant and large, corresponding to more than a 400% increase. This estimate corresponds to an additional 12 documents per year for the average substitute. Since there are 14 CFC substitutes in my sample, this implies 168 additional patents a year for CFC substitutes in aggregate. For articles, the coefficient is smaller than the coefficient in the simple difference, but remains significant and large, corresponding to more than a 95% increase. This corresponds to an additional two documents a year for the average substitute; hence, aggregating the 14 CFC substitutes, this corresponds to about 28 additional articles per year. Model 2 presents a trend-break specification. It shows that the log number of patents mentioning CFC substitutes increases with the years after 1987 by 0.22 more than the control group. Similarly, the log number of articles mentioning CFC substitutes increases with the years after 1987 by 0.10 more than the control group.

5.2 Synthetic Control for CFC Substitutes

Before examining results, I want to illustrate the benefits of the SCM. Table 8 compares the mean value over the years 1970 to 1985 of log count and topic proportions for CFC substitutes, the observed treated unit ("real S" in the table), for the comparison unit constructed through the SCM ("Synthetic S") and for the average of HAPs. Specifically, the HAPs used in calculating the average are only those from the small pool. The synthetic control, here, was constructed based on similarity with the variables "Count" and the weighted means of the five topic proportions. We see that the synthetic control matches the "real" CFC substitutes group better than the average of HAPs in terms of log count. This is the core idea motivating the use of the SCM. The topic proportions are very similar, but this could be expected since the pool of HAPs used is the small one, and the means of topic proportions within that pool are very concentrated. Table 9 illustrates how the different variables contribute to constructing the synthetic control. Within the Stata *synth* package, these weights are determined according to the amount of predictive power

that each variable has over the outcome. Hence, in the case of patent counts with weighted means of topic proportions, the outcome variable, log count, is the variable assigned greatest weights. Topic proportions contribute around 15% in constructing the synthetic control.

Table 10a summarizes the performance of the main SCM implementations for CFC substitutes in the corpus of patents. I ranked the table according to the magnitude of the pre-RMPSE with smaller pre-RMPSE at the top of the table. The lower the pre-RMPSE, the better the fit between the synthetic control and the treated unit over pre-treatment years, and therefore the more credible it is that the synthetic control appropriately proxies the counterfactual. Furthermore, recall that procedures using the small pool are more trustworthy because they limit the risk of interpolation biases and overfitting. Hence the preferred specifications here uses the small pool and the weak rule and weighted means of topic proportions. The p-values smaller than 0.01 indicate significance at the 99% level. Table 10a also reports the year in which the treatment begins to be significant at the 10% level. This is determined by calculating p-values for each year separately. We see here that the treatment effect becomes significant in most cases only starting in 1990 or 1992. The ATE for the preferred specification equals 1.0; this corresponds to a 172 % increase in patents compared to the synthetic control. To convert in the number of additional patents, I first calculate what the average count across post-treatment years is for the synthetic control: this is about 4.07 corresponding to about 59 patents a year. This gives a treatment effect close to 100 patents per year²⁸.

Similarly, table 10b provides performance summary for the main SCM procedures for CFC substitutes in the corpus of articles. Here, the preferred procedure to report the ATE uses the small pool of HAPs and weighted means of topic proportions. The ATE for this preferred specification equals 1.06 and is significant at the 99% level. This estimate translates to a 189% increase, and corresponds to about 40 additional articles per year.

Figure 11 graphically displays the results of the synthetic control method for CFC substitutes. The graphs correspond to SCM implementation for the preferred specification, that is when the SCM is implemented with log counts, using the small pool of HAPs and weighted means of topic

²⁸I multiply 172 % by 59, to obtain 100.62.

proportions. The graphs on the left-hand side represent the raw effect, that is the observed time series of the treated group along with the time series of the constructed control. On the right-hand sides are shown the placebo tests, the non-parametric tests to evaluate the significance of the results; black lines show the effect on the treated group relative to the control group, while each gray line is a placebo test performed on a unit drawn from the donor pool.

The figure illustrates what we concluded from Table 10b and 10a: the treatment effect on CFC substitutes appears significant for both patents and articles. Interestingly, we note that the black line rises above most other lines mostly as from 1990. This indicates that the treatment effect is statistically significant only after 1990. Two mechanisms here account for a delay between the moment where firms decide to reorient their R&D efforts towards CFC substitutes and the granting of a patent. First is the time required to obtain any technology worth patentable, which can broadly vary. Second, to be granted a patent, firms must submit an application which is then reviewed by patent examiners. I examine the meta-data of patent records to evaluate the average delay between applications and grants of patents in my sample. I find that the average delay is 22 months (with a standard deviation of 12 months) for patents mentioning CFC substitutes. For patents mentioning HAPs, the delay is very similar, about 23 months on average (with standard deviation of 12 months). Figure 12 graphically shows the differences between application and granting date. Overall, plotting the number of patents based on granting dates simply shifts the entire curve two years forward. Importantly, the pre-treatment periods look very similar.

Accounting for a two-year delay on average indicates that the increase in patenting on CFC substitutes happened soon after the signature Montreal. One possibility is that firms developed technologies prior to 1987 keeping them secret. When Montreal was agreed, it became worthwhile to protect their intellectual property if they hoped to commercialize the technologies. It is possible that a part of the number of patents granted in early years after 1987 results from technologies that were kept "in the drawers". However, if this was the main story, we would observe a one-time increase in the number of patents. Instead, we see a sustained increase in the 1990s onwards. This indicates that Montreal triggered a burgeoning of innovation rather than simply enabling the diffusion of technologies already developed. It is difficult to assert how long it takes firms to

develop new technologies in response to a change in incentives. We can expect such delay to vary from technology to technology even within the same technological sector. In the context of energy patenting, (Popp 2002) estimates that the mean lag occurs in 3.71 years and the median lag in 4.86 years. This implies that over one-half of the full effect of an energy price increase on patenting is experienced after just 5 years. These estimates are somewhat consistent with the shape of the yearly treatment effects obtained here.

5.3 Robustness checks

Anticipation. An important assumption supporting the SCM is that the intervention does not affect the outcome before the implementation period. In reality, anticipation effects often violated this assumption. A workaround consists in redefining the treatment year as the first period in which the outcome may react to the intervention. Although I implement the SCM using 1988 as the first year of where the treatment is active, I also replicate the procedure using 1985 as the beginning of the treatment since it was in March of that year that the Vienna Convention was adopted. The meeting in Vienna can be considered as the start of the ozone layer’s diplomatic life.

Anticipation would be problematic for the construction of a synthetic control since part of the treatment effect would become embedded in the control, and the SCM would lead to understating the treatment effect. For this reason, I also implement a range of SCM experiments redefining the treatment year as 1985 and using data only up to 1982 to construct the synthetic control. Figure 13 displays the SCM graphs for the preferred specification: it uses the small pool and weighted means of topic proportions for both patents and articles. Detailed results are presented in the appendix. Here, the earliest possible take-off would be in 1983 since I fit the synthetic control using data up to 1982. We observe that there does seem to be any takeoffs before 1987. This indicates that there has been little anticipation of the success of the treaty, consistent with the version related by Benedick (2009).

Interferences A second assumption supporting the SCM requires that there be no interferences between units, meaning that HAP molecules should not be affected by the Montreal Protocol. This is unlikely to be the case since HAPs have been under the regulatory radar for very different reasons than ozone depletion. However possibly the redirection of research efforts towards CFC substitutes could crowd out financing towards the control molecules. This is also unlikely since HAPs are used in different types of industrial activities. However I still proceed to a careful examination of the firms patenting both on CFC substitutes and the top HAPs contributing to the synthetic control.

Table 11a and 11b provides a description of the top 4 HAPs entering the synthetic control for patents and articles, respectively. We note that many of the industrial applications are not directly related to those of CFC substitutes which indicate a crowding out is unlikely. I investigate to what extent the assignees of patents on CFC substitutes and on those top 4 HAPs are similar. Unfortunately, assignee names in patent records are not standardized and the same firm can appear under different variations of the same name. I therefore use a fuzzy matching algorithm in order to match assignee names. I find that about 60% of patents mentioning CFC substitutes after 1987 are issued to assignees that never patented on any of the top 4 HAPs²⁹. Examples of such assignees are firms like 3M, Allied Chemical, BASF, Dow Chemical and Procter & Gamble.

Other Assignment Rules I consider a different rule for assigning document to molecules to test the robustness of my main results. Under the basic rule, which I call the *weak* rule, a document was assigned to group X if a molecule of group X is mentioned in the document, regardless of whether molecules from other groups are also mentioned. Now, under the new rule, which I call the *intermediate* rule, a document is assigned to group X if the molecule with the greater number of mentions is from group X . Figure 14 shows the number of patents and articles every year for each molecule group according to the three assignment rules. We note that, as expected, the weak rule displays a greater number of documents, except for HAPs for which the weak and intermediate rules overlap almost completely. Table 12a and 12b display the performance results

²⁹There are a total of 535 different assignees patenting on CFC substitutes after 1987, and 125 of those assignees also detain patents on one of the top 4 HAPs.

of the SCM procedures for patents and articles, respectively. We see results are very similar to the main specifications. The estimated treatment effects are somewhat larger than those with the weak rule. The pre-RMSPE values for patents however indicate that the synthetic control using the weak rule provided a better fit.

Count. I replicate the SCM procedures using counts, in level and not in log, as the outcome variable. Table 13a and Table 13b display the results for patents and articles, respectively. Under the weak rule of assigning documents, I find an ATE that equals about 111 additional patents every year from 1988 to 2000, significant at the 99% level. This estimate is very close to the treated effect obtained using logged counts, which was about 100 patents per year. For articles, the ATE for the preferred specification equals about 44 additional articles every year from 1988 to 2000, significant at the 99% level. Like in the case of patents, this estimate is very close to the treated effect obtained using logged counts, which was about 40 articles per year.

Using the difference-in-differences Subset of HAPs. Since I implemented a DD design using the particular subset of HAPs, I also implement the SCM using that subset as the donor pool. I find results that are comparable to the main specification. Details are reported in the appendix. For patents, the treatment effect found approximates 0.9, while for articles it is lower than 0.80. We note that the values of pre-RMSPE are higher than the ones for similar procedures using the small pool. This implies that the procedure to select the subset based on similar slope excluded some molecules which ended up being useful contributions to the synthetic control.

5.4 Annex A and Annex B Compounds

In this section, I investigate the effect of Montreal on patents and articles mentioning CFCs, that is the molecules which were being phasing out of industrial activities. These molecules are referred to as Annex A compounds because they are listed in the Annex A of the legal text. These molecules include five chlorofluorocarbons and three halons. For chlorofluorocarbons, the agreement imposed a freeze by 1989 and a 50% decrease by 1998 relative to 1986; for halons, only a freeze by 1992 was decided. In 1990, during the London revisions, twelve additional compounds became regulated.

They are listed in the Annex B of the agreement and consist of 10 other CFCs plus carbon tetrachloride and methyl chloroform. The negotiated reduction targets for each compound is shown in the Appendix. In what follows, I refer to these two groups of molecules as Annex A and Annex B.

It is difficult to make strong hypotheses about the effect of Montreal for Annex A and Annex B compounds. On one hand, Montreal can be thought of an incentive to no longer pursue any research or innovation that would make use of these molecules in new industrial contexts. But the agreement might also have spurred research efforts to help reduce the ongoing effect of such molecules on the environment as well as innovations to help recycle such components or use them more efficiently. This second effect is particularly likely as the phase-out of such molecules was scheduled to be progressive. As a result, firms were given some time to adapt and could continue using CFCs in their production.

The graphs in Figure 17 plot the yearly number of articles or patents mentioning the names of given molecules included in Annex A and B. We note that most trends are flat, except maybe for Annex A in articles which seem to increase and then decrease. Table 14 presents results from first differences specifications. Results indicate statistically significant mean shifts between before and after 1987, except for Annex B in patents; however these are small in magnitude. In figure 15, the difference-in-differences specifications indicate that a positive and statistically significant treatment effect for Annex A in patents and a negative one for Annex B in articles. The magnitudes however are small. For Annex A in patents, the coefficient corresponds to a 18% increase in the number of patents mentioning Annex A compounds. For Annex B in articles, the estimate corresponds to a 28% decrease in the number of articles mentioning Annex B compounds.

Table 16 displays the summary performance of the SCM implementations for Annex A and B in patents and articles. Almost none of the implementations find a significant treatment effect, except for Annex B in articles where a negative treatment effect with 10% significant is found when the whole sample of HAPs is used. These results indicate that Montreal did not trigger a large decrease nor a large increase in the number of patents and articles mentioning Annex A and B compounds. Figure 18 and 19 illustrate these results by displaying the graphs generated by the

SCM procedures using the small pool, and unweighted or weighted topic proportions (which ever gave lowest pre-RMPSE). The graphs show that indeed the estimated treatment effect estimated falls well within the distribution of placebo effects, at least for Annex A compounds. For Annex B compounds, the treatment effect tends to be as one of the lowest curves among all the placebos. We note that, in the case of articles, the synthetic control fails to provide a good fit, and so results cannot be trusted.

6 Conclusion

In this paper, I document that the Montreal Protocol led to a large increase in the number of patents and scientific articles mentioning the names of CFCs substitutes. This empirical evidence goes against the often-heard narrative that the negotiations at Montreal succeeded because there was little technological uncertainties as to how to solve the crisis. Looking back at the transition to CFC alternatives, it is clear that it happened both rapidly and without major technological barriers. However, it was unlikely that industrial actors and policy makers knew, *ex-ante*, it would happen this way. Instead, the large estimated treatment effect tells a story where most of the science and innovation related to CFC substitutes resulted from the signature of Montreal. Montreal triggered a series of mechanisms that provided firms and researchers clear incentives to orient their work towards CFC substitutes. The CFC phase-out created a worldwide demand for substitutes, and profit-maximizing firms had to innovate to stay in business. On the other hand, Montreal might have served as a strong focal point for the research community and might have made articles about this topic more likely to be accepted for publication. Possibly, researchers also chose to redirect their research activities towards CFC substitutes due to funding for research itself shifting towards these topics (e.g, NSF grants).

The ozone crisis has often served as a comparison for climate change. The two crisis have obvious similarities: both are about an endangered global public good requiring international cooperation, and both have been plagued by scientific uncertainties in the climate models. There is no question that an important difference is in the structure of the negotiated treaties: Montreal was binding and included enforcement mechanisms based on trade sanctions, while such mechanisms

were never discussed for climate. The binding structure of Montreal eventually ensured that industrials would face strong incentives to move to CFC alternatives. There are various opinions, however, on why a binding treaty was reached for ozone and never for climate. An often-heard claim asserts that the key difference lays in the nature of the required technological change, specifically that technological solutions were easily available at the time of negotiations for ozone. This paper therefore contributes to casting new light on the technological differences between ozone and climate: the major difference does not seem to about the state of technological uncertainties at the eve of the negotiations. These findings invite us to consider other potential differences and one of them relates to the market structure of the regulated industries. Solving the ozone crisis implied that some business units had to disappear. Solving climate change would hurt entire sectors. It is likely that this fueled greater political opposition.

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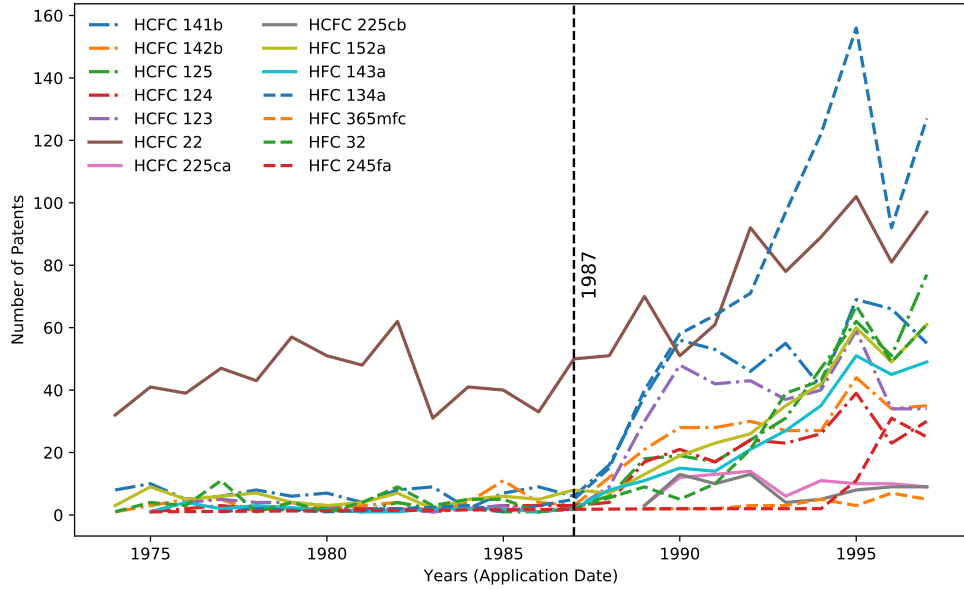
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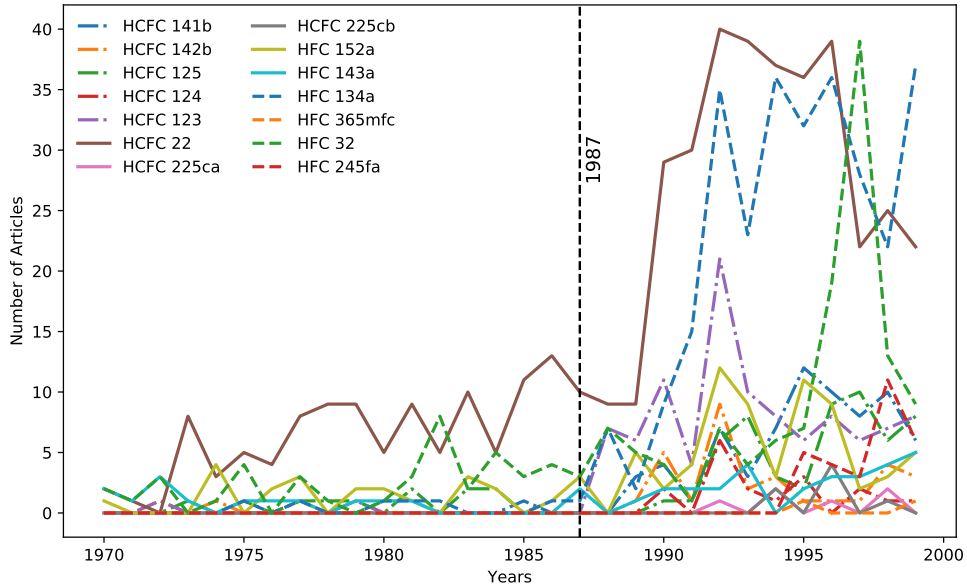
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(a) Patent counts for each CFC substitutes.



(b) Article counts for each CFC substitutes.

Figure 1: Counts in articles and patents for each CFC substitute.

Note: These graphs plot the yearly number of articles or patents mentioning the names of given CFC substitutes. We note a clear increase for most CFC substitutes in the 1990s. The year refers to the date when the assignee applied for the patent, and not when the patent was granted. There is on average a two-year delay between patent application and grant. The graph presents similar trends when using application years with the exception that the trend takes off two years later.

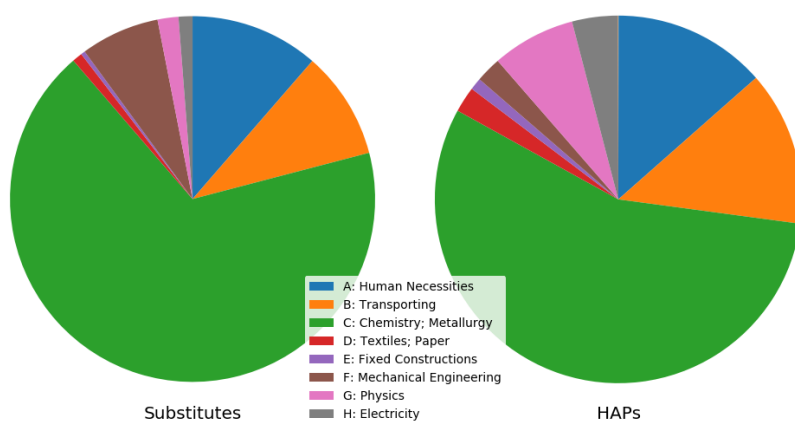
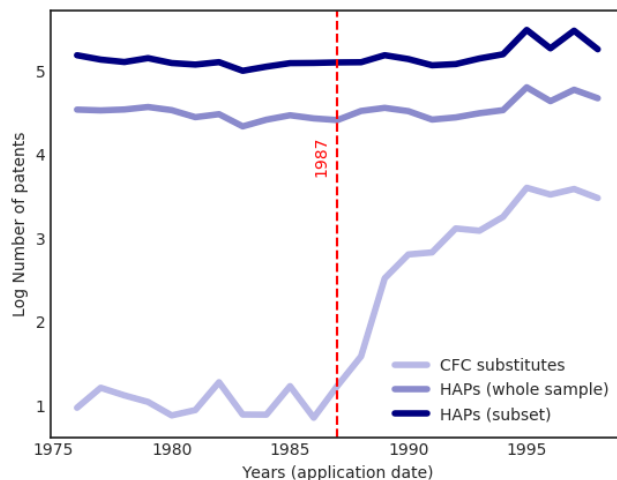
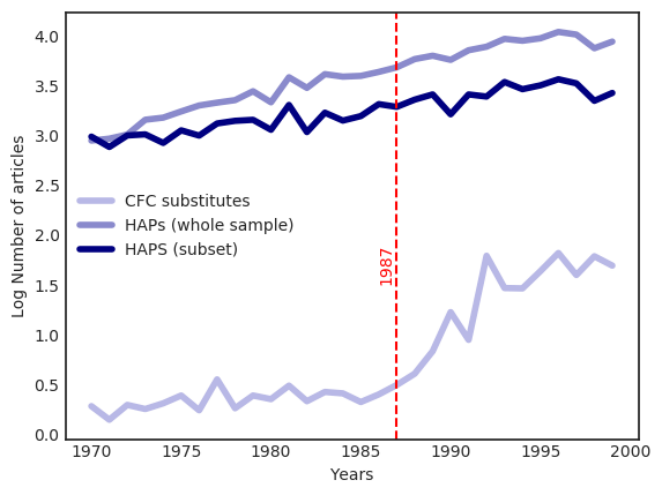


Figure 2: Top level patent codes for CFC substitutes and HAPs using the international patent classification.

The figure shows that overall patents mentioning CFC substitutes and HAPs (Hazardous Air Pollutants) fall into similar top-level codes. This motivates the use of HAPs as a control molecules to estimate the causal effect of Montreal. HAPs are a group of 171 molecules that have no relationship to ozone and that are used for diverse industrial applications.



(a) Patents.



(b) Articles.

Figure 3: Pre-trends in log counts of documents mentioning CFC substitutes and HAPs.

Note: The graph displays the pre-trends for the treated group (CFC substitutes) and the control groups. I present pre-trends for two possible control groups. The first is using the whole sample of HAPs (that is 171 molecules). The other consists in using a smaller number of HAPs: the 40 HAPs with pre-trends closest to the average CFC substitutes. Pre-trends look somewhat similar with the whole sample. Nonetheless, pre-trends are even more similar by using only the smaller subset.

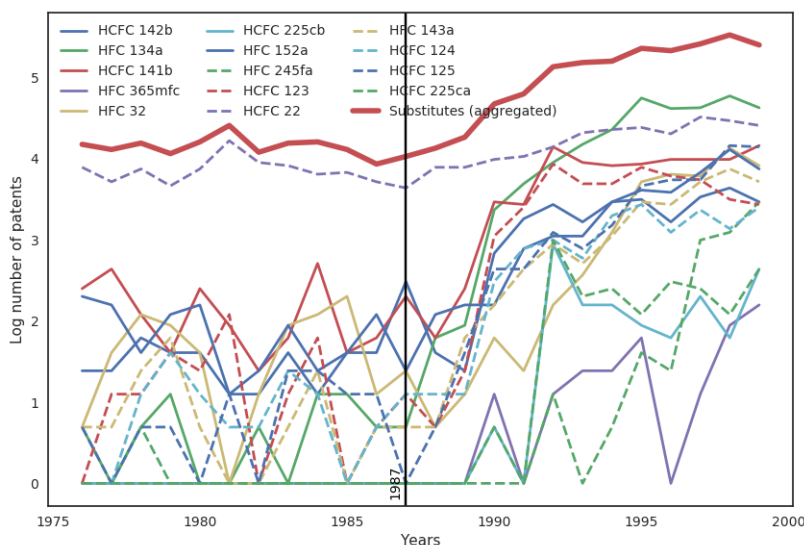


Figure 4: Patent counts in log for each CFC substitute and when aggregated. The graph illustrates the difference between considering the 14 molecules independently and considering them as one treated molecule. The thick line called "Substitutes (aggregated)" corresponds to the number of patents mentioning 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 substitute because my objective is to estimate the effect of Montreal on research and innovation on any of the substitutes rather than on one specific substitute.

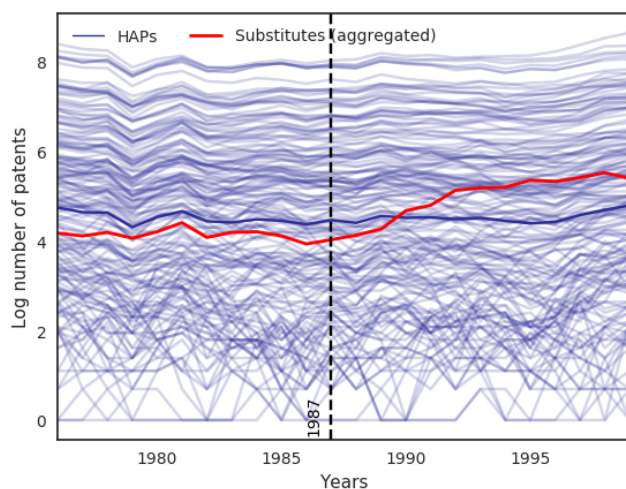


Figure 5: Patent counts in log for each HAP and for the aggregated CFC substitutes. The graph illustrates the heterogeneity of HAP molecules. The thin lines correspond to the trends for each individual HAP while the thick HAP line corresponds to the mean counts for HAPs. We see that HAPs are a diverse group of molecules. In particular, some of them have log counts much higher than the aggregated CFC substitutes. The synthetic control method will allow to construct a better control group by using only the HAPs most similar to CFC substitutes.

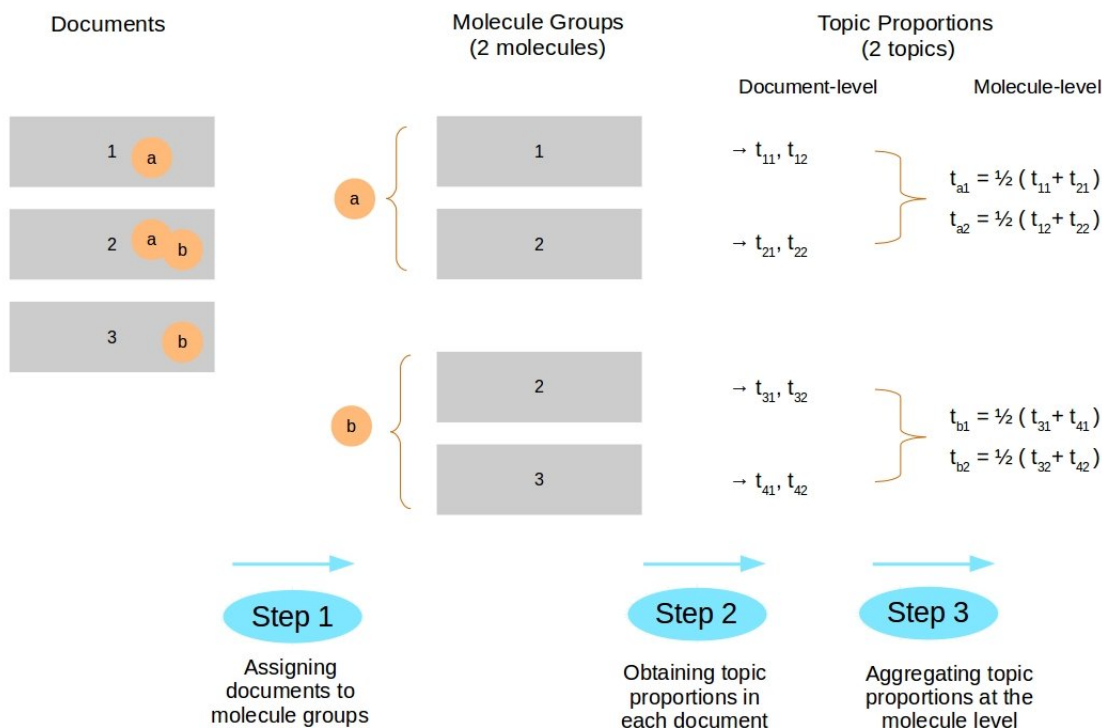
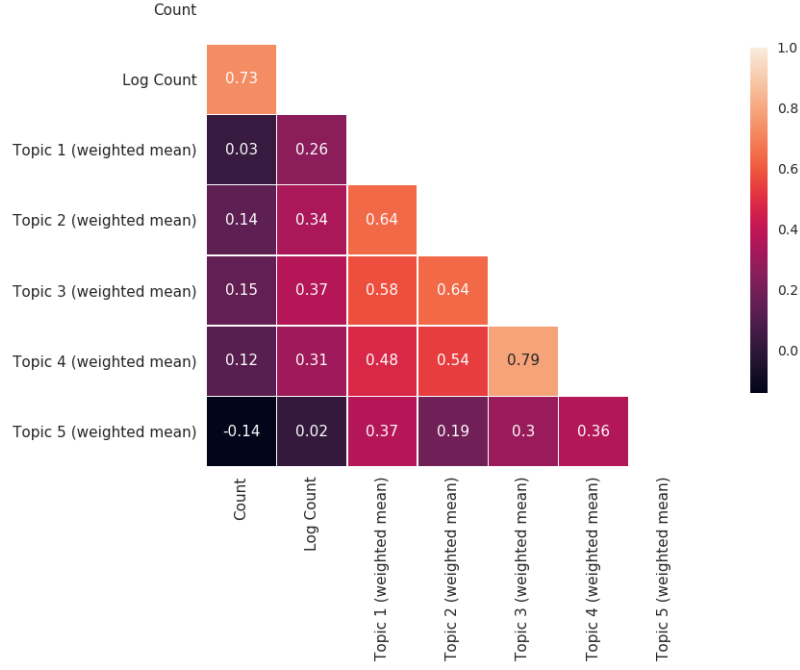
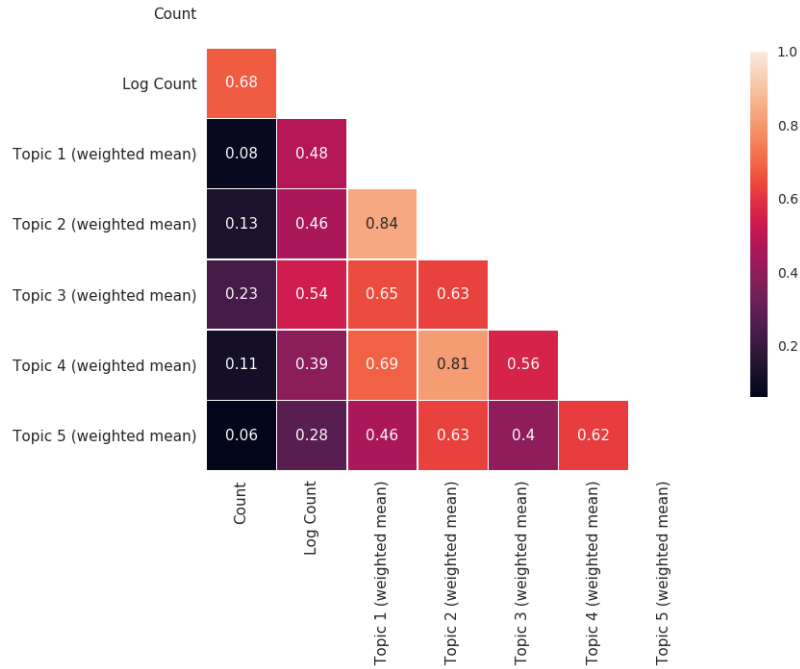


Figure 6: Schematic explanation of the methodology.

Note: Suppose we have three documents: document 1 and 2 mention molecule 'a' while document 2 and 3 mention molecule 'b'. In step 1, we aggregate documents according to their molecule group. I follow a basic rule (which I refer to as weak rule) that assign any document with at least one mention of a molecule to that molecule's group. Hence, for example, both documents 1 and 2 are assigned to the group of molecule 'a'. In step 2, we use the topic model created by the LDA algorithm to obtain the proportions of each topic in each document. $t_{i,j}$ stands for the proportion of topic j in document i . Finally, in step 3, we create a topic proportion at the molecule level by simply averaging over all the documents that mention the molecule of interest.

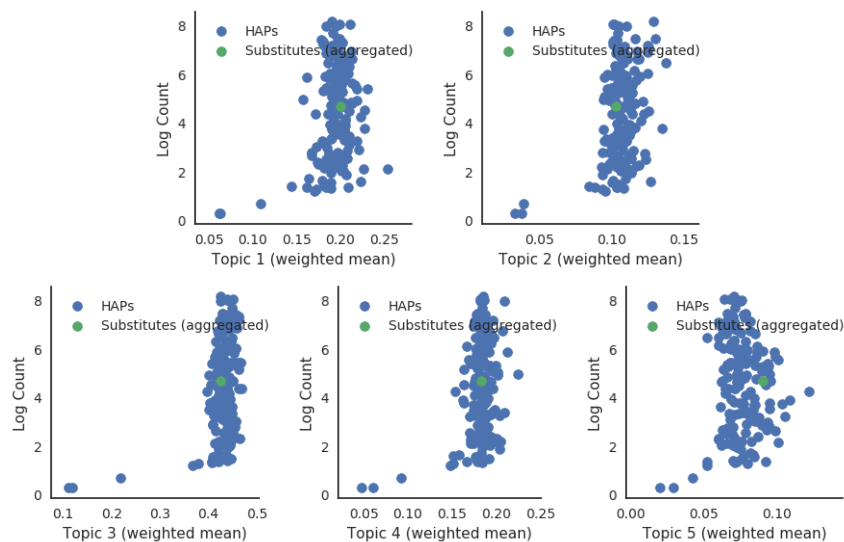


(a) Patents.

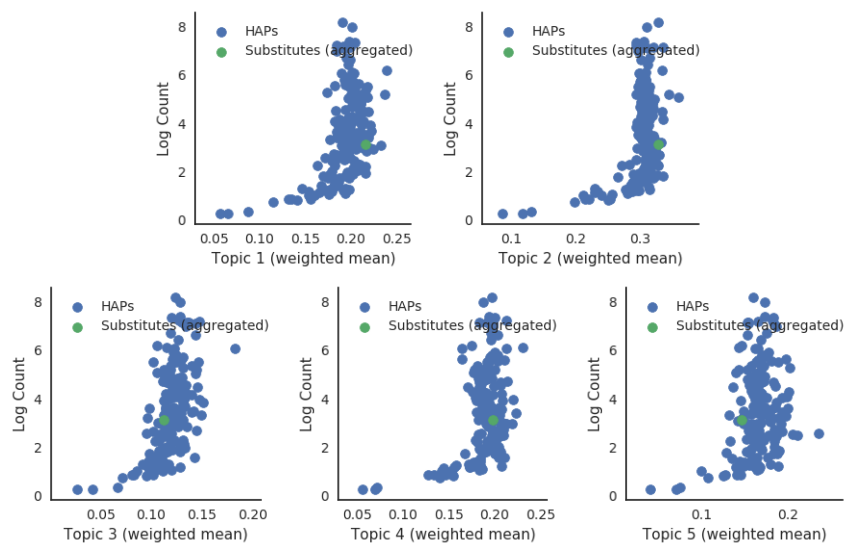


(b) Articles.

Figure 7: Correlations between topic proportions and counts using the whole sample of HAPs. Note: We see that topics somehow correlate with log counts. These heatmaps are useful to uncover the underlying relationship between topic proportions and the outcome variable of interest (log count). Indeed, the SCM procedure gives more weight to stronger predictors of the outcome variable. Since topic proportions correlate with the outcome variable, it ensures that they will contribute to the synthetic control.



(a) Patents.



(b) Articles.

Figure 8: Scatterplot of topics proportion and log count.

Note: The graphs illustrate the benefits of using topic proportions in the SCM. The scatter plots indicate that there are some clear outlier molecules: molecules with semantic contexts far from CFC substitutes. Implementing the SCM with topic proportions therefore provides a way of avoiding the use of such molecule in the construction of a comparison unit.

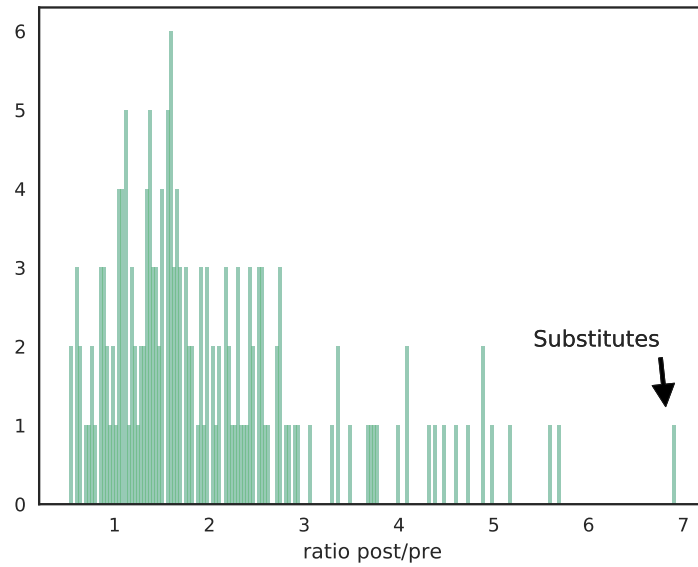
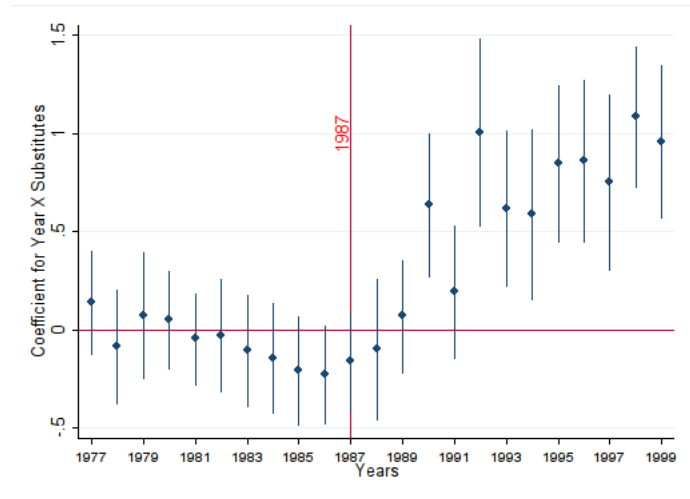


Figure 9: Distribution of post / pre RMSPE ratios for placebos for CFC substitutes.

Note: The graph displays the distribution of post-RMPSE over pre-RMPSE for the case of log count, weighted means of topic proportions, and whole sample of HAPs for patents. The figure shows that the ratio for CFC substitutes is clearly greater than all of the 168 other units. Hence the p-value in this case is $1/168$.

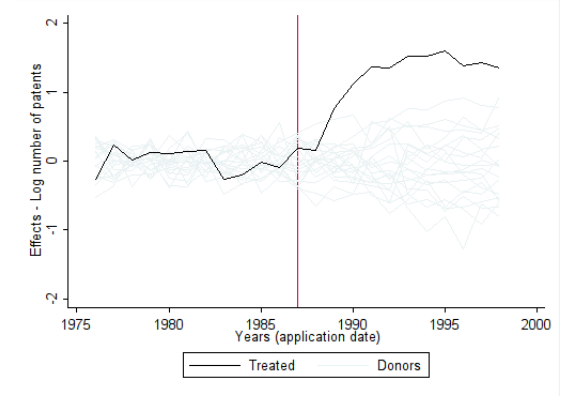
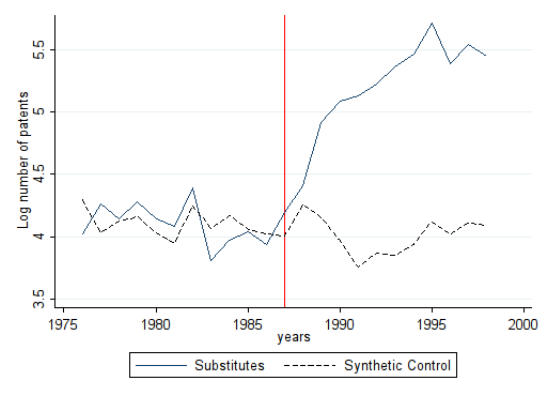


(a) Patents.

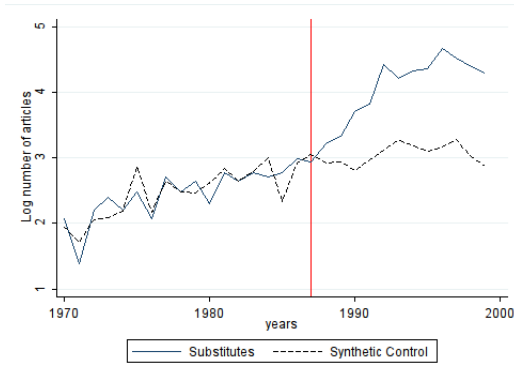


(b) Articles.

Figure 10: Differences-in-difference treatment effects by year



(a) Patents: raw effect (left) and placebo tests (right)



(b) Articles: raw effect (left) and placebo tests (right)

Figure 11: Synthetic control graphs for CFC substitutes.

Note: The graphs corresponds to SCM implementation for the preferred specification, that is when the SCM is implemented with log counts using the small pool of HAPs and weighted means of topic proportions. The graphs on the left-hand side represent the raw effect, that is the observed time series of the treated group along with the time series of the constructed control. On the right-hand sides are shown the placebo tests, the non-parametric tests to evaluate the significance of the results; black lines show the effect on the treated group relative to the control group, while each gray line is a placebo test performed on an unit drawn from the donor pool. The effect on CFC substitutes appears large and significant in both corpora. Placebo tests confirm that the effect is significant starting a few years after 1987; indeed the black line rises above most other lines as from 1990. This might correspond to a natural lag time between the redirection of research activities towards CFC substitutes and the publication or patenting of such work.

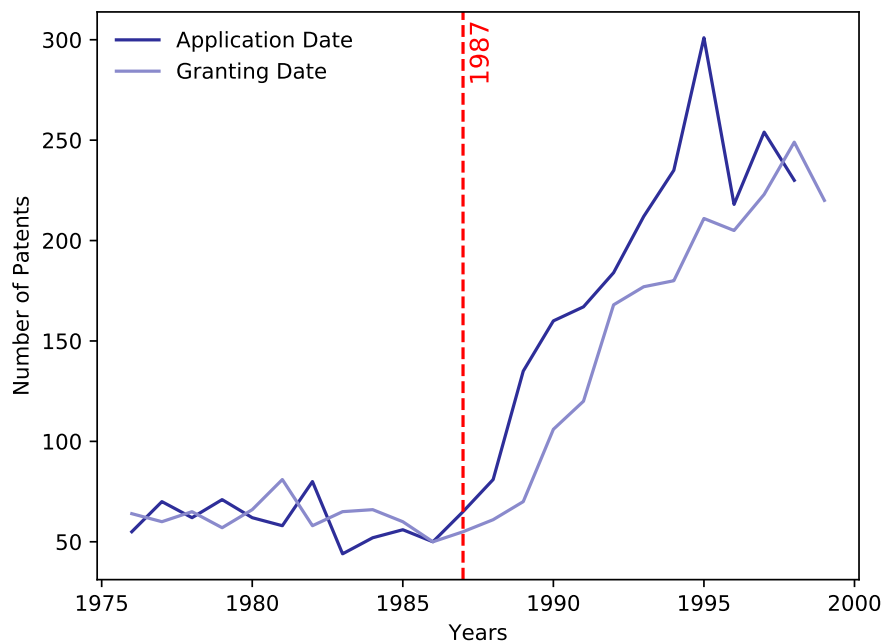
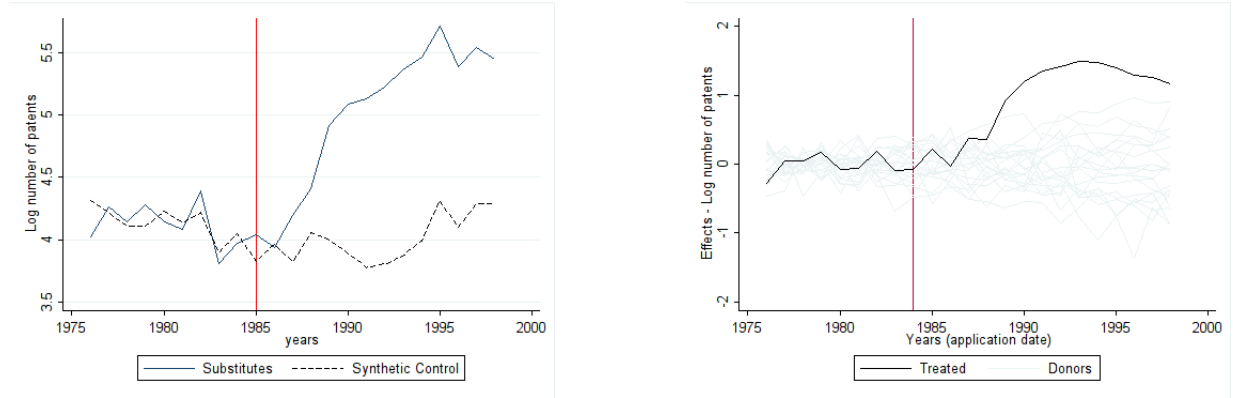
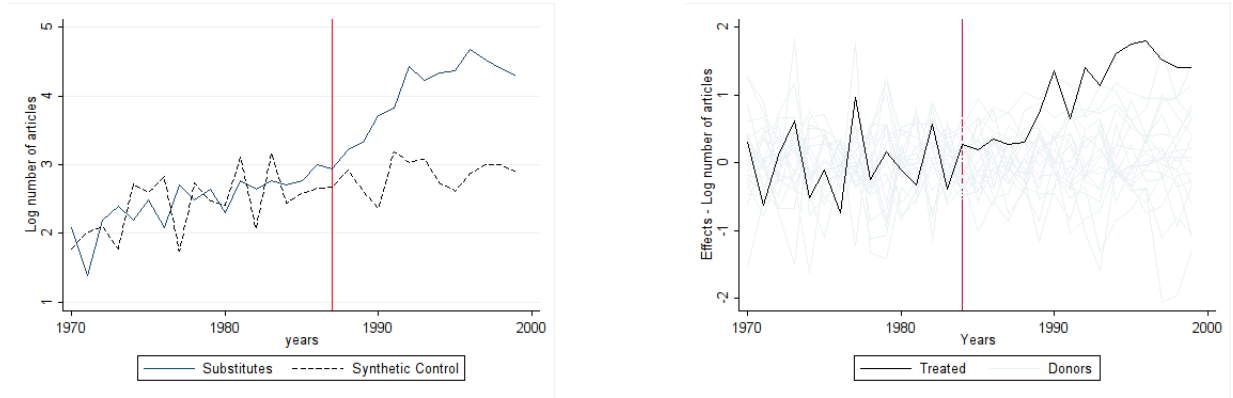


Figure 12: Patent counts over time using the application date and the grant date for CFC substitutes.

Note: The graph plots the number of patents mentioning any CFC substitutes using the application date of the patent or the granting date. The two curves are very similar, with only about a two-year delay after 1987. Precisely, there is on average a 22-month delay between application and granting, with a standard deviation of 12 months. The graph illustrates that we obtain similar results by using the application date for the main analysis.



(a) Patents: raw effect (left) and placebo tests (right)



(b) Articles: raw effect (left) and placebo tests (right)

Figure 13: Synthetic Control Graphs for CFC Substitutes Assuming Anticipation.

Note: The graphs display the results of the synthetic control method for substitutes for patents and articles assuming anticipation. For these experiments, the treatment year is redefined as 1985 and the synthetic control constructed using data up to 1982. Results are similar to previous SCM experiments. Specifically, there are no take-offs before 1990. The graphs corresponds to SCM implementations that yielded the lowest pre-RMSPE. That is, for both patents and articles, the SCM uses log count and weighted means of topic proportions. The graphs on the left-hand side represent the raw effect, that is the observed time series of the treated group along with the time series of the constructed control. On the right-hand sides are shown the placebo tests, the non-parametric tests to evaluate the significance of the results; black lines show the effect on the treated group relative to the control group, while each gray line is a placebo test performed on an unit drawn from the donor pool.

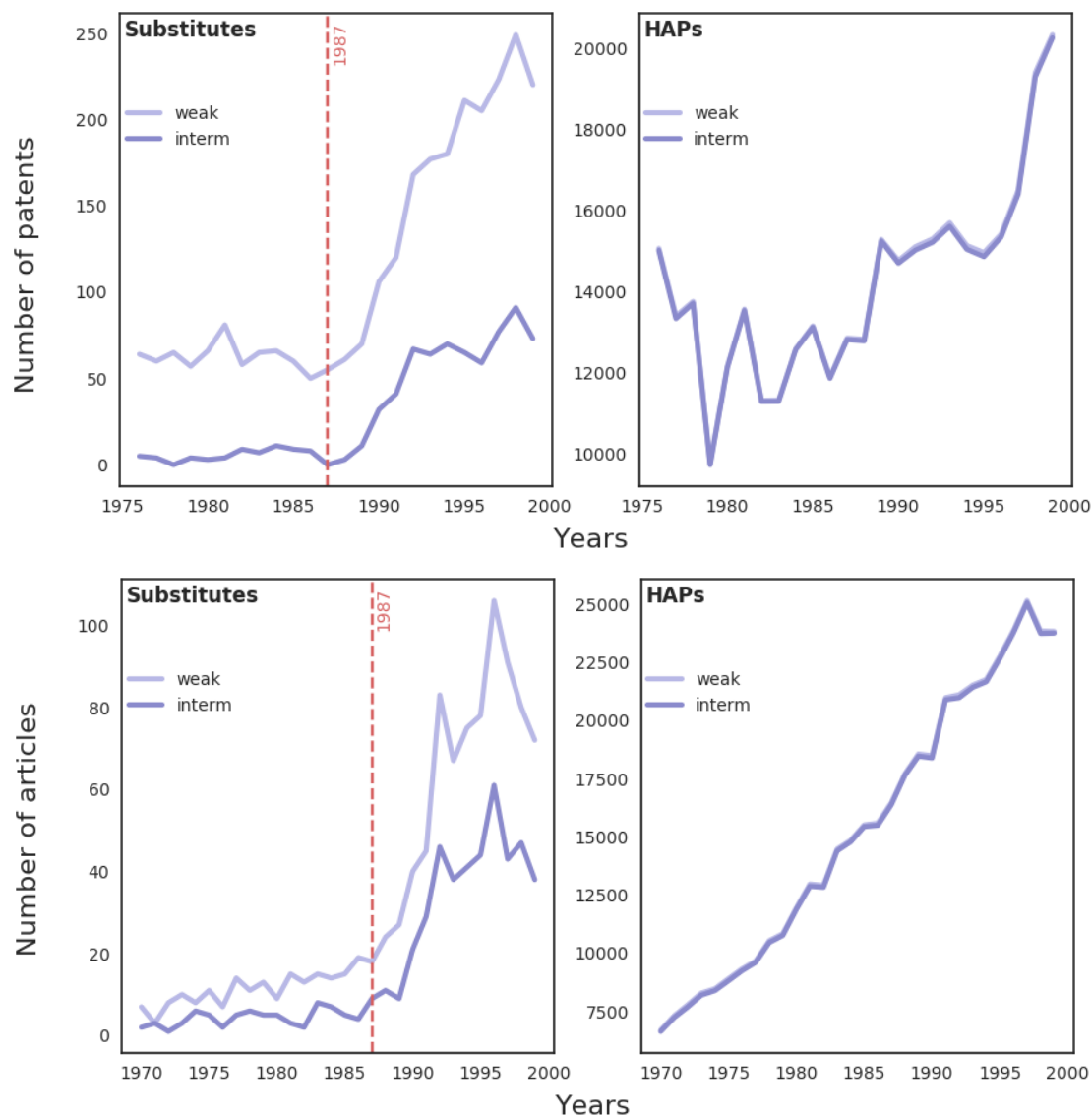
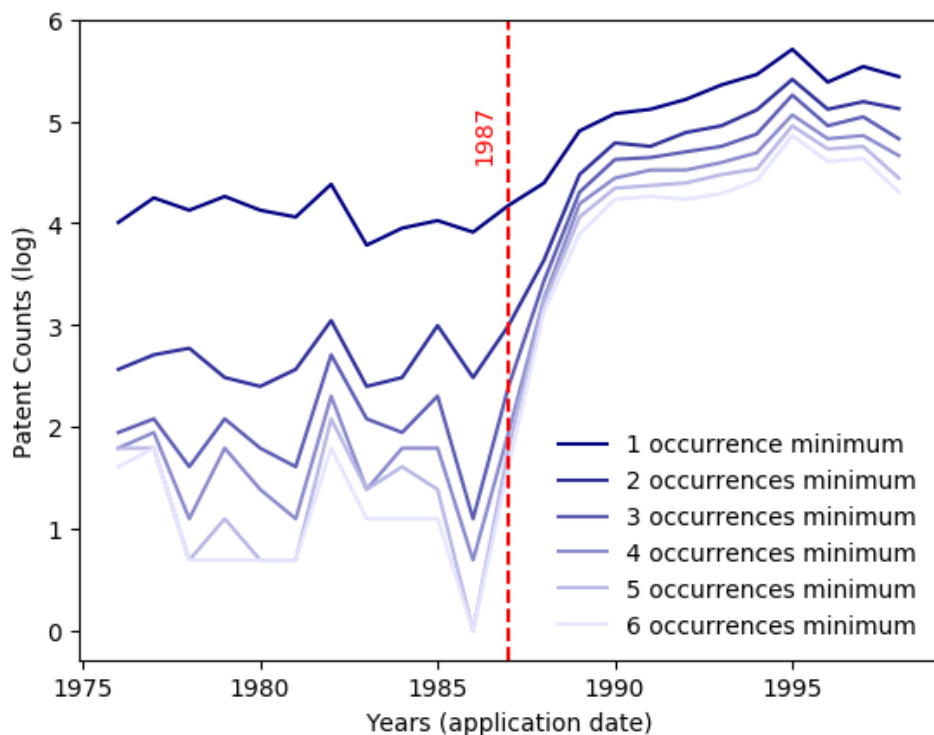
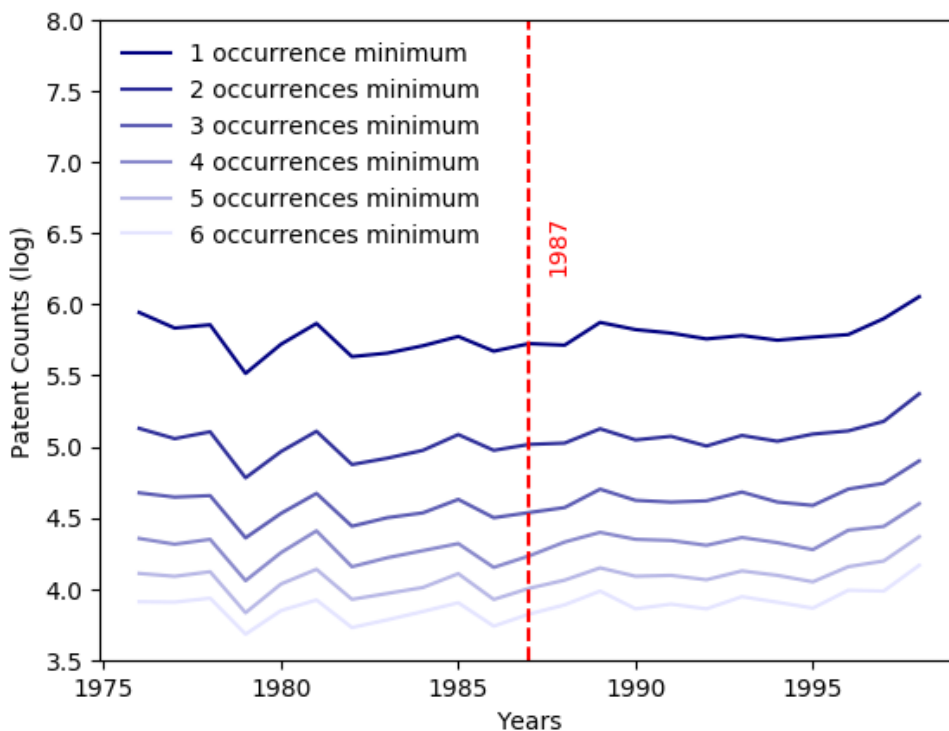


Figure 14: Yearly counts for CFC substitutes and HAPs with different assignment rules for patents and articles.

Note: The figures show the number of patents and articles each year for CFC substitutes and HAPs according to the two different assignment rules. The main results were obtained using the rule called "weak". I test the robustness of these results by using an alternative rule, which I call "intermediate". The intermediate rule is a more conservative way of assigning documents to molecules. When a document mentions several molecules, instead of assigning the document to each molecule, the document is assigned to only the molecule it mentions the most. We note that, as a result, the weak rule has a greater number of documents in the case of CFC substitutes. For HAPs, the graphs show no difference mostly due to the scale of the axis.



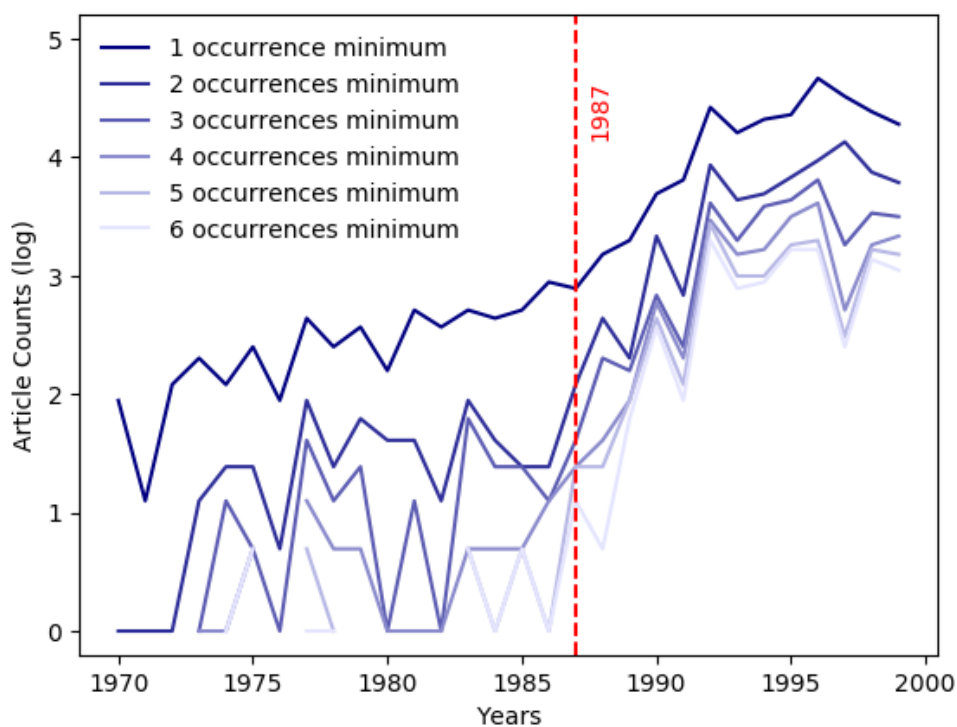
(a) CFC substitutes (aggregate)



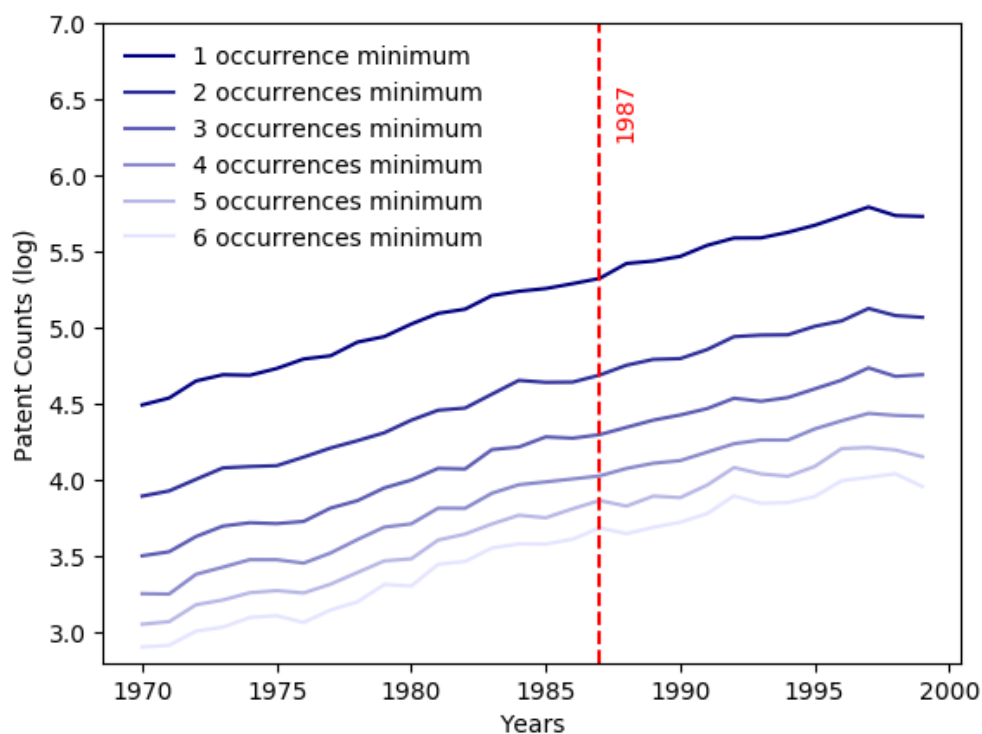
(b) HAPs (average)

Figure 15: Robustness: patent counts with minimum threshold of molecule occurrences.

Note: The graphs illustrate that focusing on patents that contain more than just on occurrence of molecule would change little of the analysis. Indeed the trend of the average HAPs remain very similar; only the levels decrease as we increase the threshold of occurrence. For CFC substitutes, focusing only on patents with greater number of occurrences in fact exacerbates the differential between the pre and post trends.



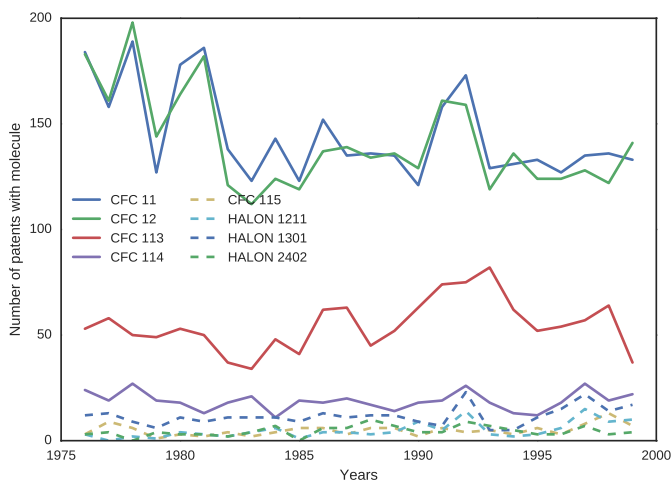
(a) CFC substitutes (aggregate)



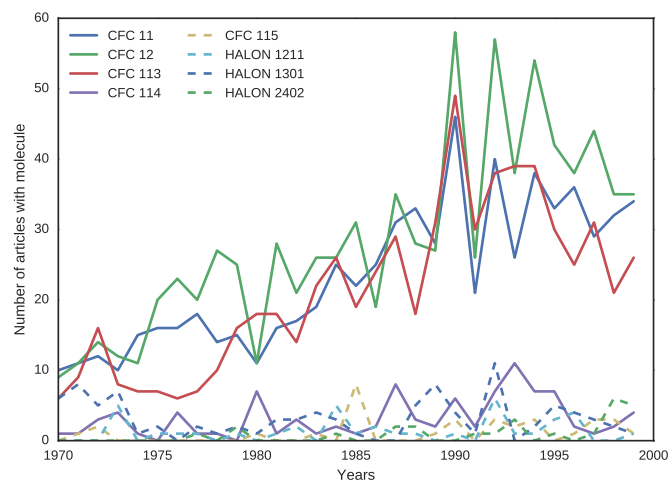
(b) HAPs (average)

Figure 16: Robustness: article counts with minimum threshold of molecule occurrences.

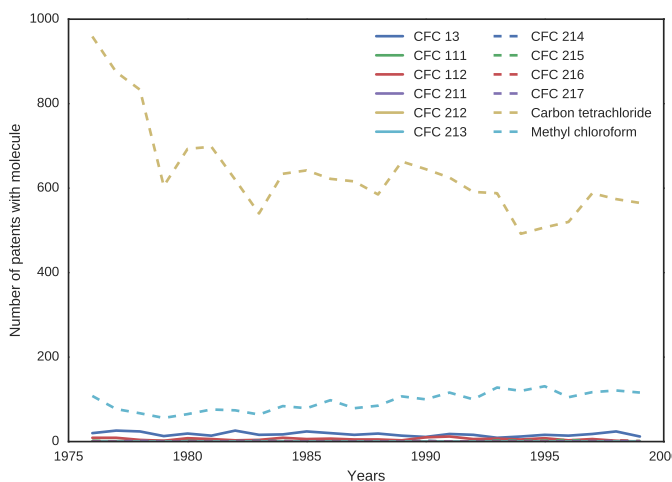
Note: The graphs illustrate that focusing on articles that contain more than just on occurrence of molecule would change little of the analysis. Indeed the trend of the average HAPs remain very similar; only the levels decrease as we increase the threshold of occurrence. For CFC substitutes, focusing only on patents with greater number of occurrences in fact exacerbates the differential between the pre and post trends.



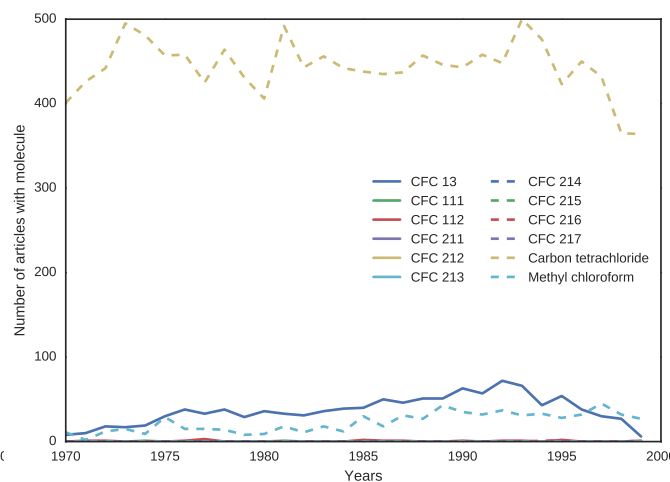
(a) Annex A: Patents.



(b) Annex A: Articles.

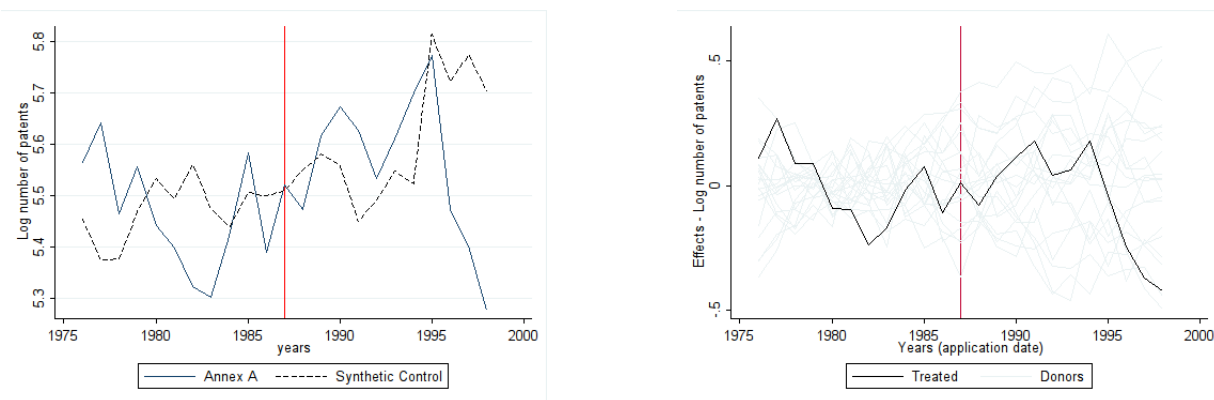


(c) Annex B: Patents.

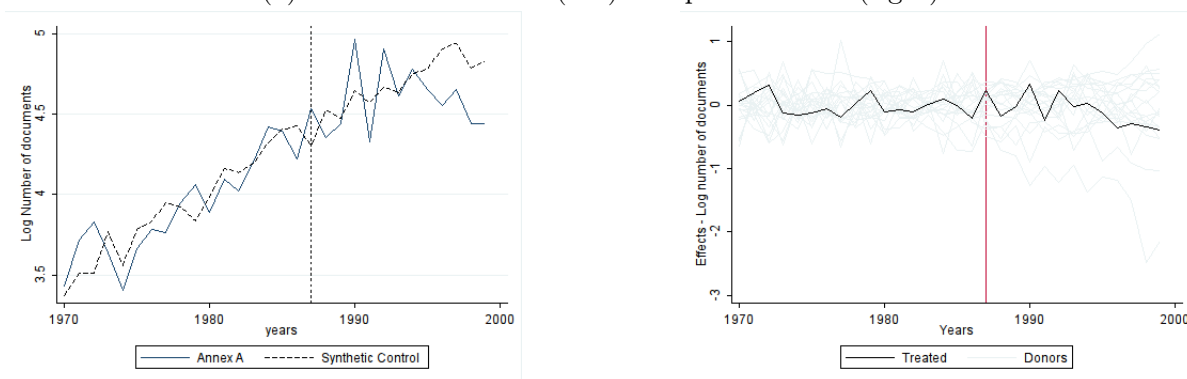


(d) Annex B: Articles.

Figure 17: Counts in articles and patents for each molecule of Annex A and Annex B. Note: These graphs plot the yearly number of articles or patents mentioning the names of given molecules included in Annex A and B. We note that most trends are flat, except maybe for Annex A in articles which seem to increase and then decrease.



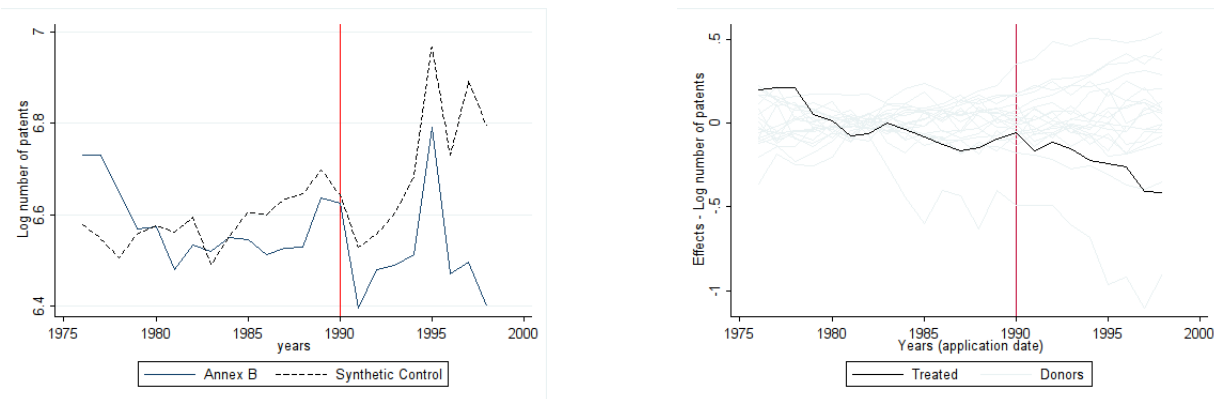
(a) Patents: raw effect (left) and placebo tests (right)



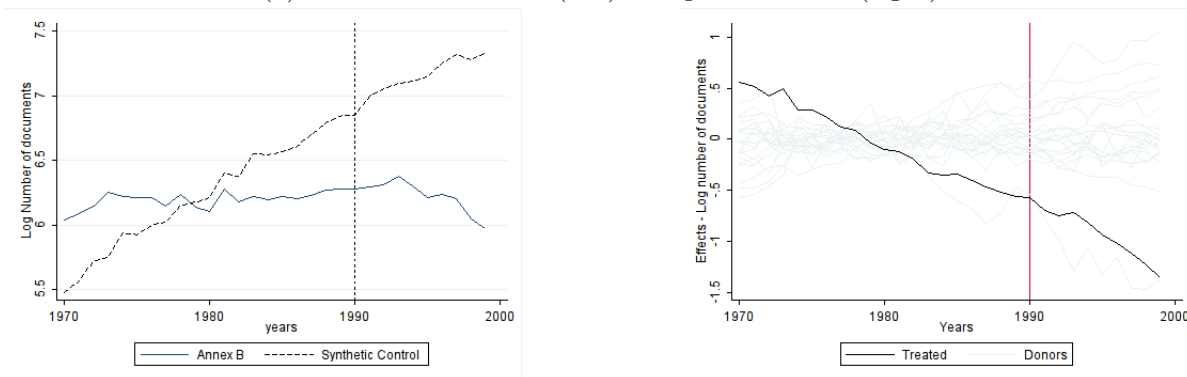
(b) Articles: raw effect (left) and placebo tests (right)

Figure 18: SCM for Annex A compounds.

Notes: Figures 18a and 18b display the results of the synthetic control method for Annex A compounds for patents and articles. There is no significant increase or decrease in the number of patents and articles mentioning Annex A compounds. In all cases, the method is implemented using the topic proportions of a LDA model with 5 topics and the weak rule for assigning documents to molecule groups. Weighted means of topic proportions are used for patent and unweighted means for articles because these are the specifications that yielded lowest pre-RMPSE. The graphs on the left-hand side represent the raw effect, that is the observed time series of the treated group along with the time series of the constructed control. On the right-hand sides are shown the placebo tests, the non-parametric tests to evaluate the significance of the results; black lines show the effect on the treated group relative to the control group, while each gray line is a placebo test performed on an unit drawn from the donor pool.



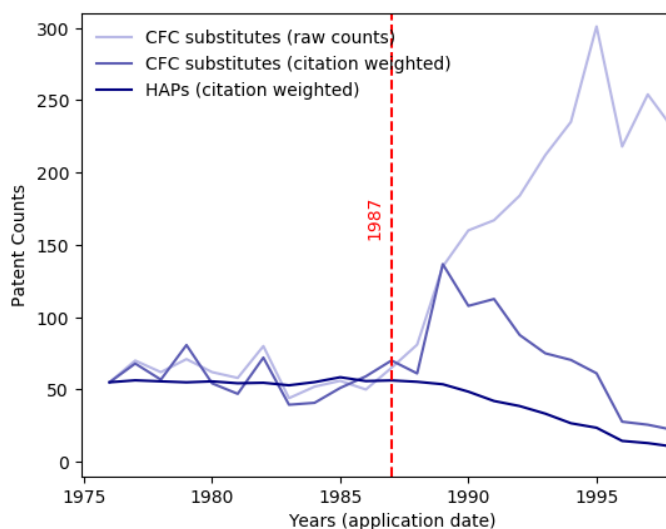
(a) Patents: raw effect (left) and placebo tests (right)



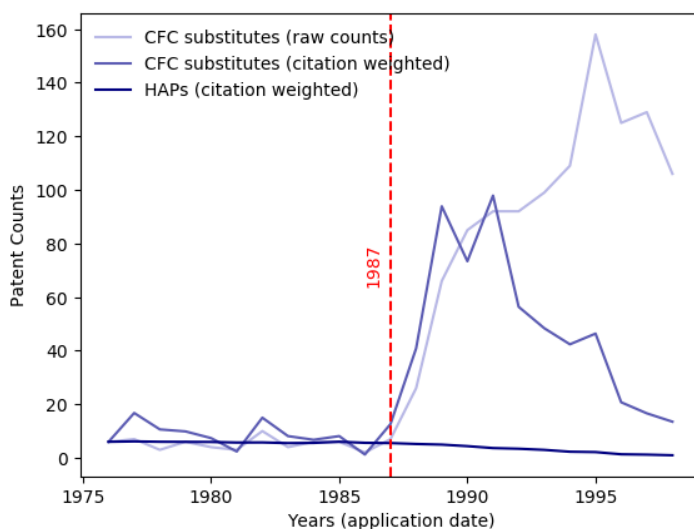
(b) Articles: raw effect (left) and placebo tests (right)

Figure 19: SCM for Annex B compounds.

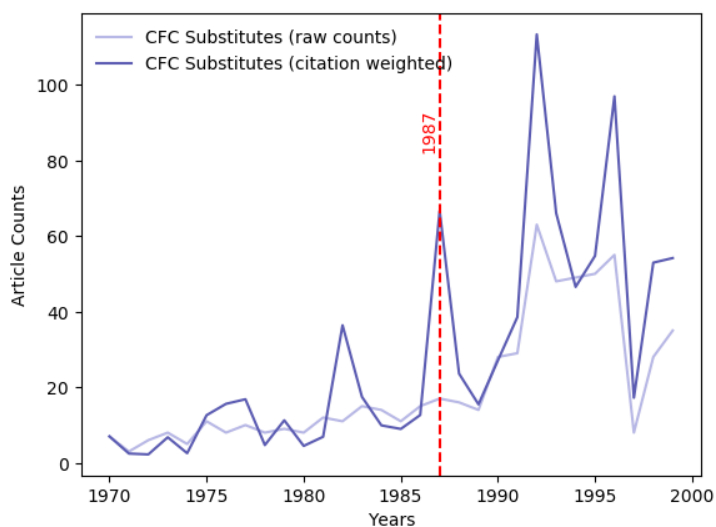
Notes: Figures 19a and 19b display the results of the synthetic control method for Annex B compounds for articles and patents. We note that in this case the synthetic control offers a poor fit to the observed data. Hence we cannot infer whether there is an increase or a decrease. In all cases, the method is implemented using the topic proportions of a LDA model with 5 topics and the weak rule for assigning documents to molecule groups. Weighted means of topic proportions are used for patent and unweighted means for articles because these are the specifications that yielded lowest pre-RMPSE. The graphs on the left-hand side represent the raw effect, that is the observed time series of the treated group along with the time series of the constructed control. On the right-hand sides are shown the placebo tests, the non-parametric tests to evaluate the significance of the results; black lines show the effect on the treated group relative to the control group, while each gray line is a placebo test performed on a unit drawn from the donor pool.



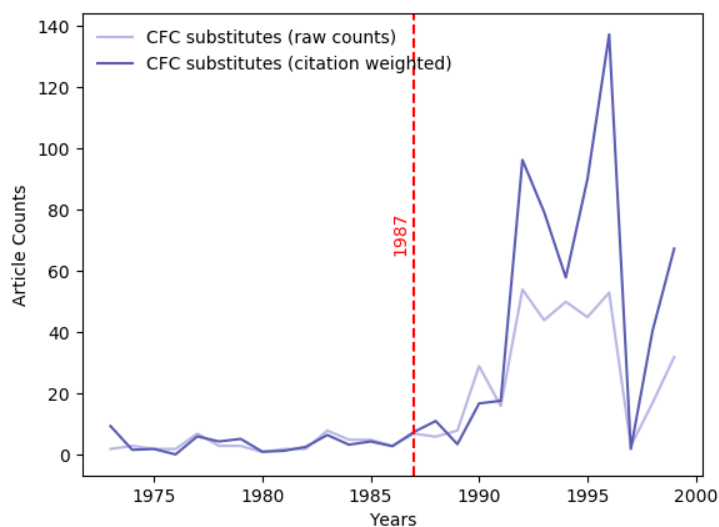
(a) Patents - one occurrence



(b) Patents - 3 occurrences



(c) Articles - one occurrence



(d) Articles - 3 occurrences

Figure 20: Citation weighted counts.

Note: The graphs illustrate that the most cited articles and patents were published after 1987. Graphs 20a and 20c include patents and articles, respectively, that mention at least one occurrence of a molecule. To test the robustness of this findings, I plot similar graphs but for patents and articles that mention at least 3 occurrences in Figure 20b and 20d. I find highly cited patents and articles are even more so concentrated after 1987.

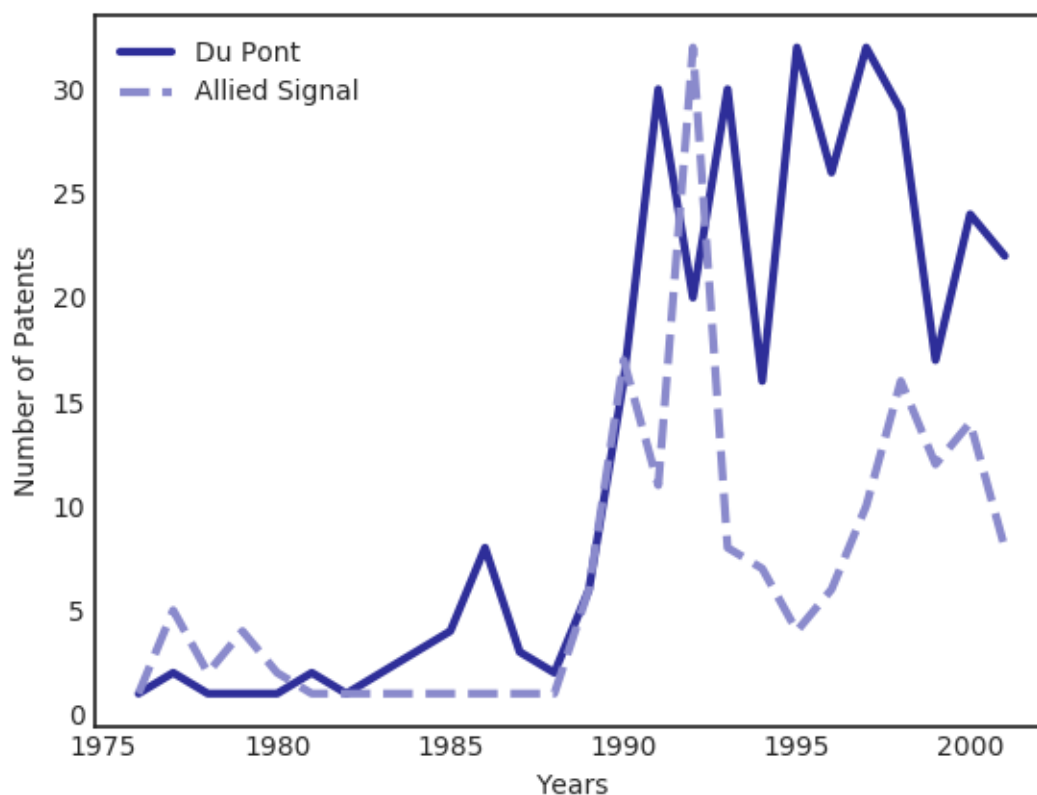


Figure 21: Patenting trends for top 2 assignees.

Note: The graph plots the number of patents mentioning CFC substitutes for the two companies with greatest number of patent grants between 1970 and 2000. We note the biggest share of patents is by far granted after 1990. We also see that Du Pont was granted about a dozen of patents around 1986. This can be interpreted as the output of the research effort Du Pont initiated around 1980.

Table 1: List of CFC substitutes.

Substitute	PAFT	AFEAS	Substitute for
HCFC-22	No, already marketed, toxicology known	Yes	CFC-11, CFC-12 in foams
HCFC-142b	No, already marketed, toxicology known	Yes	CFC-11, CFC-12 but not ideal
HFC-152a	No, already marketed, toxicology known	Yes	CFC-11, CFC-12 but not ideal
HCFC-123	Yes	Yes	CFC-11 in refrigeration
HFC-134a	Yes	Yes	CFC-12 in refrigeration (car AC)
HCFC-141b	Yes	Yes	CFC-11 in foams
HCFC-124	Yes	Yes	CFC-114 in refrigeration and sterilization
HCFC-125	Yes	Yes	CFC-115 in refrigeration and sterilization
HCFC-225ca	No, second rank candidate	Yes	
HCFC-225cb	No, second rank candidate	Yes	
HFC-32	No, second rank candidate	Yes	refrigeration
HFC-143a	No, second rank candidate	Yes	CFC-12 in refrigeration
HFC-245fa	No	No	CFC-11, HCFC-141b and HCFC-142b in foams
HFC-365mfc	No	No	CFC-11, HCFC-141b and HCFC-142b in foams

Note: The table lists 14 molecules that were at some point considered as potential CFC substitutes. The columns PAFT and AFEAS indicate whether the molecule was included in the investigations carried out by the PAFT and AFEAS. The PAFT (Program for Alternative Fluorocarbon Toxicity Testing) was created in January 1988 to work on assessing the toxicity of five possible alternatives. The AFEAS (Alternative Fluorocarbon Environmental Acceptability Study), created in December 1988, investigated the atmospheric dynamics of twelve potential CFC substitutes. I use these twelve molecules to form a first group. I also include in this group two other possible CFC substitutes mentioned in Benedick (2009) and Parson (2003). In the rest of my analysis, I track the evolution of patents and articles mentioning these 14 molecules.

Table 2: Summary statistics of meta-data

(a) Patents.			(b) Articles.	
	CFC Substitutes	HAPs	Citation Count	CFC Substitutes
Education	0.02 (0.14)	0.02 (0.14)		30.60 (72.19)
Company	0.97 (0.17)	0.96 (0.20)	Number of Authors	2.95 (2.85)
Government	0.01 (0.07)	0.02 (0.13)	Education	0.75 (0.43)
Facility	0.00 (0.07)	0.00 (0.02)	Company	0.12 (0.32)
Nonprofit	0.00 (0.00)	0.00 (0.07)	Government	0.11 (0.31)
Healthcare	0.00 (0.00)	0.00 (0.02)	Facility	0.11 (0.31)
USA	0.61 (0.49)	0.56 (0.50)	Nonprofit	0.02 (0.13)
Europe	0.21 (0.40)	0.23 (0.42)	Healthcare	0.02 (0.15)
Japan	0.17 (0.37)	0.17 (0.38)	USA	0.36 (0.48)
			Europe	0.39 (0.49)
			Japan	0.12 (0.32)

Note: The table displays summary statistics on the type and country of assignees for patents and on the country and type of affiliation for articles' authors. Information about HAPs for articles is still in progress due to quota limitation on the Scopus API. For patents, more than 96% of patents are granted to for-profit organizations. The rest is shared among organizations coming from the educational and governmental sector as well as organizations that fit the description of "facility". The majority of patents are granted to assignee domiciliated in the United States. European assignees tend to represent around 20 to 30% of patents; Japanese around 10 to 20%. We note that

For patents, the variables *Education*, *Company*, *Government*, *Facility*, *Nonprofit*, and *Healthcare* are binary variables identifying the type of patent assignee. For articles, "Education" is a dummy variable that equals 1 if at least one of the authors is affiliated with an organization in the higher education sector. "Company" is a dummy variable that equals 1 if at least one of the authors is affiliated with a for-profit private organization. "Government" is a dummy variable that equals 1 if at least one of the authors is affiliated with a governmental entity. "Facility" is a dummy variable that equals 1 if at least one of the authors is affiliated with a facility pursuing research in specialized areas (e.g. nuclear plant, particle accelerators etc...). "Nonprofit" is a dummy variable that equals 1 if at least one of the authors is affiliated with a nonprofit research institute. "Healthcare" is a dummy variable that equals 1 if at least one of the authors is affiliated with an organization where patients are treated. "USA", "Europe" and "Japan" are dummy variables that equal 1 if at least one of the authors is affiliated with, respectively, the USA, a European country and Japan. By European country, I mean any country belonging to the EU in 2016 plus Switzerland, Norway, Serbia, Ukraine, Moldova and Russia.

Table 3: Top 3 words in the five topics generated by the LDA model on patents.

	Words	Probability
Topic 1	crotononitrile	0.0090
	remote	0.0063
	dialkylhydantoin	0.0047
Topic 2	andreu	0.0141
	sulfon	0.0075
	phosphatidylinositols	0.0072
Topic 3	isopropyltrimethoxysilane	0.0323
	inducers	0.0276
	neal	0.0236
Topic 4	topcoatings	0.0071
	heterophasic	0.0054
	neal	0.0052
Topic 5	trisethyl	0.0157
	maker	0.0128
	amineprotecting	0.0066

Note: As a consequence of the nature of the corpora (patents), the words in the topics are highly technical and specialized which makes it difficult to associate one topic to a general theme.

Table 4: Summary statistics for CFC substitutes and HAPs in the small pool for patents.

Variables (pre-1986 average)	Substitutes	HAPs Mean	HAPs Min	HAPs Max	HAPs Std.Dev.
Count	64.2	71.37	41.8	101.8	21.23
Topic 1 (weighted mean)	0.2	0.2	0.16	0.23	0.02
Topic 2 (weighted mean)	0.1	0.11	0.08	0.12	0.01
Topic 3 (weighted mean)	0.43	0.43	0.39	0.47	0.02
Topic 4 (weighted mean)	0.18	0.19	0.15	0.23	0.02
Topic 5 (weighted mean)	0.09	0.08	0.06	0.12	0.02
Topic 1 (unweighted mean)	0.2	0.2	0.17	0.22	0.01
Topic 2 (unweighted mean)	0.1	0.11	0.1	0.12	0.01
Topic 3 (unweighted mean)	0.43	0.43	0.41	0.46	0.01
Topic 4 (unweighted mean)	0.19	0.19	0.17	0.22	0.01
Topic 5 (unweighted mean)	0.09	0.08	0.06	0.1	0.01

Note: The SCM imposes a constraint onto the synthetic control's weights to be non-negative and sum to 1. This is problematic in cases where the treated unit lies at the extremes of the distribution of the donor units. This table confirms that we are not in this case. Hence, there should be no penalty constraining the weights to non-negative and to sum to 1. In the table, we see that the values for CFC substitutes always fall within the range of the values for HAPs.

Table 5: Balance table between CFC substitutes and HAPs for patents.

(a) Patents.		
	HAPs	Substitutes
Number of patents	570.4 (762.8)	18.55 (25.91)
Log number of patents	5.153 (1.979)	1.999 (1.502)
Weighted mean proportion of topic 1	0.189 (0.0482)	0.140 (0.0939)
Weighted mean proportion of topic 2	0.103 (0.0274)	0.0762 (0.0669)
Weighted mean proportion of topic 3	0.410 (0.0959)	0.304 (0.198)
Weighted mean proportion of topic 4	0.176 (0.0450)	0.129 (0.0901)
Weighted mean proportion of topic 5	0.0732 (0.0236)	0.0667 (0.0508)
(b) Articles.		
	HAPs	Substitutes
Number of articles	173.2 (497.3)	3.279 (7.150)
Log number of articles	3.433 (1.834)	0.776 (1.013)
Weighted mean proportion of topic 1	0.193 (0.0475)	0.106 (0.117)
Weighted mean proportion of topic 2	0.298 (0.0661)	0.149 (0.161)
Weighted mean proportion of topic 3	0.119 (0.0364)	0.0538 (0.0658)
Weighted mean proportion of topic 4	0.189 (0.0470)	0.0944 (0.106)
Weighted mean proportion of topic 5	0.163 (0.0488)	0.0681 (0.0808)

Note: Despite pre-trends being similar, the table shows that CFC substitutes and HAPs have very different counts on average. Mean topic proportions on the other hand are similar.

Table 6: First Differences for CFC substitutes.

(a) Patents.			(b) Articles.		
	(1)	(2)		(1)	(2)
Post 1987	1.986*** (0.079)		Post 1987	1.053*** (0.067)	
Post 1987 x Years		0.183*** (0.022)	Post 1987 x Years		0.100*** (0.013)
Years		0.056*** (0.012)	Years		0.022*** (0.006)
Molecule FE	Yes	Yes	Molecule FE	Yes	Yes
R-squared	0.797	0.823	R-squared	0.649	0.686
Observations	322	322	Observations	420	420
Standard errors in parentheses			Standard errors in parentheses		
Dependent variable: Log count of patents			Dependent variable: Log count of articles		
Years are relative to 1987.			Years are relative to 1987.		
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$			* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$		

Note: Model 1 confirms that there is a significant and positive mean shift after 1987 in the number of patents and articles mentioning CFC substitutes. Model 2 shows that the change can also be modeled as a trend break. The coefficient for ‘Years’ indicates that there is a positive underlying trend for articles but not for patents.

Table 7: Difference-in-Differences for CFC substitutes.

(a) Patents.			(b) Articles.		
	(1)	(2)		(1)	(2)
Post 1987 x Substitutes	1.865*** (0.072)		Post 1987 x Substitutes	0.668*** (0.068)	
Post 1987 x Substitutes x Years		0.183*** (0.022)	Post 1987 x Substitutes x Years		0.100*** (0.013)
Substitutes x Years		0.046*** (0.012)	Substitutes x Years		-0.003 (0.006)
Years		0.010*** (0.001)	Years		0.024*** (0.001)
Year FE	Yes	No	Year FE	Yes	No
Molecule FE	Yes	Yes	Molecule FE	Yes	Yes
R-squared	0.976	0.974	R-squared	0.951	0.950
Observations	1288	1288	Observations	1680	1680
Standard errors in parentheses			Standard errors in parentheses		
Dependent variable: Log count of patents			Dependent variable: Log count of articles		
Years are relative to 1987.			Years are relative to 1987.		
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$			* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$		

Note:

Model 1 corresponds to the main differences-in-differences specification. It includes year and molecule fixed effects. The binary variable ‘Post 1987 x Substitutes’ equals 1 for observations belonging to the group CFC substitutes and after 1987. For patents, the coefficient is smaller than the coefficient in the simple difference, but remains significant and large, corresponding to more than a 400% increase. For articles, the coefficient is smaller than the coefficient in the simple difference, but remains significant and large, corresponding to more than a 95% increase. Model 2 presents a trend-break specification. It shows that the log number of patents mentioning CFC substitutes increases with the years after 1987 by 0.22 more than the control group. Similarly, the log number of articles mentioning CFC substitutes increases with the years after 1987 by 0.10 more than the control group.

Table 8: Means over pre-treatment periods for CFC substitutes in patents.

	Real S	Synthetic S	Average HAPs
Count (log)	4.17	4.17	4.22
Topic 1 (weighted mean)	0.20	0.20	0.20
Topic 2 (weighted mean)	0.10	0.10	0.11
Topic 3 (weighted mean)	0.43	0.42	0.43
Topic 4 (weighted mean)	0.18	0.19	0.19
Topic 5 (weighted mean)	0.09	0.09	0.08

Note: The table illustrates how the SCM is able to construct a better comparison unit than simply using the mean of many control units. The table shows the mean over the years 1970 to 1985 for log counts and topic proportions for the group of CFC substitutes ("Real S"), for the constructed synthetic substitute ("Synthetic S") and for the average of HAPs. Specifically the HAPs used in calculating the average are only those from the small pool. The synthetic control, here, was constructed based on similarity with the variables "Log Count" and the weighted means of the 5 topic proportions. We see that the synthetic control matches the real substitute group much better than the average of HAPs in terms of log count. This is the core idea motivating the use of the SCM. The topic proportions are very similar, but this could be expected since the pool of HAPs used is the small one and the means of topic proportions within that pool are very concentrated.

Table 9: Variable weights used in the construction of the synthetic control for patents.

	Variable Weight
Topic 1 (weighted mean)	0.04
Topic 2 (weighted mean)	0.04
Topic 3 (weighted mean)	0.02
Topic 4 (weighted mean)	0.03
Topic 5 (weighted mean)	0.02
Log Count	0.86

Note: The table displays the weights assigned to variables in the optimization procedure of the SCM. These weights are for the case of patents with log counts and weighted means of topic proportions, using the small pool of HAPs as donor pool. We note that topic proportions contribute about 15% in constructing the synthetic control.

Table 10: Performance summary of the main SCM implementations for CFC substitutes.

(a) Patents.

Topic Means	Donor Pool	Pre RMSPE	p-value	ATE	Year
unweighted	whole sample	0.12	< 0.01	0.64	1990
weighted	whole sample	0.14	< 0.01	0.83	1990
unweighted	small pool	0.18	< 0.01	0.89	1990
weighted	small pool	0.32	0.11	0.99	1990

(b) Articles.

Topic Means	Donor Pool	Pre RMSPE	p-value	ATE	Year
weighted	small pool	0.21	< 0.01	1.06	1990
unweighted	small pool	0.24	< 0.01	1.01	1992
weighted	whole sample	0.34	0.02	1.03	1990
unweighted	whole sample	0.35	< 0.01	1.19	1990

Note: The tables present the results of the main SCM specifications for patents and articles using either weighted or unweighted means of topic proportions and using either the whole sample and small pool of HAPs. The preferred specification to report the average treatment effect (ATE) uses the small pool of HAPs because it minimizes the risk of interpolation biases and overfitting. It also uses weighted means of topic proportions because it yields a lower pre-RMSPE (pretreatment root mean squared prediction error) indicating that it provides a better counterfactual. For patents, the ATE of the preferred specification is 1.0, that is a 170% increase in patents compared to synthetic control. This corresponds to about 100 patents per year from 1988 to 2000. For articles, the ATE is 1.06, that is a 190% increase in patents compared to synthetic control. This corresponds to about 40 patents per year from 1988 to 2000. "Topic Means" indicates the procedure for aggregating the topic proportions at the molecule level. If "weighted", the calculated proportion of topic j for molecule i is the mean proportion of topic j across all documents mentioning molecule i , weighted by the number of times the molecule appears in the document. "Donor Pool" indicates what sample of HAPs is used in the SCM procedure. For "small pool", the sample of HAPs used corresponds to the twenty HAPs most similar to the treated unit in terms of counts and topic proportions before 1987.

Table 11: Description of the top four HAPs contributing to the synthetic control.

(a) Patents.

Molecule	Weight	Description
Pentachlorophenol	0.33	Used as a wood preservative; Used for the formulation of fungicidal and insecticidal solutions and for incorporation into other pesticide products.
p-Xylenes	0.20	Used in the production of styrene. and as solvents in products such as paints and coatings, and are blended into gasoline.
Ethyl chloride	0.12	Used production of ethyl cellulose, use as a solvent, refrigerant, and topical anesthetic, in the manufacture of dyes, chemicals, and pharmaceuticals. As an anti-knock additive to leaded gasoline
3,3-Dimethoxybenzidine	0.11	Used as an intermediate for the production of dyes and pigments

(b) Articles.

Molecule	Weight	Description
Ethyl acrylate	0.48	Used in the manufacture of water-based latex paints and adhesives, textile and paper coatings, leather finish resins, and in the production of acrylic fibers
beta-Propiolactone	0.26	Used for vaccines, tissue grafts, surgical instruments, and enzymes, as a sterilant of blood plasma, water, milk, and nutrient broth, and as a vapor-phase disinfectant in enclosed spaces.
Dimethyl phthalate	0.24	Used in solid rocket propellants, lacquers, plastics, safety glasses, rubber coating agents, molding powders, insect repellants, and pesticides
1,1,2,2-Tetrachloroethane	0.01	Used as a solvent, in cleaning and degreasing metals, in paint removers, varnishes and lacquers, in photographic films, as an extractant for oils and fats, and in pesticides.

Table 12: Robustness check: SCM with alternative assignment rule.

(a) Patents.

Topic Means	Donor Pool	Pre RMSPE	p-value	ATE	Year
unweighted	small pool	0.37	0	1.77	1990
weighted	small pool	0.40	0	2.06	1990
unweighted	whole sample	0.40	–	1.73	1990
weighted	whole sample	0.46	0.03	1.64	1990

(b) Articles.

Topic Means	Donor Pool	Pre RMSPE	p-value	ATE	Year
weighted	small pool	0.27	0.0	1.34	1990
unweighted	small pool	0.28	0.0	1.35	1990
weighted	whole sample	0.28	0.0	1.39	1990
unweighted	whole sample	0.28	0.0	1.31	1990

Note: In this robustness check, I use an alternative rule to assign documents to molecule. The estimated treatment effects for these robustness checks are all higher than the effect estimated with the main methodology. "Topic Means" indicates the procedure for aggregating the topic proportions at the molecule level. If "weighted", the calculated proportion of topic j for molecule i is the mean proportion of topic j across all documents mentioning molecule i , weighted by the number of times the molecule appears in the document. "Donor Pool" indicates what sample of HAPs is used in the SCM procedure. For "small pool", the sample of HAPs used corresponds to the twenty HAPs most similar to the treated unit in terms of counts and topic proportions before 1987.

Table 13: Robustness checks: SCM with counts as outcome variable (instead of log counts).

(a) Patents.						
Rule	Topic Means	Donor Pool	Pre RMSPE	p-value	ATE	Year
intermediate	unweighted	whole sample	3.35	0.006	71.88	1990
intermediate	unweighted	small pool	3.41	0.000	70.87	1990
intermediate	weighted	small pool	3.70	0.000	72.28	1990
intermediate	weighted	whole sample	3.92	0.000	71.24	1990
weak	weighted	whole sample	8.74	0.000	100.92	1992
weak	unweighted	whole sample	9.68	0.000	84.52	1992
weak	weighted	small pool	10.23	0.000	109.23	1990
weak	unweighted	small pool	10.86	0.000	113.61	1990
(b) Articles.						
Rule	Topic Means	Donor Pool	Pre RMSPE	p-value	ATE	Year
intermediate	weighted	small pool	1.54	0.000	35.17	1990
intermediate	unweighted	small pool	1.78	0.000	35.52	1990
intermediate	unweighted	whole sample	1.96	0.000	35.04	1992
intermediate	weighted	whole sample	2.03	0.000	35.39	1992
weak	weighted	small pool	2.65	0.000	44.08	1990
weak	unweighted	small pool	2.86	0.000	42.6	1990
weak	weighted	whole sample	4.44	0.006	45.81	1998
weak	unweighted	whole sample	5.65	0.006	46.73	1994

Note: In this robustness check, I use counts in levels instead of in log as the outcome variable. The estimated treatment effects for these robustness checks are similar to the effect estimate with the main methodology. "Topic Means" indicates the procedure for aggregating the topic proportions at the molecule level. If "weighted", the calculated proportion of topic j for molecule i is the mean proportion of topic j across all documents mentioning molecule i , weighted by the number of times the molecule appears in the document. "Donor Pool" indicates what sample of HAPs is used in the SCM procedure. For "small pool", the sample of HAPs used corresponds to the twenty HAPs most similar to the treated unit in terms of counts and topic proportions before 1987.

Table 14: First Differences for Annex A and Annex B.

(a) Annex A - Patents.			(b) Annex A - Articles.		
	(1)	(2)		(1)	(2)
Post 1987	0.178*** (0.055)		Post 1987	0.526*** (0.070)	
Post 1987 x Years		-0.009 (0.017)	Post 1987 x Years		-0.008 (0.017)
Years		0.019* (0.011)	Years		0.034*** (0.008)
Molecule FE	Yes	Yes	Molecule FE	Yes	Yes
R-squared	0.932	0.933	R-squared	0.838	0.843
Observations	184	184	Observations	240	240
Standard errors in parentheses Dependent variable: Log count of patents Years are relative to 1987. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$			Standard errors in parentheses Dependent variable: Log count of articles Years are relative to 1987. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$		
(c) Annex B - Patents.			(d) Annex B - Articles.		
	(1)	(2)		(1)	(2)
Post 1990	0.175*** (0.058)		Post 1990	0.152*** (0.056)	
Post 1990 x Years		0.020 (0.018)	Post 1990 x Years		-0.040** (0.017)
Years		0.001 (0.007)	Years		0.022*** (0.005)
Molecule FE	Yes	Yes	Molecule FE	Yes	Yes
R-squared			R-squared		
Observations	.971	.97	Observations	.975	.977
N	207	207	N	210	210
Standard errors in parentheses Dependent variable: Log count of patents Years are relative to 1990. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$			Standard errors in parentheses Dependent variable: Log count of articles Years are relative to 1990. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$		

Note: The regressions indicate statistically significant mean shift between before and after 1987, except for Annex B in patents; however these are small in magnitude.

Table 15: Difference-in-Differences for Annex A and Annex B.

(a) Annex A - Patents.			(b) Annex A - Articles.		
	(1)	(2)		(1)	(2)
Post 1987 x Annex A	0.024 (0.055)		Post 1987 x Annex A	0.069 (0.073)	
Post 1987 x Annex A x Years		-0.009 (0.017)	Post 1987 x Annex A x Years		-0.008 (0.017)
Annex A x Years		0.005 (0.011)	Annex A x Years		0.006 (0.008)
Years		0.014*** (0.001)	Years		0.028*** (0.002)
Year FE	Yes	No	Year FE	Yes	No
Molecule FE	Yes	Yes	Molecule FE	Yes	Yes
R-squared	0.987	0.985	R-squared	0.966	0.964
Observations	736	736	Observations	960	960
Standard errors in parentheses Dependent variable: Log count of patents Years are relative to 1987. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$			Standard errors in parentheses Dependent variable: Log count of articles Years are relative to 1987. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$		
(c) Annex B - Patents.			(d) Annex B - Articles.		
	(1)	(2)		(1)	(2)
Post 1990 x Annex B	0.080 (0.063)		Post 1990 x Annex B	-0.251*** (0.065)	
Post 1990 x Annex B x Years		0.020 (0.018)	Post 1990 x Annex B x Years		-0.040** (0.017)
Annex B x Years		-0.004 (0.007)	Annex B x Years		-0.004 (0.005)
Years		0.005*** (0.002)	Years		0.026*** (0.002)
Year FE	Yes	No	Year FE	Yes	No
Molecule FE	Yes	Yes	Molecule FE	Yes	Yes
R-squared			R-squared		
Observations	.988	.987	Observations	.968	.967
N	828	828	N	840	840
Standard errors in parentheses Dependent variable: Log count of patents Years are relative to 1990. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$			Standard errors in parentheses Dependent variable: Log count of articles Years are relative to 1990. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$		

Notes: The difference-in-differences specifications indicate that a positive and statistically significant treatment effect for Annex in patents and a negative one for Annex B in articles. The magnitudes however are small.

Table 16: SCM for Annex A and B compounds.

(a) Annex A - Patents

Topic Means	Donor Pool	Pre RMSPE	p-value	ATE	Year
unweighted	whole sample	0.08	0.06	-0.01	–
weighted	whole sample	0.09	0.14	-0.0	–
unweighted	small pool	0.13	0.90	-0.09	–
weighted	small pool	0.14	0.60	-0.03	–

(b) Annex A - Articles

Topic Means	Donor Pool	Pre RMSPE	p-value	ATE	Year
unweighted	small pool	0.15	0.250	-0.12	–
unweighted	whole sample	0.15	0.471	0.08	–
weighted	whole sample	0.16	0.296	0.18	–
weighted	small pool	0.25	0.400	0.33	1990

(c) Annex B - Patents

Topic Means	Donor Pool	Pre RMSPE	p-value	ATE	Year
weighted	whole sample	0.07	0.09	-0.18	–
unweighted	whole sample	0.07	0.10	-0.16	–
unweighted	small pool	0.09	0.20	-0.23	–
weighted	small pool	0.12	0.30	-0.28	–

(d) Annex B - Articles

Topic Means	Donor Pool	Pre RMSPE	p-value	ATE	Year
unweighted	whole sample	0.15	0.036	-0.32	–
weighted	whole sample	0.16	0.112	-0.28	–
weighted	small pool	0.38	0.200	-0.86	–
unweighted	small pool	0.40	0.300	-0.86	–

Notes: All tables refer to SCM implementation using log count as outcome variable and using the weak rule of assigning documents. Almost none of the procedures yield treatment effects that are statistically significant. Most p-values are greater than 0.10. These results indicate that Montreal did not trigger a large decrease nor a large increase in the number of patents and articles mentioning Annex A and B compounds. "Topic Means" indicates the procedure for aggregating the topic proportions at the molecule level. If "weighted", the calculated proportion of topic j for molecule i is the mean proportion of topic j across all documents mentioning molecule i , weighted by the number of times the molecule appears in the document. "Donor Pool" indicates what sample of HAPs is used in the SCM procedure. For "small pool", the sample of HAPs used corresponds to the twenty HAPs most similar to the treated unit in terms of counts and topic proportions before 1987.

Table 17: Titles of the ten most cited articles mentioning CFC substitutes

Title	Year	Cited By
Methods for the synthesis of gem-difluoromethylene compounds	1996	333
A new, efficient and environmentally benign system for car air-conditioning	1993	255
High-pressure fluid-phase equilibria: Experimental methods and systems investigated (1988-1993)	1995	227
Evaporation heat transfer and pressure drop of refrigerant R-134a in a small pipe	1998	211
Gas and vapor transport properties of amorphous perfluorinated copolymer membranes based on 2,2-bistrifluoromethyl-4,5-difluoro-1,3-dioxole/tetrafluoroethylene	1996	184
Boiling of new refrigerants: A state-of-the-art review	1996	144
Condensation heat transfer and pressure drop of refrigerant R-134a in a plate heat exchanger	1999	142
Thermochemical and chemical kinetic data for fluorinated hydrocarbons	1995	130
Supercritical fluid extraction in environmental analysis	1993	121
A kinetic study of the reaction of chlorine atoms with CF ₃ CHCl ₂ , CF ₃ CH ₂ F, CFCl ₂ CH ₃ , CF ₂ ClCH ₃ , CHF ₂ CH ₃ , CH ₃ D, CH ₂ D ₂ , CHD ₃ , CD ₄ , and CD ₃ Cl at 295±2 K	1992	113

Note: These are the most cited articles among those which mentioned at least 3 times one of the CFC substitutes.

Table 18: Ten most common patent codes for patents mentioning CFC substitutes

ICL	Count	Description
C07C	569	Acyclic or carbocyclic compounds
C08G	375	Compounds of unknown constitution
C08J	294	General processes of compounding
C09K	215	Materials for applications not otherwise provided for
A61K	196	Preparations for medical, dental, or toilet purposes
C10M	112	Lubricating compositions
F25B	103	Refrigeration machines, plants, or systems; heat pump systems
C07D	74	Heterocyclic compounds
C08F	71	Macromolecular compounds obtained by reactions only involving carbon-to-carbon unsaturated bonds
C11D	71	Detergent compositions