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Induced innovation and international environmental agreements: Evidence from the ozone regime

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Abstract

This paper revisits one of the rare success stories in global environmental cooperation: the Montreal Protocol and the phase-out of ozone-depleting substances. I show that the protocol increased science and innovation on alternatives to ozone-depleting substances and argue that agreements can indeed be useful to solving global public goods problems. This contrasts with game-theoretical predictions that agreements occur only when costs to the players are low, and with the often-heard narrative that substitutes were readily available. I reconcile theory and empirics by discussing the role of induced innovation in models of environmental agreements.

Keywords: induced innovation, directed technological change, green innovation
JEL Codes: O30; Q55

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1 INTRODUCTION

Global collective action problems are some of the most pressing issues that humanity is facing. Environmental concerns such as climate change or biodiversity have seen minimal progress, but one shining example of success is the fight against ozone depletion. At the end of the 1970s, scientists warned that chlorofluorocarbons (CFCs) might destroy ozone molecules in the stratosphere and reduce the extent to which humans were protected from solar radiation. The issue rose to the top of the global agenda, and, in 1987, high-income countries negotiated the Montreal Protocol to phase out CFCs from industrial activities.

In Montreal, signatories agreed to decrease the production and consumption of CFCs following a schedule of reduction targets. The protocol included trade restrictions with non-parties in ozone-depleting substances and threats of banning trade in products made using ozone-depleting substances. Technological change unfolded rapidly, and within a decade, the production and consumption of CFCs decreased by more than 80%.[1] Such success story presents us with a formidable opportunity to study what worked.

Although the Montreal Protocol remains a point of reference in discussing global environmental problems (Barrett 1999; Sunstein 2007), the dynamics of innovation in the ozone crisis are still debated. Some, like Richard E. Benedick, the chief U.S. negotiator at Montreal, argued the agreement triggered a vast effort in research to find CFC substitutes[2]. Others claim that CFC substitutes were already available at the time of negotiations or that the industry endorsed CFC cuts because it had achieved a breakthrough (Heal 2016; Sunstein 2007).

This paper offers the first quantitative study of whether the Montreal Protocol induced science and innovation on CFC substitutes. To do so, I compile a list of 14 molecules that scientists and industry experts identified as best candidates for CFC substitutes and consider those molecules as treated by the Montreal Protocol. I then track mentions of CFC substitutes over time in scientific articles published in journals indexed by ScienceDirect and patents granted by the United States Patent and Trade Office (USPTO).

The primary hypothesis is that the Montreal Protocol provided a clear signal and power-

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[1] My calculations using UNEP data.

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

ful incentives for firms and scientists to increase work on CFC substitutes, which led to an increase in patents and scientific articles mentioning these molecules. The empirical strategy relies on comparing CFC substitutes with a control group of molecules used in industrial applications similar to CFC substitutes but with no connection to ozone, known as HAPs (Hazardous Air Pollutants). To ensure that the molecules are comparable, I use topic modeling algorithms on the text of patents and articles to construct molecule-level variables that proxy for the molecules' scientific and industrial context.

As illustrated in Figure 1, only a few patents and articles on CFC substitutes were published before 1987, and the trend before 1987 is flat, possibly indicating that the agreement was little anticipated. The difference-in-differences (DiD) suggests that the protocol led to a 400% increase in the number of patents related to CFC substitutes (relative to the pre-treatment period) and a 500% increase in the case of scientific articles. The increase becomes statistically significant, starting in 1989 for patents and 1990 for articles, two to three years after the agreement's signature.[3] The estimates are robust to a series of alternative specifications, including weighting counts by the number of occurrences of the molecule's name in the text and weighting by the number of citations that the document received. As an alternative approach, I also estimate the protocol's impact using a synthetic control method and find consistent, yet smaller, increases of about 135% for patents and 180% for articles.[4]

A possible alternative story is that firms undertook research and development before the negotiations and kept substitutes "hidden" by not filing patents until the agreement was announced. I argue that if firms kept hidden some of their innovation, we should expect a one-time increase in patent counts in the immediate aftermaths of Montreal. Indeed, patenting was the primary mechanism firms had to protect their innovations. On the one hand, trade secrets were very hard to keep in the development of CFC substitutes (Parson 2003). On the other

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[3] This delay is similar to prior results in the literature (Popp 2002) and can be attributed to the time required to turn research efforts into patent applications and published academic papers.

[4] Shapiro and Warhit (1983) estimated that limiting CFC production to 1980 levels would lead to price increases between 500% and 1000% depending on the CFC compounds. Given this, a 135% increase in patents corresponds to an elasticity between 0.14 and 0.27. These estimates are broadly consistent with related studies in different contexts, such as Popp (2002), who reports short-run and long-run energy price elasticities of 0.060 and 0.354, respectively (see Table 2 in the article) and Aghion et al. (2016), who estimate the elasticity of clean car patents with respect to gasoline prices to be between 0.843 and 0.970, depending on the specification (see Table 3 in the article).

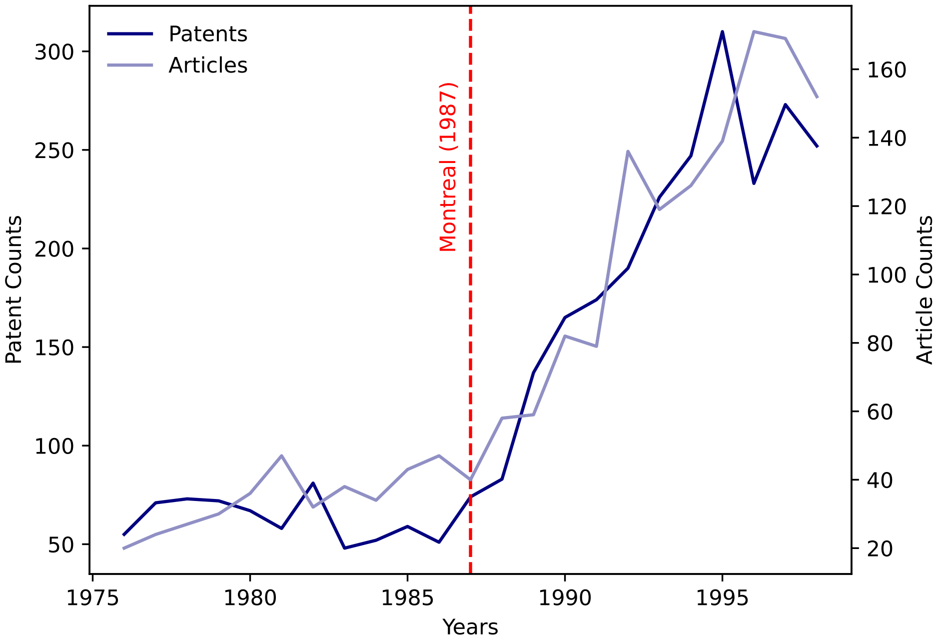

FIGURE 1

Counts of Patents and Articles Mentioning CFC Substitutes

Note: The graph plots the yearly number of patents and articles mentioning the names of any of the 14 CFC substitutes. The x-axis corresponds to the *application* date of patents granted between 1976 and 1999 and the *publication* date of articles. We note that only a few patents and articles on CFC substitutes were published before 1987 and that the trend up to 1987 is flat. After 1987, we observe a large increase in both patents and articles mentioning CFC substitutes. A version of this figure with trends for CFC compounds is shown in Online Appendix Figure I3.

hand, the relatively high degree of competition in the industry ensured that several firms were working on related technologies, and delaying patenting meant a higher risk of competitors patenting first. Assuming firms did not patent their innovation before 1987, the signature of Montreal would have acted as a strong positive shock to their incentives to seek intellectual property rights. I find that patenting activity shows no spike after the signing of the agreement but, instead, a progressive ramp up. This lends little support to the narrative that the industry had achieved some breakthrough which they would have kept secret.

The nature of the technological challenge was, in fact, not consistent with the idea of a breakthrough. First, some CFC reductions were easy to achieve, and in particular, significant cuts could be achieved simply by using CFCs more efficiently or with recovery and recycling. Some chemical substitutes also looked promising for specific applications. For example, in 1988, the FDA approved HCFC-22 for fast food foams and grocery display packaging. But, in other sectors, such as the growing refrigeration and air-conditioning markets, a full phase-out required new molecules. Consequently, from a 1987 perspective, the technological problem of reducing CFC emissions could be likened to a marginal abatement cost curve that initially had a low and flat slope for a significant amount of reductions but then gradually became steeper and with significant uncertainty.[5]

Furthermore, developing CFC substitutes was not about "new-to-the-world" compounds but rather about "new-to-the-industry" compounds that required research efforts to adapt them to many industrial applications. Indeed, chemical engineers knew that the compounds with the best potential had to present molecular structures similar to CFCs. This would ensure that their thermodynamic properties would best mimic those of CFCs and make them easier to substitute in the myriad of industrial applications that used CFCs (Pool 1988). Although these molecules had been known on paper for decades, scientists still needed to learn more about their thermodynamic properties, toxicity profile, and environmental acceptability. Firms had to experiment with new processes and formulas to retrofit installed equipment with CFC substitutes or replace them altogether.

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5. The availability of cheap reductions via recycling, efficiency measures, and specific chemical substitute applications explains why CFCs production decreased rapidly after 1987. For more information, see Online Appendix Figure A2 and Table A4.

I also investigate the possibility that mounting consumer pressure played a role in fostering science and innovation on CFC substitutes.[6] Already in 1985, scientists showed that extensive depletion of ozone was taking place over Antarctica. The so-called ozone "hole" was causally attributed to CFCs in March 1988, likely increasing the saliency of the CFC threat in the public's eyes. To further investigate the role of consumer pressure on fostering innovation on CFC substitutes, I collect data from the EPA website on all industrial applications of CFC substitutes and classify substitutes as either consumer exposed, not consumer exposed, both or undetermined. I find that the increase in patenting for molecules that were not used in consumer appliances is similar to the increase seen in the broader sample of molecules, suggesting that consumer pressure is unlikely to have driven the large increase in patenting.

At first sight, it may seem counterintuitive that the Montreal Protocol induced innovation, or more generally, did anything that would not have happened without it. As shown in Barrett (1994), theoretical models make the dismal prediction that international environmental agreements occur only when cooperation is easy to achieve, that is, when costs to the players are low and benefits high. This implies that the Montreal Protocol could not have been far from what countries would have done unilaterally. I revisit this interpretation by discussing how induced innovation can affect models of international environmental agreements. With induced innovation, marginal abatement costs decrease over time as emission reductions are undertaken. This allows for more ambitious targets to be agreed upon, even though they would have been outside of negotiation reach early on in the process.

Hence, the signature of the Montreal Protocol should be seen as a first modest step in a series of increasingly ambitious agreements. The targets agreed in 1987 required a 50% cut by 1998, while those negotiated in the London and Copenhagen amendments (in 1990 and 1992, respectively) enforced a complete ban and added a broader range of molecules to the list of regulated ozone-depleting substances. The targets agreed in 1987 may be interpreted as modest because they encoded what the industry thought feasible over a reasonable period. This did not mean the industry already had all the necessary knowledge and technologies. But it meant that they expected that they could meet the targets with sufficient investments in research and

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[6] Yet another possibility could be the existence of research grants or subsidy programs specifically financing research and development work on CFC substitutes. To my knowledge, no such programs were ever implemented.

development. Notably, the agreement ensured a leveled playing field for all firms competing in the CFC industry. Indeed, contrary to many other agreements, a key aspect of the Montreal Protocol is that it built in an enforcement mechanism. Montreal included trade restrictions, and threats of banning trade in any products made using CFCs, making it economically binding.

Agreements close to the non-cooperative equilibrium, like Montreal, should not be seen as agreements where costs to the players are low, but rather as agreements where costs are *expected* to be low. Between expectation to realization come the actual efforts of doing research and development, of implementing ideas that exist only on paper and that still require experimentation and tinkering. Such endeavors improve technologies making them more affordable and increasing the scope of their uses. By inducing firms to innovate, Montreal reduced the expected cost of further emission abatement. In turn, this made it easier for governments and industries to negotiate binding amendments with more ambitious targets.

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

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

(Milliman and Prince 1989; Porter and Van Der Linde 1995). Several studies investigate the effect of such agreements on pollution outcomes (Aichele and Felbermayr 2011; Finus and Tjøtta 2003; Kellenberg and Levinson 2014), but they seldom look at the impact on science and innovation.[7]

This paper also contributes to the literature on the economics of international environmental agreements (Barrett 1994; Battaglini and Harstad 2016; Harstad, Lancia, and Russo 2019) and ozone cooperation (Auffhammer, Morzuch, and Stranlund 2005; Barrett 1994, 2003; Murdoch and Sandler 2009). In particular, Barrett (1999) suggested Montreal's trade measures solved the enforcement problem, and Wagner (2016) further argued they promoted full participation in the protocol, ensuring its almost-universal ratification. Outside of economics, research has examined aspects relating to negotiations and diplomacy (Andersen and Sarma 2012; Benedick 2009) as well as qualitative accounts of corporate strategy and innovation (Falkner 2005; Mulder 2005; Parson 2003; Smith 1998; Taddonio, Sarma, and Andersen 2012).

The paper first provides background information in Section 2. Section 3 then describes the data, Section 4 outlines the empirical strategy, Section 5 presents the main results, and Section 6 considers mechanisms and alternative hypotheses. Finally, Section 7 discusses the role of induced innovation in theoretical models of global environmental cooperation to reconcile the empirical results with the literature on international environmental agreements. Section 8 concludes.

2 BACKGROUND

2.1 Theory and Hypotheses

When factors of production become more expensive, technological change tends to be biased towards them, so to make their use more efficient or substitute them. Such theory of *induced innovation* was initially developed by Hicks (1932), but the concept has reappeared in the past two decades under the phrase "directed technical change," encompassing not just price effects but also market size and regulatory effects (Acemoglu 1998). The idea was later augmented to

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[7] One exception is Dekker et al. (2012) who focuses on transboundary air pollution.

include environmental policies. In the simplest model, environmental regulations force firms to allocate inputs (labor or capital) to pollution reduction or restrict the choice of technologies and inputs in the production process (Milliman and Prince 1989). As such, environmental regulations are modeled as extra costs.

The theory of *induced innovation* argues that environmental policies induce firms to innovate in the hope of offsetting regulation-imposed costs, at least partially.[8] The reasoning can easily be extended to international environmental agreements. Agreements oblige firms to adapt their production processes. The signature on its own immediately changes expectations regarding future domestic environmental policies, as long as firms perceive the agreement as binding. Arguably, this is what happened with the Montreal Protocol.

Montreal included trade restrictions with non-parties in products containing those ozone-depleting substances and a threat of banning trade in products made using ozone-depleting substances. The trade restrictions effectively acted as a mechanism for free-rider deterrence and leakage prevention, rendering the agreement binding. Therefore, the main hypothesis is that Montreal credibly signaled firms that the continued use of CFCs would become increasingly costly, and induced them to innovate. Richard Benedick, the U.S. head negotiator at Montreal, argued that "(it) was evident (...) that the protocol was in fact moving industry in directions that two years earlier had been considered impossible" (Benedick 2009, Chap.8 p.104.). However, Benedick only refers to articles published in the *New York Times* and *Chemical and Engineering News* to support his claim.

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

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[8] The *Porter Hypothesis* goes further arguing the extra costs imposed by environmental policies can sometimes be even more than fully offset (Ambec et al. 2013; Porter and Van Der Linde 1995).

because the costs of doing so were low relative to benefits.

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

2.2 Events That Led to Montreal

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

In the late 1970s, the issue began to take prominence in the media and policy circles. A few countries and firms unilaterally decided to take action. In August 1977, the U.S. Congress wrote into law a CFC ban on aerosols by 1978,[9] and firms such as DuPont removed CFCs from their spray products because they worried about their public image. These pre-Montreal domestic regulations and corporate decisions targeted a particular industrial application of CFCs for which cheap physical substitutes existed (e.g., pump-action sprays instead of aerosol sprays). In essence, these were zero-cost unilateral moves that did not require significant research efforts. The low numbers of patents and articles between 1970 and 1987 in Figure 1 indicate that neither aerosol regulations nor consumer pressure seemed to have stimulated science and innovation on the 14 CFC substitutes I consider in that period.[10] In 1980, the EPA proposed to freeze other uses beyond aerosols, but U.S. industry blocked the initiative.[11]

At the beginning of the 1980s, concerns over ozone depletion waned. Uncertainties in the science of atmospheric ozone seemed irreducible, and the year 1981 saw the inauguration of a strongly anti-regulatory American administration. In Europe as well, many governments persisted in opposing environmental regulations that would harm manufacturers. Parson (2003)

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

[10] These 14 CFC substitutes were targeting foams, refrigeration and solvent applications of CFC.

[11] Regulations for ozone-depleting substances were approved by the US Congress only in 1990 via the Clean Air Act amendment.

provides a detailed qualitative account of firms' reactions during this period. Although some manufacturers initially started research on potential substitutes in the late 1970s, these efforts quickly came to an end around 1981. Manufacturers stopped such R&D programs because they estimated that CFC substitutes would cost around two to five times more than CFCs. It made no sense to continue working on these substitutes with little sign of regulations underway.[12]

The political context of Montreal's negotiations was not without its surprises. In his account of the diplomatic efforts, Benedick (2009) emphasizes the great uncertainty of the negotiations' outcome until the last minute and argues that some exceptional turns of events unlocked the situation. In particular, Reagan unexpectedly overruled his administration and approved the agreement. The U.S. President had skin cancer removed twice in the past, and it has been suggested that Reagan's life experiences weighed heavily on his decision. On the European side, the most prominent opponent to CFC regulations, the United Kingdom, left the European Community Presidency, leaving Germany, Denmark, and Belgium, firm proponents, as the head negotiators. Importantly, in this account of the negotiations, the agreement succeeded independently from the state of R&D activities on CFC substitutes.

2.3 Which Molecules Were "Treated"?

CFCs are a group of molecules with a particular structure: they contain only carbon, chlorine, and fluorine atoms. This structure drives their particularly attractive thermodynamic properties: they are unusually stable, nonflammable, nontoxic, and noncorrosive. Initially, CFCs somewhat embodied the miracle of modern chemistry as they were ideal for manufacturing many consumer goods. They were first commercially used in 1928 as cooling fluids for refrigerators and were specifically designed to substitute other dangerous refrigerants that were either toxic or inflammable (Parson 2003). Best of all, they were cheap to produce, and so they became broadly used in many different industries such as foams, refrigeration, air-conditioning, aerosols, fire protection, and solvents. CFCs are great refrigerants because they vaporize at low temperatures and are very energy-efficient coolants. As aerosols, they were used in cosmetics, household products, pharmaceuticals, and cleaners. Their nonreactive property also made them

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[12] For details, see Parson (2003, Chap.3 p.53 and Chap.7 p.173).

key products for cleaning microchips and telecommunication equipment.

Strategies for reducing CFCs included physical substitutes (like pump-action sprays instead of aerosol sprays) or recycling.[13] However, the most critical applications, such as air-conditioning units, needed chemical substitutes. The intricate relationship between molecular structure and industrial properties implied that the set of possible substitutes was limited: good candidates required a molecular structure similar to CFCs but with fewer chlorine atoms. Such compounds are known as hydro-chlorofluorocarbons (HCFCs) and hydro-fluorocarbons (HFCs). For example, CFC-12 is a compound that contains two chlorine atoms. When a hydrogen atom replaces one chlorine, we obtain a potential CFC substitute called HCFC-22. When hydrogens replace the two chlorines, we obtain another potential CFC substitute called HFC-32.[14]

It was public knowledge that the quest for CFC substitutes lay in the realm of HCFCs and HFCs. These molecules had been known for a long time, at least on paper and in the lab.[15] Hence, developing CFC substitutes was not so much about ”new-to-the-world” compounds but instead about ”new-to-the-industry” compounds. The key technological challenges lay in making large-scale production cost-efficient, redesigning processes and equipment already installed, and learning about environmental acceptability and human toxicity.[16]

I compile a list of potential substitutes using historical records. In December 1988, a report was issued to investigate the atmospheric dynamics of 12 potential CFC substitutes. Importantly, this report, known as the Alternative Fluorocarbon Environmental Acceptability Study

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[13] Montreal did not impose a total ban on CFCs which meant that CFCs would still be used, even in high-income countries; in low- and middle-income countries, their use was not yet regulated. The announcement of the freeze and progressive phase-out probably encouraged firms to cease developing new applications for CFCs. However, it may also have prompted them to develop more efficient ways of using CFCs or methods for recycling, which could translate into new patents and articles. Therefore, the impact of the Montreal Protocol on patenting related to Annex A and B compounds is inherently uncertain. It may have led to more patents for certain applications and fewer for others, making it challenging to establish a strong prior on the net effect.

[14] More details are available in Online Appendix Figure A1.

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

[16] Two potential substitutes were already in production: HCFC-22 at a large scale and HCFC-142b at a small scale. For this reason, they were considered as potentially the cheapest and fastest substitutes. Unfortunately, HCFC-22’s toxicity severely limited its applications outside of foams, and HCFC-142b was not considered for refrigerant applications because its thermodynamic properties were too different and would have required changes in equipment and processes.

(AFEAS), did not cover aspects of the molecules related to industrial activities but merely how the molecules may interact with human health and the environment once released in the atmosphere. In this paper, I include the 12 compounds studied in the AFEAS report as well as two other possible CFC substitutes mentioned in Benedick (2009) and Parson (2003).[17]

3 DATA DESCRIPTION

3.1 Patents

I follow prior literature in using patent counts as a proxy for innovation.[18] In the chemical industry, patenting is an essential way of protecting competitive advantage from new products and processes (Sampat 2018). Since chemicals can often be "reverse engineered," secrecy offers a limited mode of appropriation and strong incentives exist to use patenting either to protect inventions from being copied or to prevent competitors from patenting related inventions (W. M. Cohen, Nelson, and Walsh 2000).[19]

I collect the texts contained in the abstract and summary description of USPTO patent grants published between 1976 and 2000.[20]. The cleaning procedure involves a series of standard steps such as lowercasing or removing punctuation.[21] Patents contain the names, addresses, and affiliations of inventors and assignees, which I categorize by type (e.g., business, education, or government). To associate patents to specific countries, I use the country of the assignee. When patents have no assignee but only inventors, I use the country of the inventor. More details about how the meta-data is cleaned, matched, and classified by type are provided in the Online Appendix A. I use the OECD Citations database File to obtain data on the number of forward citations received by each patent.[22] Finally, I sort patents by application date as

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[17] HFC-245fa and HFC-365mfc are mentioned as possible substitutes in foams. Online Appendix Table A2 shows the name and additional information about all molecules considered in the analysis.

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

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

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

[21] Full details are provided in Online Appendix A.

[22] OECD, Citations database, February 2019

opposed to the date when they are granted to use a better measure of when the ideas present in the patents initially emerged.

3.2 Articles

The development of CFC substitutes required a better understanding of the fundamental thermodynamic properties of the proposed molecules and how they would interact with humans and the environment. Following prior literature, I use counts of scientific articles as a proxy for increases in such knowledge.[23] I collect scientific articles published between 1970 and 2000 in journals indexed by ScienceDirect, which hosts articles from about 2,500 academic journals published by Elsevier. The sample provides excellent coverage of journals in fields related to engineering and physical sciences and allows to characterize trends in the emergence of scientific knowledge related to CFCs substitutes. I used ScienceDirect's API to download the full text of articles in journals from the following disciplines: chemistry, chemical engineering, engineering, environmental science, materials science, and physics and astronomy.[24] After a series of cleaning procedures described in Online Appendix A, I obtain a total number of 1,811,301 articles. For data on affiliations and citation counts, I query the Scopus search API, and use the Global Research Identifier Database to classify authors' affiliations (e.g., education or company).[25]

3.3 Searching for Molecule Names

Chemical compounds often go by several names; for example, HCFC-22 has 39 other possible names, such as chlorodifluoromethane or algeon 22. I develop an automatic script to collect all possible names on SciFinder, a database of chemical information maintained by the American Chemical Society, and search through the text of patents and articles for any occurrence of

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

[24] Journals are listed by disciplines on Elsevier's website: https://www.elsevier.com/solutions/sciencedirect/content/journal-title-lists.

[25] https://www.grid.ac/

these names.[26] The frequency with which molecules are mentioned in any one document can vary widely. As a robustness check, I construct a measure of counts weighted by the number of occurrences of molecules in the documents in Section 5.2.

In total, I find 3270 patents and 1926 articles mentioning at least one CFC substitute. Online Appendix Tables G1, G2. and G3 illustrate the types of patents and articles that mention CFC substitutes. The most common patent codes are related to chemical compounds containing halogen atoms. The most cited articles focus on physical characteristics or new synthesis routes, while the most cited patents correspond to innovations in the pharmaceutical sector. Indeed, CFCs were essential components of aerosol delivery systems for certain medications. For instance, the most frequently cited patent pertains to an aerosol formulation incorporating P134a and salbutamol, a drug commonly used to alleviate asthma symptoms and chronic obstructive pulmonary disease.[27] More than 96% of patents are granted to for-profit organizations, while the rest is filed by educational and public sector organizations. American assignees represent about 60% of patents, European around 25%, and Japanese around 12%.[28]

4 EMPIRICAL STRATEGY

4.1 A Sharp Post-1987 Increase

In this section, I examine the temporal trends in the yearly count of documents about CFC substitutes. As Figure 1 illustrates, the numbers of patents and articles increase after the signature of Montreal in 1987.[29] I quantitatively investigate these temporal patterns with first-difference specifications. Equation 1, below, models a mean shift while Equation 2 models a trend-break.

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[26] I look for any English name listed in SciFinder but I do not look for chemical symbols. The articles' text is usually the output of optical character recognition, and chemical symbols and formulae are too often rendered with mistakes. A full list of all the possible names of CFC substitutes is shown in Online Appendix Table A6.

[27] The prevalence of pharmaceutical applications in highly-cited patents may not necessarily indicate superior patent "quality" compared to inventions in other sectors. Instead, it may simply reflect the industry's tendency to produce and cite numerous patents.

[28] Online Appendix Table G4 displays summary statistics about countries and affiliations of patent assignees and authors of articles.

[29] Online Appendix Figure C1 plots time-series similar to Figure 1, but each CFC substitutes separately. The post-1987 increase is present for most substitutes.

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

$$\text{Count}_{mt} = \alpha + \beta_1 \times Years \times \lambda_{post1987} + \beta_2 \times Years + \lambda_m + \varepsilon_{mt} \tag{2}$$

$Count_{mt}$ is the number of documents mentioning molecule m in year t; $\lambda_{post1987}$ 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. The main hypothesis is that β_0 and β_1 are both positive for CFC substitutes, implying significant increases in research and patenting activities relating to CFC substitutes after 1987 once Montreal passed.

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

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

4.2 Hazardous Air Pollutants as a Comparison Group

HAPs is an umbrella term for molecules categorized as *hazardous air pollutants* that became monitored under the 1990 Clean Air Act due to adverse ecological impacts and human health concerns including cancer, asthma, congenital disabilities, reproductive effects, and neurodevelopmental effects. Examples include benzene, chromium, or formaldehyde.[30]

HAPs are potentially an appropriate comparison group for CFC substitutes because they are used in a multitude of industrial applications. I provide more evidence of the similarity between HAPs and CFC substitutes in Subsection 4.4 using patent codes and topic proportions.[31] Importantly, HAPs are also unrelated to ozone depletion and are therefore not affected by the Montreal Protocol.[32]

One possible concern, however, is that research efforts on CFC substitutes and HAPs are substitutes to each other and that research on CFC substitutes crowds out research on HAPs. This would violate the Stable Unit Treatment Value Assumption (SUTVA), which requires that the response of the treated unit depends only on the treatment assigned to that unit and that there are no spillovers between units in different treatment groups. Comparing patents assignees of CFC substitutes and HAPs, I find that 75% of CFC substitutes assignees never patented on HAPs.[33] Few firms are active in both CFC substitutes and HAPs, which supports the SUTVA.[34]

Another concern is that other policies may have impacted research and innovation related to HAPs during the same period of analysis. In particular, in 1990, an amendment to the Clean Air Act required the EPA to promulgate regulations establishing emission standards for large sources of HAPs. However, since the EPA only published the initial promulgation schedule in 1993, HAPs are not, in practice, impacted by this policy change until later in the period that I consider.[35] I nonetheless take a conservative approach and limit my analysis to the time-period

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[30] The full list of HAPs is displayed in Online Appendix Table A5.

[31] To collect patents and articles related to HAPs, I proceed in the same way as for CFC substitutes. The search procedure may lead to measurement error with over-detection if documents mention molecules that are not core to the subject of the document, but there is no reason to believe that the measurement error rate would differ for treated and control molecules.

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

[33] For this exercise, I focused on the top HAPs entering the synthetic control.

[34] Examples of assignees that file patents related to both CFC substitutes and HAPs include 3M, Allied Chemical, BASF, Dow Chemical, and Procter & Gamble. These are all very large and broad companies from the chemical industry which likely would host CFCs and HAPs activities in different business units.

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

until 1992 for patents and 1995 for articles. The additional three-year period for articles is to account for further delays between submission and publication of scientific articles.[36]

4.3 Topic Modeling

I use a Latent Dirichlet Allocation (LDA) algorithm to model which *topics* are present in the documents (Blei 2012; Blei and Lafferty 2009). In this context, a topic means a distribution over words, and a document a distribution over topics. The *number* of topics is a parameter chosen by the experimenter. I run several LDA models, each with a different number of topics, and compute their coherence score (Röder, Both, and Hinneburg 2015).[37]

For each corpus, I choose the lowest number of topics that offers the highest coherence score, which is 20 for patents and 15 for articles.[38] Online Appendix Tables B1 and B2 provide the full list of words the topics contain. The documents are highly technical, and topics can be challenging to interpret. For example, for patents, the most likely word in Topic 1 is "polymer" (with probability 0.61). Then come "catalyst" and "carbon." A trained chemist may suggest labeling Topic 1 "Catalysts on polymer substrates."[39]

I then use the trained topic models to generate document-level variables called topic proportions. These variables take values between 0 and 1 and indicate to what extent a topic is present in a document. Said differently, the model uses the words appearing in a document to infer the proportion of each topic in that document. I aggregate topic proportions at the molecule level by calculating weighted means where the weights are proportional to the number of times a document mentions a molecule.[40] The molecule-level topic proportions describe quantitatively what the documents with molecule i talk about. In other words, they help measure the molecule's chemical and industrial characteristics.

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

[37] Online Appendix Figure B2 shows that coherence increases with the number of topics up to a certain point.

[38] I train the algorithm on the set of documents that mention at least one molecule (either a CFC or CFC substitute ro HAPs).

[39] Catalysts are molecules (typically "metals", word 7 in topic 1) used to start and maintain chemical reactions. They are often made more effective by being attached to a polymer substrate (which will contain some "carbon" atoms). Hence, the production of such catalysts often involves a "polymerization" process (word 6 in topic 1) where free "radicals" (word 13 in topic 1) ensure the addition of new monomers to the polymer chain.

[40] Online Appendix Figure B1 summarizes these steps.

4.4 Similarity between HAPs and CFC Substitutes

This section provides more evidence of the similarity between HAPs and CFC substitutes. First, I document that patents about CFC substitutes and patents about HAPs are associated with similar technology codes. Figure 2 illustrates this point by showing the distribution of 3-digit International Patent Classification (IPC) codes. We note, for example, that both corpora contain many patents related to class C08 (Organic Macromolecular Compounds) and C07 (Organic Chemistry).

Topic proportions provide another, more continuous, way to characterize how similar molecules are. Figure 2b illustrates the variation in topic proportions across molecules. Some HAPs have values of topic proportions that stand out as outliers, indicating that they present semantic contexts that are very different from those of CFC substitutes. In short, topic proportions will be useful to control for differences across molecules.

To quantitatively document the distance between CFC substitutes and HAPs, I compute cosine similarities in the vector space of patent codes and topic proportions for the HAPs included in the difference-in-differences control set and the synthetic control donor pool. Since patent codes provide an easy correspondence to industry codes, I also compute cosine similarities in the vector space of NACE codes. For simplicity, I group the 14 CFC substitutes together and calculate the distance between each HAP and this “Aggregate” CFC substitute.

I find that many HAPs have high similarities. For the subset in the DiD control group, the 75th percentile HAP has similarities of 0.47, 0.62, and 0.97 in the space of 4-digit IPC codes, weighted topic proportions, and NACE codes, respectively. For HAPs in the SCM donor pool, the 75th percentile similarities equal 0.73, 0.82, and 0.99 for 4-digit IPC codes, weighted topic proportions, and NACE codes, respectively.[41] Not all HAPs present a high similarity, but my empirical strategy will ensure that more weight is placed on those that do to estimate treatment effects.[42]

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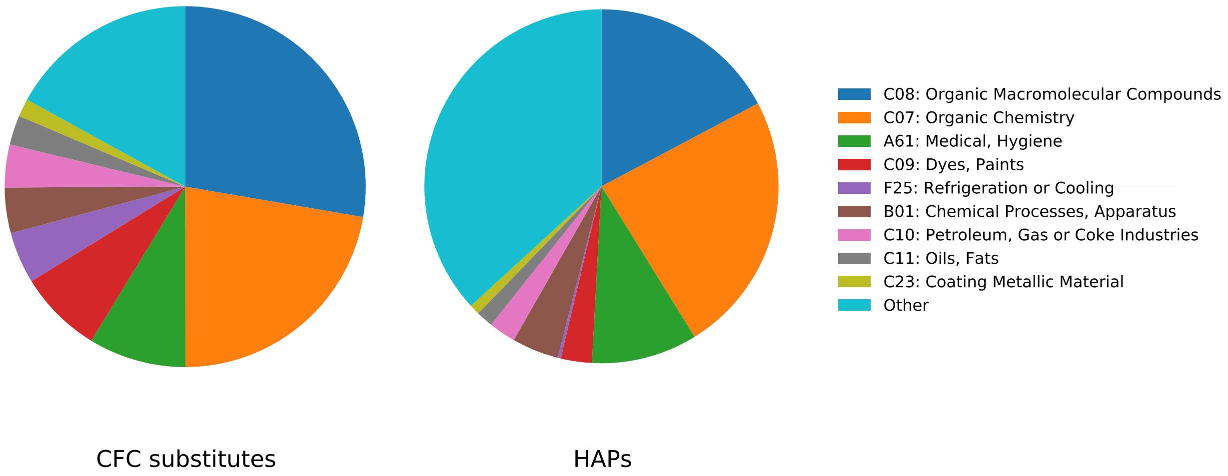
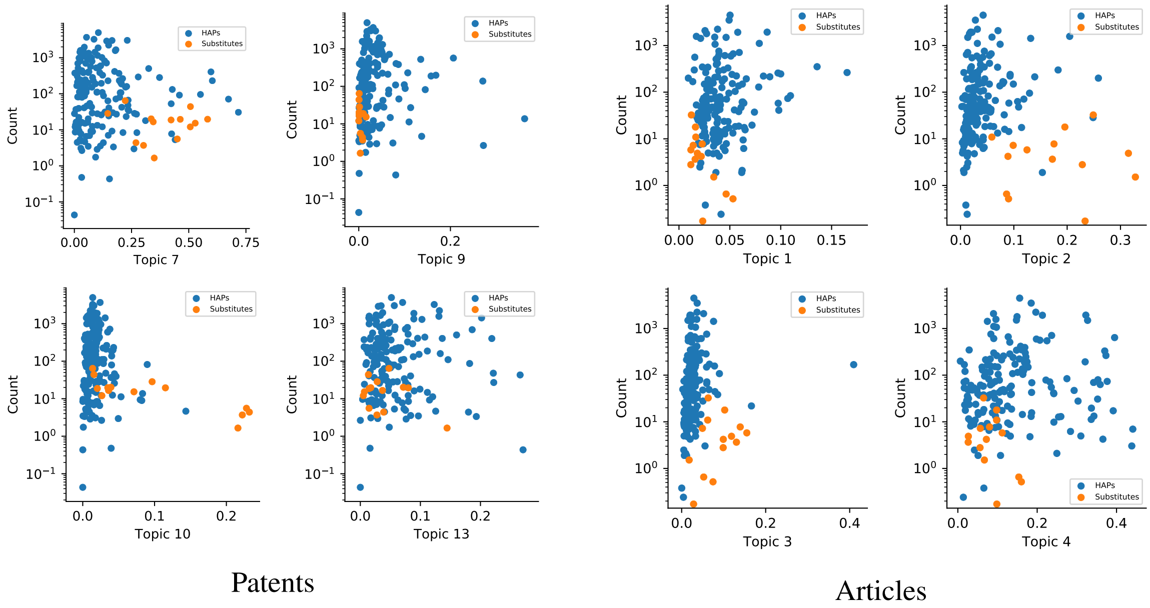
[41] Full results are available in Online Appendix Table D1, D2 and D3.

[42] As explained in Section 5, the DiD control group is constructed such that it contains the HAPs with the closest pre-trends and the SCM donor pool such that it contains the HAPs with most similar pre-period counts. As a result, similarity in terms of topics or codes is not a criterion for inclusion. Instead, topic proportions are used as control variables in the DiD and in the SCM.



(a) Patent IPC Codes



(b) Topics Proportions and Counts for Selected Topics

FIGURE 2
CFC substitutes vs. HAPs

Note: Figure 2 shows that patents mentioning CFC substitutes and HAPs fall into similar patent codes. HAPs are a group of 171 molecules that have no relationship to ozone and that are used for diverse industrial applications. The figure confirms that the two groups of molecules present remarkable similarities, which motivates the use of HAPs as control molecules to estimate the causal effect of the post-Montreal regime. The patent codes are from the international patent classification (IPC). Figure 2b illustrates the variation across HAPs and CFC substitutes in topic proportions and document counts. Topic modeling allows to measure the proportions of different topics in documents. They are averaged over all documents mentioning a given molecule (across all years in the sample). The x-axis on the figure above plots the average topic proportion for a given molecule. The y-axis shows the average number of documents mentioning a given molecule. The graphs highlight that CFC substitutes and HAPs don’t always have comparable topic proportions indicating that their semantic contexts can be very different. Using topic proportions in the DiD and synthetic control methods therefore provides a way of controlling for variation in how different molecules are mentioned in the text of documents.

5 RESULTS

5.1 Difference-in-Differences

HAPs are related to industrial activities similar to those of CFC substitutes, but some are more similar to CFC substitutes than others. In particular, some have much higher counts than the average CFC substitute.[43] In what follows, I exclude from the control group HAPs that have average pre-period counts larger than ten times that of the average CFC substitute. I then rank the remaining HAPs according to how close their pre-trend is to that of the average CFC substitute. The control group is constructed such that it contains the 28 HAPs with the closest slope. I choose the number of HAPs to be *28* so that the control group has twice as many units as the treated group. Figure 3a shows that pre-trends for the treated and control groups are parallel.

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

$$Count_{mt} = \alpha + \beta_0 \cdot D_m \cdot Post_t + \lambda_t + \lambda_m + \gamma_t \cdot X_{mt} + \varepsilon_{mt} \tag{3}$$

$$Count_{mt} = \alpha + \beta_1 \cdot Years \cdot Post_t \cdot D_m + \beta_2 \cdot Years \cdot Post_t + \beta_3 \cdot Years + \lambda_t + \lambda_m + \gamma_t \cdot X_{mt} + \varepsilon_{mt} \tag{4}$$

$Count_{mt}$ stands for the number of documents mentioning molecule m in year t; $Post_t$ equals one when $t > 1987$; D_m equals one if the molecule belongs to the treated group; $Years$ is a continuous variable indicating the number of years relative to 1987; λ_m are molecule fixed effects; λ_t are year fixed effects; X_{mt} is a vector of topic proportions. β_0 identifies the DiD estimate. The primary hypothesis is that β_0 and β_1 are positive. Furthermore, Online Appendix Table E1 displays balance tables for topic proportions and highlights that, for most topics, proportions are significantly different across the two groups. They may, therefore, capture relevant variation.

The dependent variable is best suited to be modeled as count data, but since results do not differ much from the simpler easy-to-interpret linear specification with counts in levels,

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[43] See Online Appendix Figure D1 and D2 for details.

I report the latter as the main specification for ease of interpretation. Results using Poisson pseudo-maximum likelihood regressions are shown in Online Appendix Table E4.

Table 2 displays the main results. Model 1 and 5 correspond to the differences-in-differences specification without any controls. The binary variable "Post 1987 x Substitutes" equals 1 for observations belonging to CFC substitutes after 1987. Model 2 and 6 control for topic proportions and is the preferred specification. The coefficient is large and statistically significant for patents: it corresponds to an additional 21 patents on average per year per substitute from 1988 to 1992. Since there are 14 CFC substitutes in the sample, this implies 294 additional patents a year for CFC substitutes in aggregate. It is equivalent to almost a 400% increase relative to the pre-period mean number of patents (which equals 5.4).

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

Figure 3b displays the year-by-year coefficients corresponding to Model 2. We note that, for patents, the treatment effect is statistically significant, starting in 1989 and keeps increasing with time. We should expect a delay between the moment firms and inventors decide to redirect their efforts towards CFC substitutes and the moment when they are ready to apply for a patent. However, the time required to obtain any technology worth patenting can vary broadly from technology to technology, even within the same technological field. We can expect some patents to be "low-hanging fruits," i.e., inventions requiring just a few months of R&D work before applying for a patent. Hence, it is not surprising to observe a significant treatment effect as early as two years after Montreal. Others have documented similarly fast treatment effects. In the context of energy patenting, Popp (2002) estimates that the mean lag between a change

TABLE 1
First Differences Results

	(1) Patents	(2) Patents	(3) Articles	(4) Articles
Post 1987	29.51	6.10	13.02	2.11
	(2.11)	(2.63)	(1.07)	(1.58)
Post 1987 x Years		3.95		1.44
		(0.44)		(0.28)
Years		-0.03		0.16
		(0.25)		(0.06)
Molecule FEs	Yes	Yes	Yes	Yes
Bootstraped SE	Yes	Yes	Yes	Yes
R-squared	0.64	0.74	0.58	0.63
Observations	322	322	406	406

Standard errors in parentheses. Variable 'Years' is relative to 1987.
Time period: 1976-1998 for patents; 1970-1998 for articles

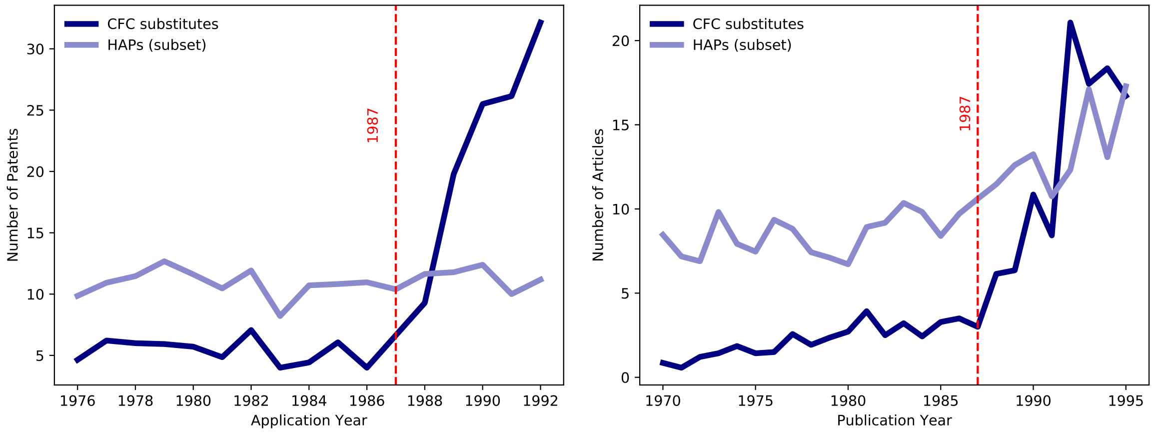
Note: The table presents regression results for first-difference specifications. Model 1 and 3 confirm that there is a significant and positive mean shift after 1987 in the number of patents and articles mentioning CFC substitutes. Model 2 and 4 indicate that the change can also be modeled as a trend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

TABLE 2
Difference-in-Differences Results

	(1) Patents	(2) Patents	(3) Patents	(4) Patents	(5) Patents	(6) Articles	(7) Articles	(8) Articles	(9) Articles	(10) Articles
Post 1987 x Substitutes	16.54	21.38	21.12	0.46	3.44	7.58	12.20	12.63	-0.27	1.44
	(1.74)	(2.15)	(2.06)	(2.68)	(2.49)	(1.12)	(1.53)	(1.69)	(1.63)	(2.48)
Post 1987 x Substitutes x Years				5.23	5.77				1.82	2.06
				(1.01)	(0.83)				(0.38)	(0.50)
Substitutes x Years				0.05	-0.00				-0.03	0.11
				(0.12)	(0.13)				(0.08)	(0.16)
Years				-0.07	-0.09				0.18	0.21
				(0.06)	(0.07)				(0.03)	(0.04)
Post 1987				1.18	1.21				0.97	0.91
				(0.65)	(0.76)				(0.45)	(0.51)
Year FEs	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	No
Molecule FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	No	No	Yes	No	Yes	No	No	Yes	No	Yes
Bootstraped SE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.84	0.85	0.86	0.85	0.87	0.63	0.63	0.64	0.63	0.64
Observations	714	595	595	714	595	1092	846	846	1092	846

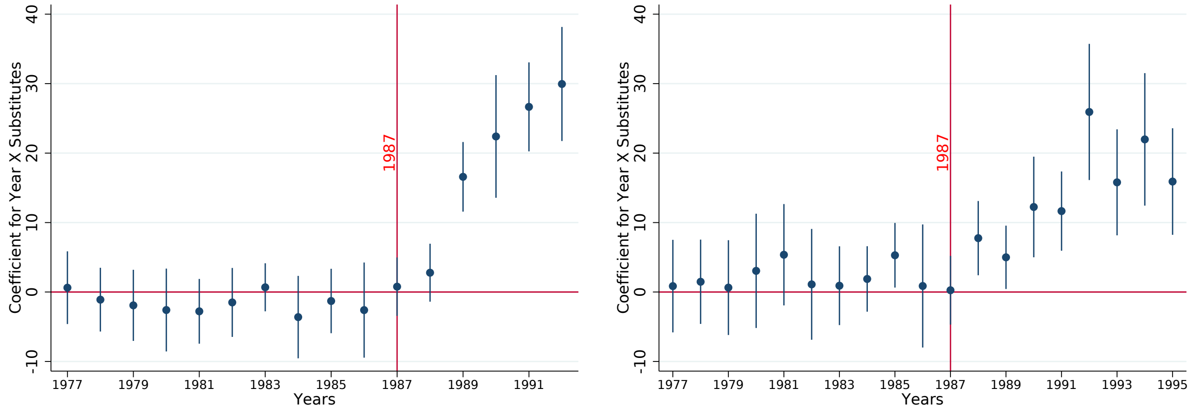
Standard errors in parentheses. Variable 'Years' is relative to 1987.
Time period: 1976-1992 for patents; 1970-1995 for articles

Note: The table presents OLS regression results for difference-in-difference specifications. Model 1 and 5 confirm that there is a significant and positive increase after 1987 in the number of patents and articles mentioning CFC substitutes compared to the control group. Columns 3 and 8 control for topic proportions. This helps ensure that the change in document counts is not driven by a change in demand for particular industrial applications as captured by topic proportions. Topic proportions are missing for years when a molecule is not mentioned in any patent or article. As a result, the numbers of observations are smaller in Columns 3 and 8 compared to 1 and 6. For comparability, Columns 2 and 7 display the same specification as Columns 1 and 6 but using the sample of observations used in the estimation of Columns 3 and 8.



Patents Articles

(a) Trends in Counts of Documents Mentioning CFC Substitutes and HAPs



Patents Articles

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

FIGURE 3
Difference-in-Differences

Note: Figure 3a display the trends for the treated group (CFC substitutes) and the control group constructed using a subset of the HAP molecules that have counts and trends before 1987 closest to the average CFC substitutes. A version of this figure with trends for CFC compounds is shown in Online Appendix Figure I4. Figure 3b shows the difference-in-differences treatment effects by year controlling for topic proportions. For patents, the treatment effect is statistically significant, starting in 1989 and keeps increasing with time. For articles, the treatment effect is significantly different from zero from 1990 onwards.

in energy prices and patenting on energy-saving technologies occurs in 3.71 years.

For articles, the treatment effect is significantly different from zero from 1990 onwards (see Panel b in Figure 3b). Since the data only contains the publication date of articles (as opposed to submission date), the lag between treatment and its effect also accounts for processing and reviewing time at academic journals which, in chemistry and engineering, takes around nine months on average (Björk and Solomon 2013).

Using HAPs to construct a counterfactual, the treatment effect captures the overall impact of the protocol's signature, the country-by-country ratifications,[44] and the amendments to the protocol that happened in 1990 and 1992 (in London and Copenhagen, respectively). It also includes, therefore, the implementation of these international treaties into domestic regulations. In the US, this was done through the Clean Air Act amendment of 1990. The counterfactual represents a world without any of those interventions, that is, a world with limited unilateral actions. This serves as a suitable reference point, considering the inherent difficulties associated with addressing global public goods problems. The absence of costly unilateral actions before 1987 is further testimony to those challenges.[45]

5.2 Robustness Checks

I run additional DiD specifications controlling for lags of counts. A typical model of science and innovation is one with positive knowledge externalities: patents or articles lead to more patents and articles as scientists and inventors build on previous work. Controlling for lagged count allows capturing such a cumulative mechanism. Model 2 in Online Appendix Table E2 confirms that the treatment variable remains statistically significant in both patents and articles. Model 3 shows that results are robust to considering, as an alternative outcome variable, counts weighted by the number of forward citations each document receives. Citations can be interpreted as the publication's degree of influence (or "quality"). Panel a and c in Online Appendix Figure E1 show that pre-trends in citation weighted counts look similar across CFC substitutes

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[44] The USA ratified in April 1988, European countries in December 1988. Online Appendix Table A3 provides the ratification dates for key signatories. It is worth noting that there is little variation over time, as all high-income countries ratified between April and December of 1988.

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

and HAPs for both patents and articles.

Similarly, Model 4 shows that the results are robust to considering patent and article counts weighted by the number of times the molecule appeared in each document (molecule "occurrence"). Panel b and d in Online Appendix Figure E1 show that pre-trends in occurrence-weighted counts look similar across CFC substitutes and HAPs in patents. For articles, a small pre-trend indicates that when articles contain the name of CFC substitutes, they tend to mention these substitutes more often over the years. I provide more details about trends in counts for different thresholds of occurrences in Online Appendix Figure E2.

5.3 Synthetic Control Method

The DiD strategy implemented above assumes that the counts of patents and articles for each molecule are independent. However, molecules are often mentioned together in the same documents: in fact, 40% of patents mention more than one molecule.[46] Instead of considering molecules as separate units of observations, an alternative strategy is to group them together and count the number of documents mentioning any of the 14 CFC substitutes. This strategy is equivalent to considering the 14 molecules as one treated unit, which I refer to as the "aggregate CFC substitute". To illustrate, Figure 4 plots both the number of patents mentioning each CFC substitute, as well as the number of patents mentioning any of the 14 CFC substitutes, i.e., the "aggregate CFC substitute".

I obtain an estimate of the treatment effect on the "aggregate CFC substitute" by implementing a synthetic control method (SCM). This allows me to construct a counterfactual molecule that mimics the evolution of CFC substitutes in aggregate. The synthetic control method emerged as a way to evaluate the effects of interventions that affect aggregate quantities (Abadie, Diamond, and Hainmueller 2010, 2015; Abadie and Gardeazabal 2003; Athey and Imbens 2017). Many interventions are implemented at an aggregate level and impact a small number of large entities, such as cities, school districts, or states. I enlarge the application of SCM to a new kind of aggregate entity: field of scientific and engineering inquiry.

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

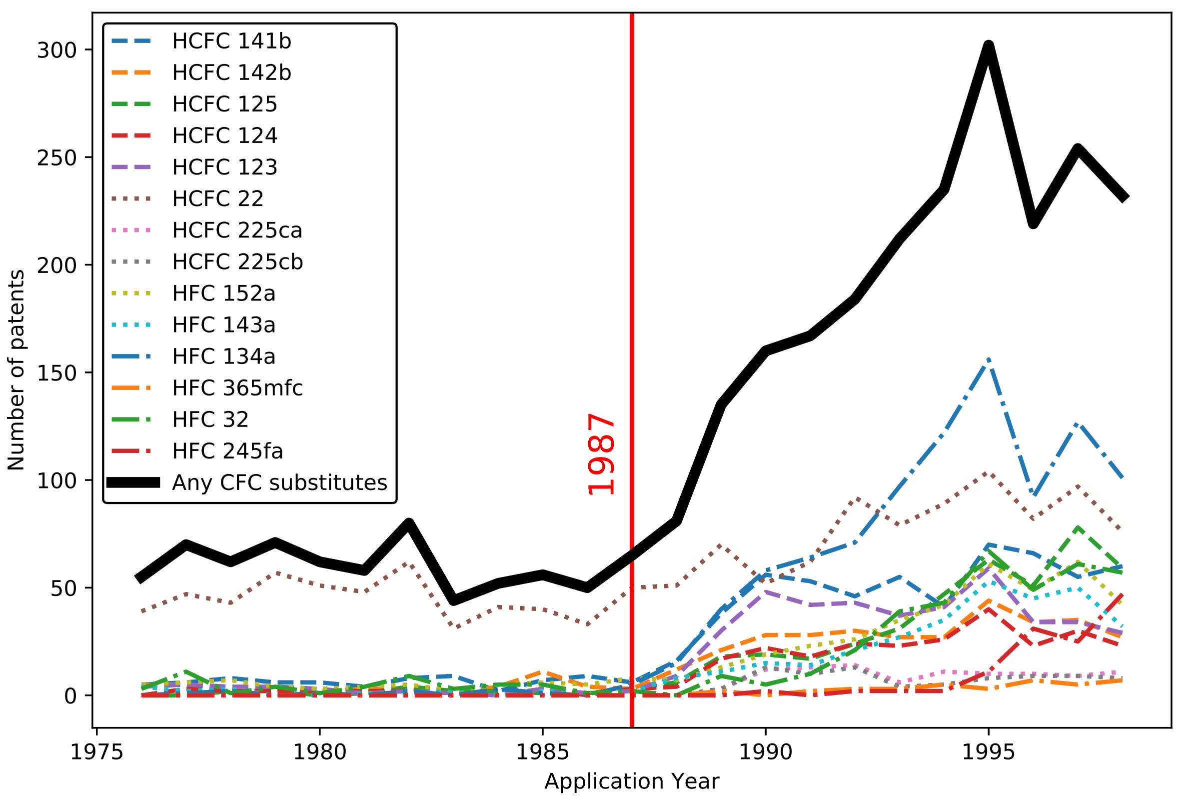
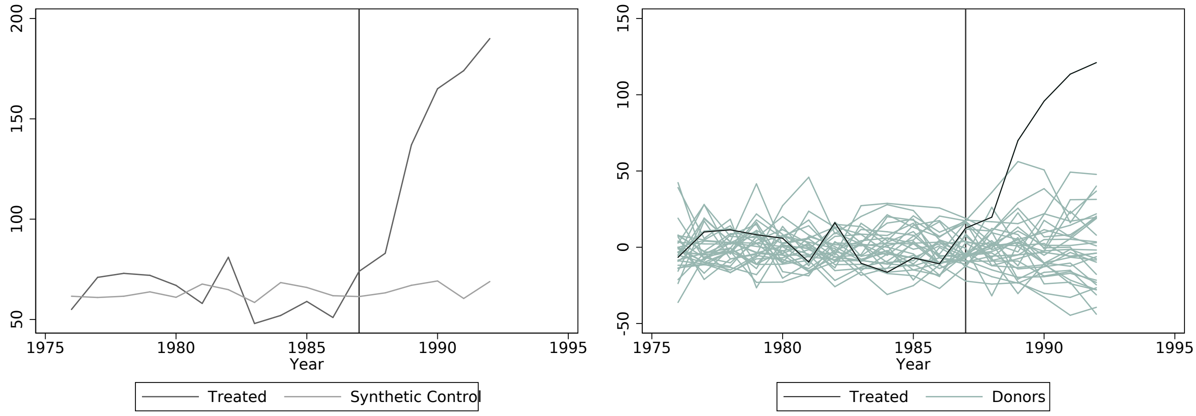


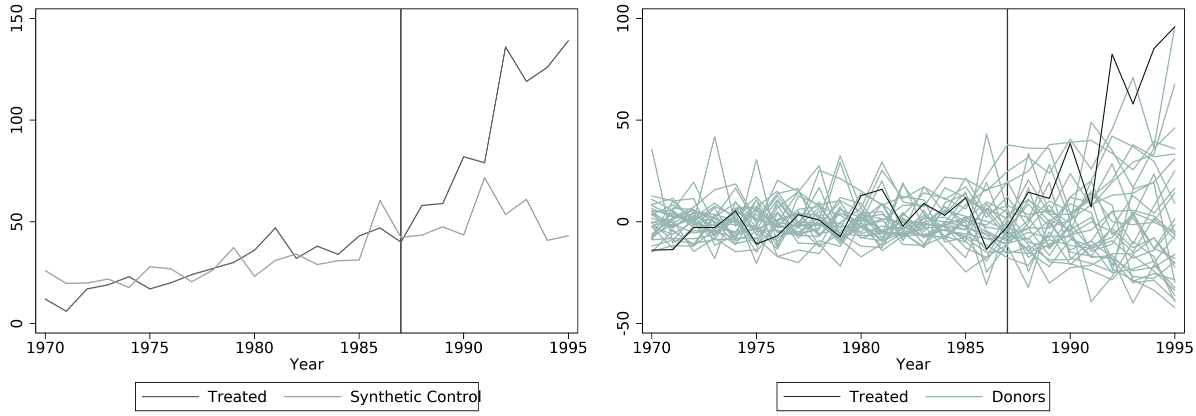
FIGURE 4

Patent Counts for Each CFC Substitute and for the "Aggregate" CFC Substitute

Note: The graph illustrates the difference between considering the 14 separately or together combined as one treated molecule. Since the names of different CFC substitutes often appear simultaneously in the same documents, the time series of CFC substitutes are not independent of each other. The thick line labeled "Any CFC substitutes" corresponds to the number of patents mentioning any of the 14 CFC substitutes. It is equivalent to considering the 14 compounds as one and only one molecule. I implement the synthetic control method on this "aggregated CFC substitute." Online Appendix Figure F1 displays a similar graph for articles.



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



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

FIGURE 5

Synthetic Control Method Graphs for CFC Substitutes

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

The synthetic control method consists of using a weighted average of a set of control units with the weights chosen so that the weighted average is similar to the treated unit in the pre-treatment years along some selected covariates and the outcome variable.[47] The outcome variable here is the number of patents (or articles) that mention any of the 14 molecules. The synthetic control is constructed by fitting the values of pre-treatment counts and topic proportions. The treatment year is the first year in which the treatment becomes active: this is defined as 1988 since Montreal was agreed in 1987. To be conservative, I use data only up to 1985 to fit the synthetic control.[48] Topic proportions are averaged over the entire pre-1985 period, while the outcome, count, is not.[49]

As explained by Abadie, Diamond, and Hainmueller (2015), reducing the size of the donor pool can limit the risk of over-fitting and interpolation biases. Following their advice, I use a smaller donor pool containing only the thirty HAPs closest to the treated unit in terms of counts.[50] For inference, I follow the non-parametric approach method suggested by Abadie, Diamond, and Hainmueller (2010) and Abadie, Diamond, and Hainmueller (2015). The approach is akin to implementing placebo tests wherein each unit in the control group is assumed to have received the treatment in the year 1987. The "true" treatment effect can then be compared to the distribution of placebo treatment effects. A p-value is calculated as the fraction of placebo effects that are greater than or equal to the effect estimated for the "true" treated unit. As suggested by Abadie, Diamond, and Hainmueller (2010), I compute the ratios of post-RMSPE over pre-RMSPE and examine where the treated unit lies in the distribution of those ratios.[51]

Figure 5 graphically displays the results of the synthetic control method for CFC substitutes. The graphs on the left-hand side represent the raw effect, which is the observed time series of

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[47] Online Appendix F provides more details on the theoretical foundations for the synthetic control method.

[48] As a robustness check, I used only data from the first part of the pre-period (from 1976 to 1980 for patents and from 1970 to 1978 for articles) to fit the synthetic control. In both cases, the synthetic control predicted the trend well in the second part of the pre-period, and the results were virtually unchanged. This analysis is shown in Online Appendix Figure F5.

[49] Online Appendix Table F3 displays the value of each variable's contribution to the synthetic control.

[50] I also check that there is no risk of extrapolation. See Online Appendix Table F1

[51] The pre-RMSPE measures lack of fit between the path of the outcome variable for any particular unit and its synthetic counterpart: the pre-RMSPE of unit 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.

the treated group along with the time series of the constructed synthetic control. Graphs on the right-hand side show the placebo tests to evaluate the significance of the results; the black lines represent the effect on the treated group relative to the control group, while each gray line is a placebo test performed on a unit drawn from the donor pool. The treatment effect on CFC substitutes appears significant for both patents and articles. We note that the black line rises above most other lines, after 1989. This indicates that, as in the DiD, the treatment effect is statistically significant, starting in 1989. For articles, the treatment effect is statistically significant, starting in 1992.

Graphically, the treatment effect corresponds to the area between the two curves on the left-hand side graphs. Numerically, it corresponds to 84 (resp. 49) additional patents (resp. articles) per year on average between 1988 and 1992 (resp. 1995). This roughly corresponds to 135% and 177% increases in patents and articles. To examine more closely the constructed control unit, I collect information about the top HAPs that enter its composition (see Online Appendix Table F2). We note that the synthetic control picked up HAPs that have broad industrial applications (not unlike CFC substitutes). In particular, we find industrial applications similar to CFC substitutes (e.g., coatings or solvents).

6 MECHANISMS AND ALTERNATIVE EXPLANATIONS

6.1 Mechanisms

This section provides descriptive details about the increase in research and innovation fostered by Montreal. In Figure 6, we could already note that the increase in patenting applies to almost all CFC substitutes. Three molecules see strong increases in the three years that follow the signature of Montreal: HFC 134a, HCFC 141b, and HCFC 123.[52] These substitutes were the most promising in terms of thermodynamic properties. Their vapor pressures were similar to CFC-11 and CFC-12, which implied they could be used with little change to equipment and operations (Manzer 1990; Parson 2003, p.54). Despite their promise, however, firms had no

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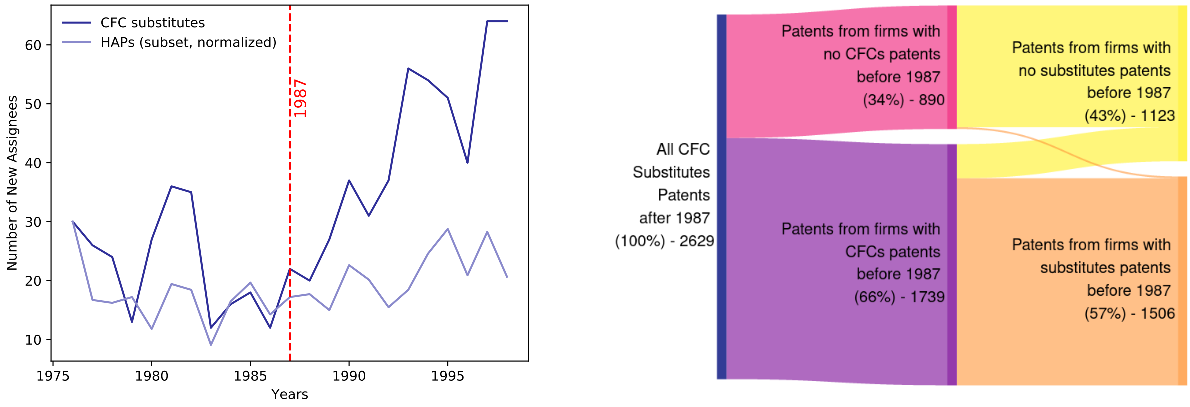
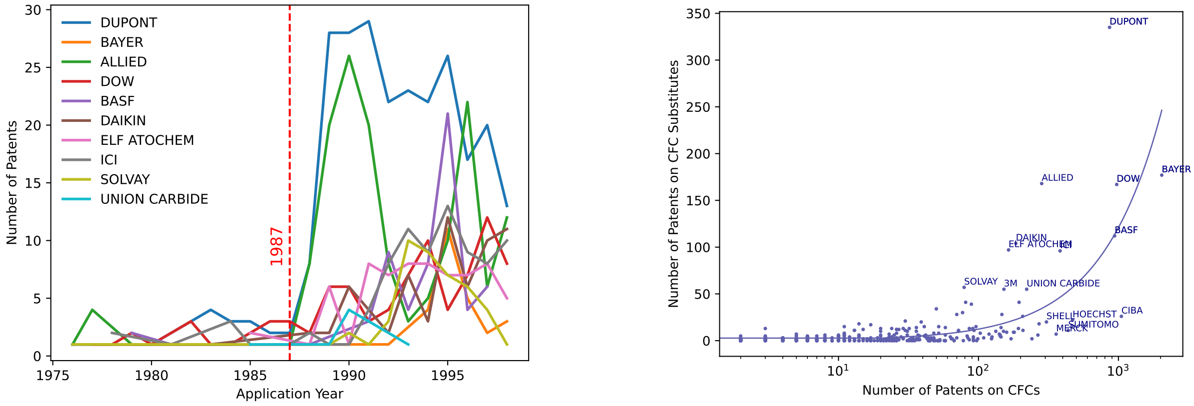
[52] HFC 134a patents increase from an average of one patent a year before 1987 to about 30 per year during the period 1987 to 1990. Similarly, HCFC 141b patents increase from 7 to 30, and HCFC 123 patents from 2.6 to 22.5.



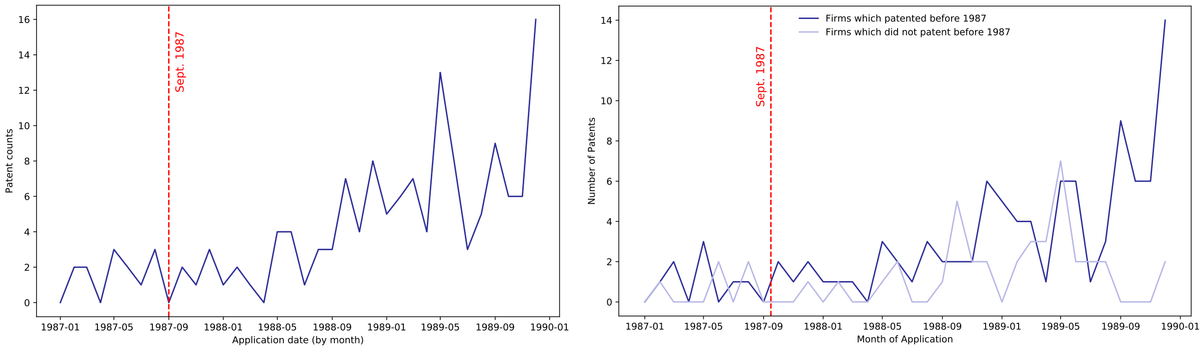
(a) New Entrants Over Time

(b) Patenting by Type of Firms



(c) Top Patenting Firms

(d) Patenting on CFCs and CFC Subtitutes



(e) Monthly Counts - All Assignees

(f) Monthly Counts: Old vs. New Entrants

FIGURE 6

Firms and Patenting on CFC Substitutes

Note: Figure 6a displays the number of assignees that are "new", i.e., assignees that apply for a patent on CFC substitutes or HAPs for the very first time in a given year. The figure shows that, after 1987, many firms with no prior experience on CFC substitutes begin patenting. The data for HAPs is normalized such that y-axis values are equal to those of CFC substitutes in 1976. To limit noise, the sample used to generate the table contains only documents with at least three occurrences of CFC substitutes. Figure 6b highlights that those new entrants are responsible for 43% of CFC substitutes patents after 1987 (top right flow colored in yellow) while firms that had already patented on CFC substitutes are responsible for 57% of those patents. Figure 6c shows the patenting activities of the top 10 firms over time. The scatterplot on Figure 6d indicates that firms with more CFC patents are also those with more CFC substitutes patents. For this graph, the patent counts include patents filed in any year. Figure 6e and 6f show the monthly trends in count of patents mentioning CFC substitutes. Panel 6f shows the monthly count of patents mentioning CFC substitutes for firms that patented on CFC substitutes before 1987 vs. those who did not. The period "Before 1987" includes the year 1987. To limit noise, the sample used to generate the table contains only documents with at least three occurrences of CFC substitutes.

prior commercial experience with those compounds, and deploying them required research and development on all aspects, from toxicity, process testing, and synthesis routes.

Similar technological codes are associated with patents before and after 1987, although many codes with low or no frequency before 1987 become important after 1987. That is the case, for example, of code C10M which corresponds to “Lubricating compositions; Use of chemical substances either alone or as lubricating ingredients in a lubricating composition.”[53] I also find that the increase in the number of patents mentioning CFCs applies to all countries and a substantial increase for patents with assignees located in Japan and the UK.[54]

Next, I examine the assignees behind CFC substitutes patenting. The first takeaway is that almost all patents come from private sector firms, both before and after Montreal (97% and 96%, respectively). Interestingly, Figure 6a reveals a post-1987 significant increase of ”new entrants”, i.e., firms that did not file any patents for CFC substitutes prior to 1987. In total, there are 566 firms identified as the assignees of post-1987 CFC substitutes patents. 87% of these firms are ”new entrants” who have not filed CFC substitutes patents before 1987, while a minority of 13% are ”incumbents” who have filed such patents previously. Figure 6b provides a breakdown of the post-1987 CFC substitutes patents by type of firms, showing that a majority of these patents (57%) are filed by incumbents (bottom right orange flow), while new entrants are responsible for 43% (top right yellow flow). Figure 6c zooms in on the top 10 patenting firms and shows how their patenting evolved over time. We note that Dupont and Allied are by far the most active and the quickest to patent after Montreal, but others such as Dow, Elf Atochem, or Daikin also ramp up patenting quickly. Finally, the scatterplot in Figure 6d indicates that firms with more CFC patents are also those with more CFC substitutes patents. I also find that, at the firm-level, the number of patents before 1987 (either on CFCs or on CFC substitutes) correlates positively with the number of CFC substitutes patents after 1987.

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[53] Other examples include “Macromolecular compounds obtained otherwise than by reactions only involving carbon-to-carbon unsaturated bonds” (C08G), “Cleaning or de-greasing of metallic material by chemical methods other than electrolysis” (C23G), and “Detergent compositions; Use of single substances as detergents; Soap or soap-making; Resin soaps; Recovery of glycerol” (C11D).

[54] See Online Appendix Table G5 and Online Appendix Figure G1 and G2 for more details.

6.2 Were CFC Substitutes Kept "Secret"?

In this section, I examine whether firms may have incurred significant innovation efforts related CFC substitutes before the signature of the Montreal Protocol, without patenting but instead keeping their technologies as trade secrets. At the end of the 1970s, a few firms announced R&D investments into CFC substitutes. Although the same firms, soon after, announced the termination of those same R&D programs, it has been suggested that they developed key technologies which they kept secret. Here, I argue that, if that had been the case, we should expect a one-time increase in patent counts in the immediate aftermaths of Montreal.

As explained by Parson (2003), trade secrets are difficult to keep when developing CFC substitutes development. The key remaining barriers were to prove suitability for specific applications. This could not be done in secret as it required partnerships with customers (e.g., electronic manufacturers that used CFCs as a cleaning agent). Developing new synthesis processes could, in theory, be done in secret. However, several firms were working on the same molecules. When competitors work on closely related projects, delaying patenting increases the risk that a competitor patents first. Incentives to be first to patent were therefore particularly strong. If, until Montreal, firms thought policy pressure was low, they may have elected not to patent. However, once the protocol is signed, they have tangible incentives to patent any old technologies that they may have previously been developed as fast as possible to outrun possible competitors.

If CFC substitutes were kept secret, we should then observe an immediate peak in the number of patents in the few months following the signature of the agreement. Figures 6e and 6f plot the number of patents mentioning CFC substitutes month by month in the two years that followed Montreal. On the first graph, we note the absence of a patenting peak after 1987, which provides support against the hypothesis that technologies related to CFC substitutes had been kept secret. The second graph presents trends for assignees that never patented on CFC substitutes before 1987 and those who did. Suppose the R&D carried out before Montreal was a key driver to the post-Montreal increase in patenting. In that case, we may observe significant differences in patenting trends between firms with and firms without prior patenting experience on CFC substitutes. Although a gap seems to build up over time, trends look mostly similar.

While dozens of firms actively patented on CFC substitutes, two firms, in particular, dominate the landscape: DuPont and Allied. Online Appendix Figure G3 zooms in on these two actors. Figure G3a shows that most patents granted to DuPont and Allied were applied for after 1989, and in particular, Figure G3b shows that there is no sudden peak patenting right after Montreal. Instead, we observe a gradual ramping up of patenting activity. Figure G3c illustrates that the patents from DuPont and Allied, which received the highest number of citations, mostly originate from 1989 to 1991. Figure G3d indicates, however, that, in the weeks that followed Montreal, both DuPont and Allied applied for patents that would go on receiving a high number of citations. This seems to indicate that DuPont and Allied likely had a first-mover advantage on some technologies.[55] However, the ramping up in patenting activity from 1990 onwards supports the claim that, even for DuPont and Allied, most of the innovative activity started after Montreal. Of course, this does not mean that no knowledge existed at all. After all, some patents were filed before 1987. But it indicates that it is unlikely that particular pieces of knowledge or technologies had been hidden.

6.3 Was Consumer Pressure a Potential Driver?

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

There are very few empirical analyses suggesting that consumer pressure is effective (Lyon and Maxwell 2002; Popp, Hafner, and Johnstone 2011), and they all deal with local pollutants

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

such as toxic chemical emissions. We could reasonably expect consumer pressure to be less effective for a global air pollutant such as ozone. As profit-maximizing entities, firms would have few incentives to incur R&D costs without the guarantee of a large market, and without the guarantee that their foreign and domestic competitors do the same. To investigate the role of consumer pressure for innovation on CFC substitutes, I leverage the fact that not all molecules were involved in consumer-facing applications (e.g. industrial applications). Restricting the analysis to substitutes whose applications were not exposed to consumers allows setting aside the possible influence of public opinion.

I use data available on the EPA SNAPs website to identify which CFC substitutes were not exposed to consumers. The EPA website lists a total of 1001 requests corresponding to a given substance for a given application. As part of the implementation of the Montreal Protocol, the EPA was in charge of controlling which substitutes firms could use. To this end, any firm using or producing substitutes had to request authorization for specific substance-application pairs. An example is HCFC-225cb for Electronics Cleaning. I manually classify applications as either consumer exposed, not consumer exposed, or undetermined. In doing so, I identify 6 CFC substitutes that are not consumer exposed. The typical applications requested for these CFC substitutes are related to industrial activities invisible to consumers: e.g., centrifugal chillers, foam blowing agents for rigid polyurethane, or precision cleaning.

I find that, for almost all CFC substitutes that were arguably not exposed to consumers, the number of patents increases sharply after 1987. This is indicative that consumer pressure and public opinion did not play an essential role in driving innovation in the aftermath of the Montreal protocol.[56]

In addition, I also investigate whether consumer exposure played a role in the induced innovation response by examining whether CFC substitutes that were exposed to consumers had a stronger response than those that were not. To do this, I estimate specifications similar to those in Columns 1 and 2 of Table 2, but with an additional interaction term with a binary variable that equals 1 for CFC substitutes with applications exposed to consumers and 0 for those that are not.

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[56] The trends for both exposed and non-exposed CFC Substitutes are shown in Online Appendix Figure G16.

The coefficient on the interaction term is not interpreted as causal here because there is no quasi-random variation in the assignment of consumer exposure status. However, the analysis shows that CFC substitutes exposed to consumers have a stronger response than those not exposed, but the effect disappears when controlling for topic proportions, indicating that other molecule-level characteristics, such as the types of industrial applications or the thermodynamic or safety profiles, may explain why consumer-exposed molecules exhibit a stronger response.[57]

7 TOWARDS A THEORY OF ENVIRONMENTAL AGREEMENTS WITH INDUCED INNOVATION

The role of the Montreal Protocol in solving the crisis has been intensely discussed. In particular, in a seminal article, Barrett (1994) developed a theory of international environmental agreements which interpreted Montreal's success as a case of cheap cooperation. Murdoch and Sandler (1997) also argued that some countries, and especially the USA, accepted to sign Montreal because the costs of doing so were low. Core to their argument is the existence of a cost-benefit analysis issued by the EPA in 1987, concluding that the estimated benefits (mostly from cancers avoided) overwhelmed the estimated costs to the industry. Montreal being "cheap" has often been rephrased as the idea that substitutes existed. However, it is more exact to interpret it as an agreement that industries and governments expected to be technologically feasible within the time frame agreed upon.

This paper highlights that, even if Montreal encoded what some thought feasible from a technological point of view, much experimentation and R&D investments were still required. As a result, the agreement induced innovation. By considering the effects of international agreements on innovation, we are given the opportunity to re-interpret Montreal's success. The first key point is that Montreal's original targets can be seen as modest. Diplomats, in fact, failed to negotiate a full ban in 1987 (against which the industry actively lobbied). Real success instead should be seen in the later amendments (London in 1990 and Copenhagen

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[57] Full results are shown in Online Appendix Table G6.

in 1992), where more ambitious reduction targets were agreed and other molecules added to the list of regulated compounds. Montreal may not have been very ambitious, but, it set up a credible enforcement mechanism that changed firms' expectations about CFCs and, hence, induced innovation. In doing so, it contributed to lowering down the perceived costs associated with a complete phase-out.

Conceptualizing agreements as a vehicle for inducing innovation bears important implications for interpreting the theory of international agreements. Prior work has studied many aspects of cooperation, including how technology shapes cooperation outcomes (Harstad, Lancia, and Russo 2019). But the role of innovation is usually not explicitly considered. Induced innovation suggests that as efforts are made to reduce emissions, the costs associated with those efforts will decrease over time. In other words, abatement costs should decrease over time as abatement actions are undertaken. But previous studies have mainly represented the costs of emission reduction as remaining constant over time.

In this section, I revisit some of these prior studies to discuss how induced innovation would affect models of international environmental agreements. I first start with the seminal contribution of Barrett (1994). In this simple setup, N countries pollute and decide whether or not to pay for pollution abatement. The costs are incurred by each country separately, while the benefits of abatement accrue to all. Free-riding incentives, therefore, arise: countries would be better off if all were to abate a high amount of emissions (the cooperative level), but the Nash equilibrium of the game leaves all countries at a lower amount of abatement (the non-cooperative level).

Barrett (1994) then examines the conditions for successful self-enforcing agreements. He shows that large coalitions occur only when the cost of abatement is low; unfortunately, this is also when countries would find it beneficial to reduce emissions unilaterally. In other words, there is little difference between the non-cooperative and cooperative equilibria: the gains from cooperation are low. This is the essence of the dismal conclusion about self-enforcing agreements: they only appear when we don't really need them. And in this context, the Montreal Protocol has been featured as a poster example.

This paper instead emphasizes that success in the fight against ozone depletion should be seen in the London and Copenhagen amendments, which took place in 1990 and 1992, respectively, where targets were renegotiated. Looking back from 1987, these more ambitious targets were not considered economically viable and, in line with theoretical predictions, were not incorporated into the Montreal Protocol.

Adding induced innovation to Barrett (1994)'s model demonstrates that, despite starting with agreements where cooperation gains are small, over time, induced innovation allows us to successfully negotiate targets that used to be unattainable. A simple way to model induced innovation is to assume that the marginal costs of abatement decrease with the amount of abatement done in the previous periods.

By enforcing some emission reductions in period t (even if only the "cheap" emissions), the agreement forces firms to do new things, experiment, and develop new or improve old technologies. These processes pave the way for lowering the marginal cost of abatement in the next period, and large coalitions can arise where they used to be unlikely. In other words, in 1987, the London and Copenhagen targets were too expensive, but induced innovation made them within reach of an agreement a few years later.

Other theoretical work has examined how technology shapes outcomes in international environmental agreements. Still, these papers do not explicitly consider "innovation", or in other words, the possibility that abatement costs may decrease over time. For example, Harstad, Lancia, and Russo (2019) study how investments in various types of technologies influence whether the agreement is self-enforcing. They show that the best subgame-perfect equilibrium requires countries to strategically overinvest in "clean" technologies as it reduces the temptation to defect.

In this context, investing in technologies is akin to building energy infrastructure before the emission decision is taken. The comparative statics highlight that it is harder to motivate compliance when investment costs in clean technologies are high; this result is equivalent to the findings in Barrett (1994) that there are no large self-enforcing coalitions when abatement costs are high. In Harstad, Lancia, and Russo (2019), investment costs are fixed, but induced innovation could simply be modeled as such costs going down over time (e.g., by making them a function of prior investments). This, in turn, would make it easier to motivate compliance.

To summarize, the success story of Montreal is better summarized as a repeated cooperation game where induced innovation enabled emission reduction ambitions to ratchet up. As such, the evidence presented points to co-evolution of international environmental agreements and innovation efforts. At each stage, binding reductions forced firms to innovate and develop technologies to comply. With each realized innovative step, expectations for further progress increased, and the expected costs of abatement decreased. More aggressive reductions were then perceived as affordable, and stakeholders (both public and private) became willing to bind themselves to more ambitious targets.

8 CONCLUSION

Tackling environmental problems often relies on developing and diffusing new technologies. Understanding the drivers of technological change is, therefore, a critical input to improving the prospects of environmental cooperation. In this paper, I document that the Montreal Protocol led to the development of CFCs substitutes. This empirical evidence goes against the conventional narrative that alternatives technologies were readily available before the treaty. By showing that a low-ambition but binding agreement such as the Montreal Protocol did encourage the development of technological solutions, this paper suggests such agreements are potent tools that dynamically increase the net benefits of environmental protection and may therefore also be useful to deal with current problems such as climate change.

SUPPLEMENTARY MATERIAL

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

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FOR ONLINE PUBLICATION

Online Supplementary Material
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Induced Innovation and International Environmental Agreements: Evidence from the Ozone Regime

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June 18, 2023

Contents

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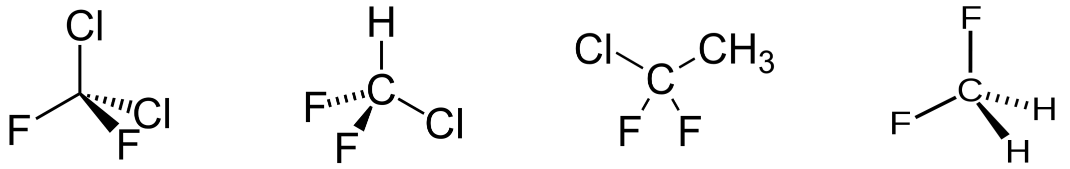
A Other Useful Background Information

A1 Additional Information about CFC Substitutes and Phase-Out Schedule



(a) CFC-12 (b) HCFC-22 (c) HCFC-142b (d) HFC-32

Figure A1: Molecular Structure of CFCs, HCFCs and HFCs

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

Table A1: Montreal Protocol Phaseout Schedules

Chemicals	1987 Montreal Protocol	1990 London Revisions	1992 Copenhagen Revisions	1995 Vienna Revisions	1995 Vienna (article 5)
Annex A/I Chlorofluorocarbons 11,12,113,114,115	baseline 1986 freeze 1989 20% 1993 50% 1998	baseline 1986 freeze 1989 50% 1995 85% 1997 100% 2000	baseline 1986 freeze 1989 75% 1994 100% 1996	no change	baseline 1995/97 freeze 1999 50% 2005 85% 2007 100% 2010
Annex A/II Halons 1211, 1301, 2402	baseline 1986 freeze 1992	baseline 1986 freeze 1992 50% 1995 100% 2000	baseline 1986 freeze 1992 100% 1994	no change	baseline 1995/97 freeze 2002 50% 2005 100% 2010
Annex B/I Other CFCs 10 chemicals	no controls	baseline 1989 20% 1993 85% 1997 100% 2000	baseline 1989 20% 1993 75% 1994 100% 1996	no change	baseline 1998/2000 20% 2003 85% 2007 100% 2010
Annex B/II Carbon tetrachloride	no controls	baseline 1989 85% 1995 100% 2000	baseline 1989 85% 1995 100% 1996	no change	baseline 1998/2000 85% 2005 100% 2010
Annex B/III Methyl chloroform	no controls	baseline 1989 freeze 1993 30% 1995 70% 2000 100% 2005	baseline 1989 freeze 1993 50% 1994 100% 1996	no change	baseline 1998/2000 freeze 2003 30% 2005 70% 2010 100% 2015
Annex C/I Hydrochlorofluorocarbons 40 chemicals	no controls	mandatory re-porting nonbiding resolution on phase-out: 2020 if possible, but no later than 2040	baseline 1989 freeze 1996 35% 2004 65% 2010 90% 2015 99.5% 2020 100% 2030	baseline 1989 one change	baseline 2015 freeze 2016 100% 2040
Annex C/II Hydrobromofluorocarbons 34 chemicals	no controls	no controls	100% 1996	no change	100% 1996
Annex E Methyl bromide	no controls	no controls	baseline 1991 freeze 1995	baseline 1991 freeze 1995 25% 2001 50% 2005 100% 2010	baseline 1995/98 freeze 2002

Note: Source: Benedick (2009)

Table A2: Details about CFC Substitutes

Substitute	PAFT	AFEAS	Substitute for	Notes
HCFC-22	No, already marketed, toxicology known	Yes	Included in Annex C. CFC-11, CFC-12 in foams	cheapest, fastest substitute, already at large scale production at the end of 1986 but due to toxicity concerns, not appropriate for aerosol use. FDA approved it for foams in 1988 for fast foods and for grocery display packaging.
HCFC-142b	No, already marketed, toxicology known	Yes	CFC-11, CFC-12 but not ideal	Included in Annex C. Considered because already at small scale production in 1986 but their thermodynamic propertiesare very different and would have required changes in equipment and process. DuPont 1988 process for coproduction of HCFC 141b and 142b
HFC-152a	No, already marketed, toxicology known	Yes	CFC-11, CFC-12 but not ideal	Considered because already at small scale production in 1986 but their thermodynamic propertiesare very different and would have required changes in equipment and process.
HCFC-123	Yes	Yes	CFC-11 in refrigeration	Included in Annex C. Vapor pressure similar to CFC-11 and CFC-12 implied no need to change equipment. However no commercial experience. estimated at $1.5-2/lb in 1986. DuPont patent commercial synthesis route 1988. large plant in 1990 for production. Still some toxicity concerns.
HFC-134a	Yes	Yes	CFC-12 in refrigeration (car AC)	vapor pressure similar to CFC-11 and CFC-12 implied no need to change equipment. However no commercial experience. estimated at $3/lb in 1986. oct 1990 first commercial plant ICI, then DuPont. Both DuPont and ICI announced important catalyst breakthroughs in 1992, which roughly doubled their capacity.
HCFC-141b	Yes	Yes	CFC-11 in foams	Included in Annex C. Vapor pressure similar to CFC-11 and CFC-12 implied no need to change equipment. However no commercial experience. DuPont 1988 process for coproduction of HCFC 141b and 142b. Appeared to be the most promising alternative initially (1987-1988) but in late 1988 its ODP was found much higher than thought (about 10 percent). EPA banned its use as a solvent in 1993. required phase out of production by 2003. Moderate inflammability.
HCFC-124	Yes	Yes	CFC-114 in refrigeration and sterilization	Included in Annex C. Less suitable properties but could be used in blends
HCFC-125	Yes	Yes	CFC-115 in refrigeration and sterilization	less suitable properties but could be used in blends
HCFC-225ca	No, second rank candidate	Yes		Included in Annex C.
HCFC-225cb	No, second rank candidate	Yes		Included in Annex C.
HFC-32	No, second rank candidate	Yes	refrigeration	considered in blends for refrigeration. Inflammability and compressor discharge made it problematic alone. Both DuPont and ICI opened HFC-32 plants in the summer of 1992. by 1993, DuPont, Allied, ICI, and Atochem were all marketing various patented refrigerant blends
HFC-143a	No, second rank candidate	Yes	CFC-12 in refrigeration	less suitable properties but could be used in blends
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	

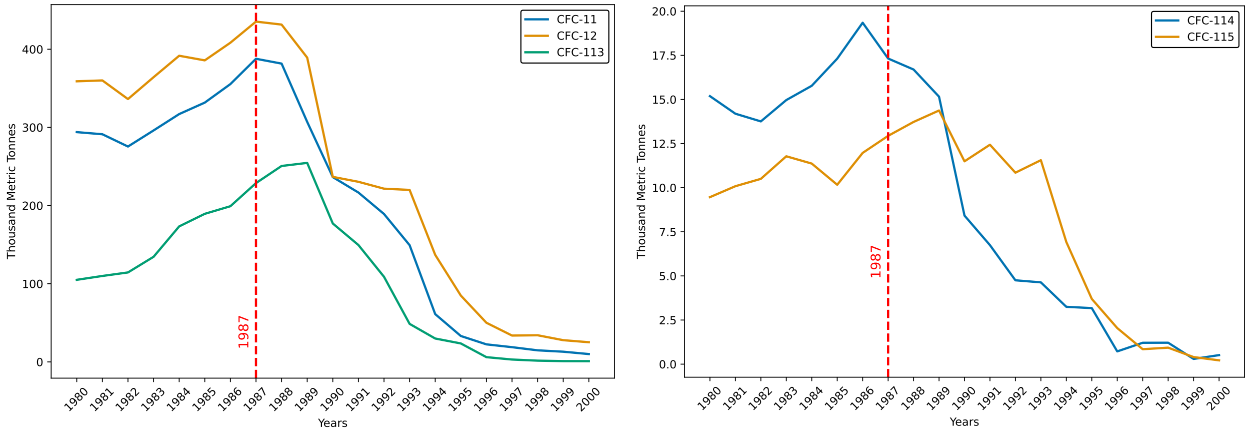
Note: Information collected from (Parson 2003) and (Benedick 2009). Note: the cost of CFC-12 in 1986 was $0.65/lb.

Table A3: OECD Countries and Date of Ratification of the Montreal Protocol

Country	**Date of Signature**	**Date of Ratification**
United States	1987-09-16	1988-04-21
Norway	1987-09-16	1988-06-24
Sweden	1987-09-16	1988-06-29
Canada	1987-09-16	1988-06-30
New Zealand	1987-09-16	1988-07-21
Japan	1987-09-16	1988-09-30
Luxembourg	1988-01-29	1988-10-17
Portugal	1987-09-16	1988-10-17
Russian Federation	1987-12-29	1988-11-10
European Union	1987-09-16	1988-12-16
Denmark	1987-09-16	1988-12-16
Germany	1987-09-16	1988-12-16
Italy	1987-09-16	1988-12-16
Ireland	1988-09-15	1988-12-16
Netherlands	1987-09-16	1988-12-16
Spain	1988-07-21	1988-12-16
United Kingdom	1987-09-16	1988-12-16
France	1987-09-16	1988-12-28
Switzerland	1987-09-16	1988-12-28
Greece	1987-10-29	1988-12-29
Belgium	1987-09-16	1988-12-30
Hungary		1989-04-20
Austria	1988-08-29	1989-05-03
Australia	1988-06-08	1989-05-19
Iceland		1989-08-29
Poland		1990-07-13
Israel	1988-01-14	1992-06-30
Slovenia		1992-07-06
Czech Republic		1993-01-01
Slovakia		1993-05-28
Lithuania		1995-01-18
Latvia		1995-04-28
Estonia		1996-10-17

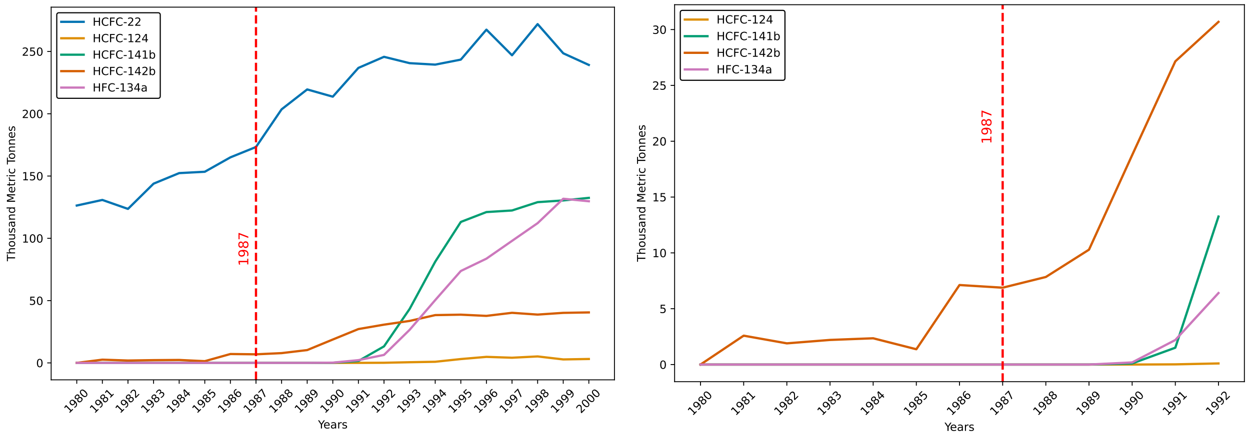
Note: Source: https://ozone.unep.org/all-ratifications

A2 Discussion of Production Trends of CFCs, HCFCs and HFCs



(a) CFC-11, CFC-12 and CFC-113

(b) CFC-114 and CFC-115



(c) HCFCs and HFCs

(d) HCFCs and HFCs: Zooming In

Figure A2: Global Production of CFCs, HCFCs and HFCs

Production Trends of CFCs. Panel a and b of Figure A2 plot the production data for the five CFC compounds included in the Annex A of the Montreal protocol. The first three (CFC-11, -12, and -113) were produced in pretty high quantities, while the others, CFC-114 and -115, were produced in much smaller volumes (the scale y-axis is different on the two graphs). The trends are all quite similar. Production was on the rise until around 1988, then decreased rapidly. The 50% reduction is achieved by 1993 or 1994 for the first three CFCs, by 1990 for CFC-114, and by 1995 for CF-115. (See table below). It took about six or more years to get to 50% or higher reductions. An exception is CFC-114, whose production decreased even faster. By 1997, ten years after the signature of Montreal, production of all five of these CFCs decreased by 90% or more.

As a reminder, the agreed targets (in Montreal) for these compounds were a freeze by 1989, a 20% reduction by 1993, and a 50% reduction by 1998 (relative to the 1986 baseline). So not only are these impressive downward trends, but they happened ahead of the negotiated schedule. In brief, these trends crystallize well why the case of the ozone layer has been considered such a success story.

Table A4: Percentage Reductions Over Time

Years	CFC-11	CFC-12	CFC-113	CFC-114	CFC-115
1987	9%	7%	15%	-10%	8%
1988	7%	6%	26%	-14%	15%
1989	-14%	-5%	28%	-22%	20%
1990	-33%	-42%	-11%	-56%	-4%
1991	-39%	-44%	-25%	-65%	4%
1992	-47%	-46%	-45%	-75%	-9%
1993	-58%	-46%	-76%	-76%	-3%
1994	-83%	-66%	-85%	-83%	-42%
1995	-91%	-79%	-88%	-84%	-69%
1996	-94%	-88%	-97%	-96%	-83%
1997	-95%	-92%	-98%	-94%	-93%
1998	-96%	-92%	-99%	-94%	-92%
1999	-96%	-93%	-99%	-98%	-97%
2000	-97%	-94%	-100%	-97%	-98%

Mechanisms Behind CFCs Reductions. Let me provide more background on what it took to decrease CFC consumption. Because CFCs were used in many industrial applications, several complementary strategies were also used to reduce their uses. One was via the adoption of chemical substitutes (the focus of this paper), but significant reductions could also be achieved via recycling and increasing the efficiency with which CFCs were used. The latter was particularly helpful for some solvents and foam applications. For example, in 1988, flexible foam producers announced they would introduce recycling, and American automakers agreed to increase the use of recycled CFCs in automobile air conditioners (Benedick 2009).

Here is a more detailed account of the substitutions options on the eve of the Montreal as assessed by Richard Benedick, ambassador, and chief United States negotiator in Montreal (page 119, Chapter: The Road to Helsinki):

> *Aerosols, which still accounted for about one-third of global CFC consumption, were obvious candidates for early virtual elimination (a small exception might be considered for certain unique pharmaceutical applications). Emissions from CFC 113 solvents in the electronics and other industries which had grown to about 16 percent of worldwide consumption, could be cut substantially by a combination of substitutes and better containment and recycling practices. Japan, for example, had become particularly efficient in recovering over 95 percent of CFC solvents, in contrast to the United States, where there was much room for improvement. Similarly, large reductions in CFC use for plastic-foam production, which amounted to about one-fourth of global consumption, appeared technically feasible through recycling and substitution.*
>
> *For refrigeration and air conditioning, however, representing 25 percent of the world's CFC consumption, feasible alternatives were not yet obvious-and this was the fastest-growing sector. There were also no chemicals with equivalent characteristics to halons for their specialized and important uses in fighting fires in aircraft, electronic equipment, oil rigs, nuclear power plants and vessels, and defense installations. However, confining halons to the most essential purposes, combined with eliminating such wasteful practices as spraying areas purely for testing, could bring some reductions.*

These accounts provide a nuanced picture highlighting that some cuts were expected to be easy while others were uncertain. In short, CFCs were used in many ways, and some only required innovation to phase out CFCs. And so, innovation was not needed to begin reducing CFC consumption. Still, innovation was needed for substantial cuts, especially in the refrigeration and air-conditioning sector. This explains why global CFC production started decreasing rapidly, even before chemical substitutes were fully developed for all applications.

Production Trends of HCFCs/HFCs. Panel c and d of Figure A2 display the production trends of some key HCFCs and HFCs. It shows that two were already in production before 1987: HCFC-22 at large scale and HCFC-142b at small scale.

Because HCFC-22 was already produced on a large scale, it was considered as potentially the cheapest and fastest substitute. The FDA approved it for foams in 1988 for fast foods and grocery display packaging. But unfortunately, due to toxicity concerns, it could not be considered for aerosol use and as a refrigerant.

HCFC-142b also focused some attention because it was already in small-scale production in 1986. Ultimately, it was not considered for refrigerant applications because its thermodynamic properties were too different, which would have required changes in equipment and processes.

A crucial point here, therefore, is that, even though the molecules were readily available, it was unclear to what extent they could subtitute CFCs in specific applications, especially for refrigeration.

The other HCFCs and HFCs on the graph have no production until 1990. They started in limited quantities in 1991 and grew significantly in 1995. There is, therefore, a lag of about three years between Montreal and the beginning of small-scale production and almost eight years to see significant scale-up. This is undoubtedly rapid but not inconceivable, especially given how close the new molecules were chemically speaking. For example, Parson (2003) mentions that some former CFC plants could be converted into HCFC production. For more details, see page 177 and 180, in Chapter 7: Industry Strategy and Technical Innovation, 1987–1992.

A3 Comprehensive List of Molecules Names

Table A5: List Molecules in Each Treatment Group

CFC Substitutes	HCFC 22, HCFC 123, HCFC 124, HCFC 125, HCFC 141b, HCFC 142b, HCFC 225ca, HCFC 225cb, HFC 134a, HFC 143a, HFC 152a, HFC 245fa, HFC 32, HFC 365mfc
Annex A	CFC 11, CFC 12, CFC 113, CFC 114, CFC 115, HALON 1211, HALON 1301, HALON 2402
Annex B	CFC 13, CFC 111, CFC 112, CFC 211, CFC 212, CFC 213, CFC 214, CFC 215, CFC 216, CFC 217, Carbon tetrachloride, Methyl chloroform
HAPs	Acetaldehyde, Acetamide, Acetonitrile, Acetophenone, 2-Acetylaminofluorene, Acrolein, Acrylamide, Acrylic acid, Acrylonitrile, Allyl chloride, 4-Aminobiphenyl, Aniline, o-Anisidine, Asbestos, Benzene, Benzidine, Benzotrichloride, Benzyl chloride, Biphenyl, Bis(2-ethylhexyl)phthalate (DEHP), Bis(chloromethyl)ether, Bromoform, 1,3-Butadiene, Calcium cyanamide, Caprolactam, Captan, Carbaryl, Carbon disulfide, Carbonyl sulfide, Catechol, Chloramben, Chlordane, Chlorine, Chloroacetic acid, 2-Chloroacetophenone, Chlorobenzene, Chlorobenzilate, Chloroform, Chloromethyl methyl ether, Chloroprene, Cresols/Cresylic acid, o-Cresol, m-Cresol, p-Cresol, Cumene, 2,4-D, salts and esters, DDE, Diazomethane, Dibenzofurans, 1,2-Dibromo-3-chloropropane, Dibutylphthalate, 1,4-Dichlorobenzene, 3,3-Dichlorobenzidene, Dichloroethyl ether ether), 1,3-Dichloropropene, Dichlorvos, Diethanolamine, N,N-Dimethylaniline, Diethyl sulfate, 3,3-Dimethoxybenzidine, Dimethyl aminoazobenzene, 3,3'-Dimethyl benzidine, Dimethyl carbamoyl chloride, Dimethyl formamide, 1,1-Dimethyl hydrazine, Dimethyl phthalate, Dimethyl sulfate, 4,6-Dinitro-o-cresol, and salts, 2,4-Dinitrophenol, 2,4-Dinitrotoluene, 1,4-Dioxane, 1,2-Diphenylhydrazine, Epichlorohydrin, 1,2-Epoxybutane, Ethyl acrylate, Ethyl benzene, Ethyl carbamate, Ethyl chloride, Ethylene dibromide, Ethylene dichloride, Ethylene glycol, Ethylene imine, Ethylene oxide, Ethylene thiourea, Ethylidene dichloride, Formaldehyde, Heptachlor, Hexachlorobenzene, Hexachlorobutadiene, Hexachlorocyclopentadiene, Hexachloroethane, Hexamethylene-1,6-diisocyanate, Hexamethylphosphoramide, Hexane, Hydrazine, Hydrochloric acid, Hydrogen fluoride, Hydrogen sulfide, Hydroquinone, Isophorone, Lindane, Maleic anhydride, Methanol, Methoxychlor, Methyl bromide, Methyl chloride, Methyl ethyl ketone, Methyl hydrazine, Methyl iodide, Methyl isobutyl ketone, Methyl isocyanate, Methyl methacrylate, Methyl tert butyl ether, 4,4-Methylene bis(2-chloroaniline), Methylene chloride, Methylene diphenyl diisocyanate, 4,4'-Methylenedianiline, Naphthalene, Nitrobenzene, 4-Nitrobiphenyl, 4-Nitrophenol, 2-Nitropropane, N-Nitroso-N-methylurea, N-Nitrosodimethylamine, N-Nitrosomorpholine, Parathion, Pentachloronitrobenzene, Pentachlorophenol, Phenol, p-Phenylenediamine, Phosgene, Phosphine, Phosphorus, Phthalic anhydride, Polychlorinated biphenyls, 1,3-Propane sultone, beta-Propiolactone, Propionaldehyde, Propoxur, Propylene dichloride, Propylene oxide, 1,2-Propylenimine, Quinoline, Quinone, Styrene, Styrene oxide, 2,3,7,8-Tetrachlorodibenzo-p-dioxin, 1,1,2,2-Tetrachloroethane, Tetrachloroethylene, Titanium tetrachloride, Toluene, 2,4-Toluene diamine, 2,4-Toluene diisocyanate, o-Toluidine, Toxaphene, 1,2,4-Trichlorobenzene, 1,1,2-Trichloroethane, Trichloroethylene, 2,4,5-Trichlorophenol, 2,4,6-Trichlorophenol, Triethylamine, Trifluralin, 2,2,4-Trimethylpentane, Vinyl acetate, Vinyl bromide, Vinyl chloride, Vinylidene chloride, Xylenes, o-Xylenes, m-Xylenes, p-Xylenes

Table A6: List of Substitutes and Their Possible Names

HCFC 22
Chlorodifluoromethane
Algeon 22
Algofrene 22
Algofrene 6
Arcton 22
Arcton 4
CFC 22
Daiflon 22
Difluorochloromethane
Difluoromethyl chloride
Difluoromonochloromethane
Dymel 22
Electro-CF 22
F 22 (halocarbon)
FC 22
FC 22 (halocarbon)
FKW 22
Flugene 22
Forane 22
Freon 22
Freon R 22
Frigen 22
Fron 22
Genetron 22
HFA 22
Halon 22
Haltron 22
Isceon 22
Isotron 22
Khladon 22
Korfron 22
Monochlorodifluoromethane
Propellant 22
R 22
Refrigerant 22
Refrigerant R 22
Solkane 22
Ucon 22

HCFC 123
2,2-Dichloro-1,1,1-trifluoroethane
1,1,1-Trifluoro-2,2-dichloroethane
1,1,1-Trifluorodichloroethane
1,1-Dichloro-2,2,2-trifluoroethane
CFC 123
Dichloro(trifluoromethyl)methane
F 123
F 123 (halocarbon)
FC 123
Freon 123
Fron 123
HFA 123
Khladon 123
R 123
Solkane 123

HCFC 124
2-Chloro-1,1,1,2-tetrafluoroethane
1,1,1,2-Tetrafluoro-2-chloroethane
1,1,1,2-Tetrafluorochloroethane
1-Chloro-1,2,2,2-tetrafluoroethane
CFC 124
F 124
F 124 (halocarbon)
FC 124
Freon 124
Fron 124
Khladon 124
R 124

HCFC 125
Ethane, pentafluoro- (6CI,7CI,8CI,9CI)
1,1,1,2,2-Pentafluoroethane
1,1,2,2,2-Pentafluoroethane
Ecolo Ace 125
F 125
FC 125
Freon 125
Fron 125
HFA 125
HFC 125
HFO 125
Khladon 125
Pentafluoroethane
R 125

HCFC 141b
1,1-Dichloro-1-fluoroethane
1-Fluoro-1,1-dichloroethane
141B
Asahiklin AK 141b
CFC 141b
CG 141b
Daiflon 141b
Dichlorofluoroethane
F 141b
Forane 141b
Forane DGX
Fron 141b
Genesolv 2000
Genetron 141b
HFA 141b
HFC 141b
Isotron 141b
Khladon 141b
R 141b
RC 14
Refrigerant 141b
Solkane 141b

HCFC 142b
1-Chloro-1,1-difluoroethane
1,1-Difluoro-1-chloroethane
CFC 142b
Daiflon 142b
Dymel 142
F 142b
FC 142b
FKW 142b
Freon 142b
Fron 142b
Genetron 101
Genetron 142b
HFA 142b
Propellant 142B
R 142b
Solkane 142b
α-Chloroethylidene fluoride

HCFC 152a
1,1-Difluoroethane
Algofrene 67
Dymel 152
Dymel 152A
Ethylidene fluoride
F 152A
FC 152a
FKW 152a
Formacel Z 2
Fron 152a
Genetron 152A
HFA 152a
HFC 152a
HFO 152a
Propellant 152A
R 152a
Solkane 152a TG 152a

HCFC-225ca
3,3-Dichloro-1,1,1,2,2-pentafluoropropane
1,1,1,2,2-Pentafluoro-3,3-dichloropropane
1,1-Dichloro-2,2,3,3,3-pentafluoropropane
Fron 225
R 225b
R 225ca

HCFC-225cb
1,3-Dichloro-1,1,2,2,3-pentafluoropropane
1,1,2,2,3-Pentafluoro-1,3-dichloropropane
AK 225G
AK 225cb
Asahiklin AK 225G
HFC 225bc
R 225a
R 225cb

HCFC 134a
1,1,1,2-Tetrafluoroethane
1,2,2,2-Tetrafluoroethane
AK 134a
Arcton 134a
Ecolo Ace 134a
F 134A
FC 134a
Forane 134a
Freon 134a
Fron 134a
Genetron 134a
HC 134a
HFA 134
HFA 134a
HFA P134a
HFC 134a
Halon 134A
KLEA 134a
Khladon 134a
Meforex 134a
Norflurane
P 134A
R 134a
RF 134a
Refrigerant R 134a
SUVA 134a
Solkane 134a
TG 134a

HCFC 143a
1,1,1-Trifluoroethane
CFC 143A
F 143A
FC 143a
Freon 143a
Fron 143a
HCF 143a
HFA 143a
HFC 143a
HFO 143a
Methylfluoroform
R 143a
TG 143a

HFC 245fa
1,1,1,3,3-Pentafluoropropane
1,1,3,3,3-Pentafluoropropane
245fa
Enovate 245
Enovate 245fa
Enovate 3000
Genetron 245fa

HFC 32
Difluoromethane
Ecolo Ace 32
F 32
FC 32
Forane 32
Freon 32
Genetron 32
HFA 32
HFO 32
Methylene difluoride
R 32
R 32 (refrigerant)

HFC 365mfc
1,1,1,3,3-Pentafluorobutane
2,2,4,4,4-Pentafluorobutane

Forane 365mfc
HFC 365
HFO 365mfc
R 365
R 365mfc
Solkane 365
Solkane 365mfc

B Cleaning Procedures and Topic Modelling

B1 Cleaning procedure

1 Patents

- Cleaning steps to search and count the number of times a molecule name appear in the text:
  - Lowercase
  - Replace the following punctuation signs by an empty string: , - ( )
    For example, '3-Amino-2,5-dichlorobenzoic acid' becomes '3amino25dichlorobenzoic acid'
  - Replace any other type of punctuation by a space
- Cleaning steps to transform the text into a list of words (necessary for topic modeling)
  - Normalize hyphenated words
  - Normalize quotation marks
  - Normalize unicode strings
  - Replace any punctuation by a space
  - Lowercase
  - Replace any number by the string '˙NUMBER˙'
  - Use tokenizer algorithm in Python's Spacy to tokenize strings
  - Remove stopwords (list taken from Python's package sklearn (ENGLISH˙STOP˙WORDS)
  - Remove tokens strictly smaller than five characters
- Build bigram model based on text as a list of words (I use a minimum count of 5 occurrences)
- Transform text into lemmatized ngrams (using Spacy's lemmatizer)
- Build the dictionnary from lemmatized ngrams (filtering no less than in 10 documents and not more than into 60% of the corpus).
- Build LDA models from lemmatized ngrams

2 Articles

The cleaning procedure for articles follow closely the one adopted for patents. However, more specific steps are required. For most articles, the full text downloaded from ScienceDirect is the result of an imperfect conversion of images into machine-encoded text: some words are not well recognized especially when the article contained mathematical symbols and equations. Words are also sometimes not properly separated by space. Additionnaly, the texts typically contain a list of references.

- Detect reference list and remove. I use a simple rule: if the word ’references’ is found in the text, and if the word is located towards the end of the document (after 80% of it to be precise), I truncate the document to everything that is before. (This step is done before searching and counting molecule names).

- In addition to removing tokens that are shorter than 5 characters, I also remove tokens that are longer than 15 characters. Althgouh this simple rule may result in dropping important scientific words, it also effectively removes most of the many strings with incoherent combinations of characters.

- Drop non-English articles. Some articles seem not to be written in English. For this reason, I use Google’s CLD2 library in Python to detect every document’s language, and drop those that are detected with large enough confidence as not being English.

3 Meta-Data

Scopus’s meta-data provides the name and geographic localization of authors’ affiliations. However, Scopus does not provide information about these organizations. In particular, knowing the share of articles affiliated with public vs. private entities would be interesting. To that aim, I leverage the Global Research Identifier Database[1] (GRID) which provides information about a worldwide collection of organizations associated with academic research. In particular, GRID classifies an entity as one of the following types: education, company, government, facility, non-profit, health care[2].

An organization is classified as “education” if it can grant degrees, as “company” if it is a business entity with the aim of gaining profit, as “government” if it is operated mainly by a government, and as “health care” if it is a place that treats patients. Facilities encompass building or facilities researching specific areas and usually containing specific equipment (e.g., a nuclear plant). Nonprofits include charities but also non-governmental research institutes[3].

Unfortunately, the name of the organizations and its geographical location are often reported differently in Scopus and GRID. To match as many entities as possible, I first look for exact matches, then for approximate ones using tools such as fuzzy matching in python. Still, many remained unmatched. I then manually match any organization appearing, at least, three times or more in the data. There were about 300 of such organizations.

For patents, the bulk data provided by the UPSTO contains meta-data. Names and addresses of the inventors and assignee are therefore more readily available. I use the country of the assignee, and when the patent has no assignee, I use the country of the inventor. The USPTO data, however, does not classify assignee by type of organization (e.g., company, education or non-profit). The GRID database here is not as useful because most patents originate from businesses; GRID encompasses some for-profit entities with major research activities, but many patentees are in fact small companies unlikely to be listed under GRID.

To match patent assignees to an organization type, I implement a more basic strategy. I leverage the presence of certain tokens in the name of the assignees to infer their type. For example, the

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1. https://www.grid.ac/
2. There are two other classifications: “archive” and “other.” For more information, see https://www.grid.ac/pages/policies
3. For example, in the USA, the National Academy of Sciences is classified as a non-profit.

"Inc." abbreviation in the name *Flow Vision, Inc.* tells us that it is a for-profit organization. Other such tokens includes "corp.", "co.", "plc", "llc", "limited" or "company", as well as "& cie"[4]. Similarly, I identify organizations containing tokens such as "university" or "school" as being of the "education" type, and those containing tokens such as "govern", "ministr" or "agency" as being of the "government" type. The use of these simple rules helps me match about 36529 out of 45820 assignee names. Out of the 7899 remaining, I manually match those that appear at least ten times in my data (about 200 of them). I leave the rest with no type information.

B2 Topic Modeling

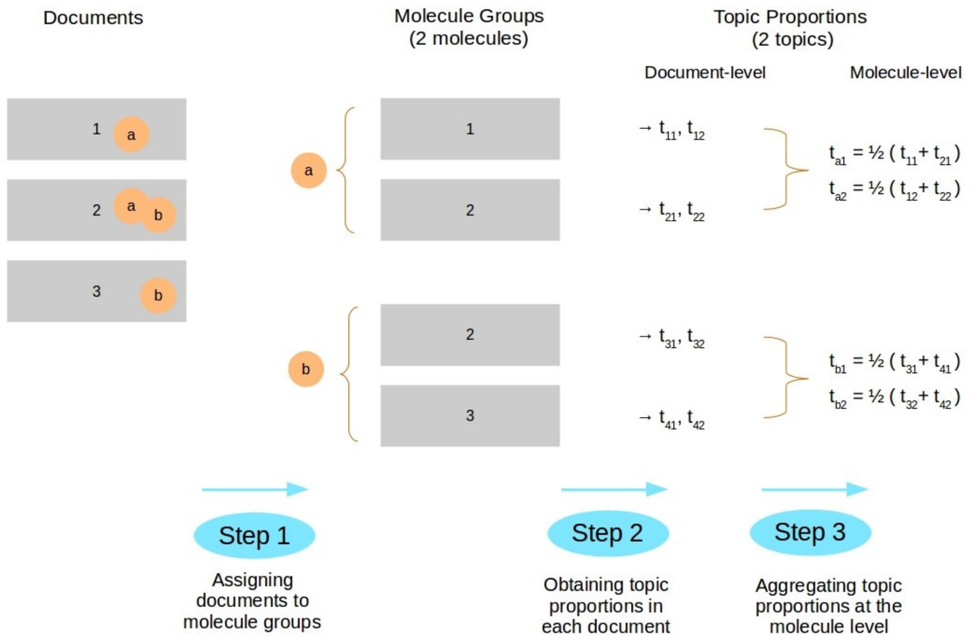

Figure B1: Schematic Explanation of the Methodology

Note: Suppose there are three documents: document 1 and 2 mention molecule 'a' while document 2 and 3 mention molecule 'b'. In step 1, I aggregate documents according to their molecule group. I follow a basic rule that assign any document with at least one mention of a molecule to that molecule's group. In step 2, I use topic modeling to obtain the proportions of topics in each document. t_i, j stands for the proportion of topic j in document i. Finally, in step 3, I create a topic proportion at the molecule level by averaging over all the documents that mention the molecule of interest.

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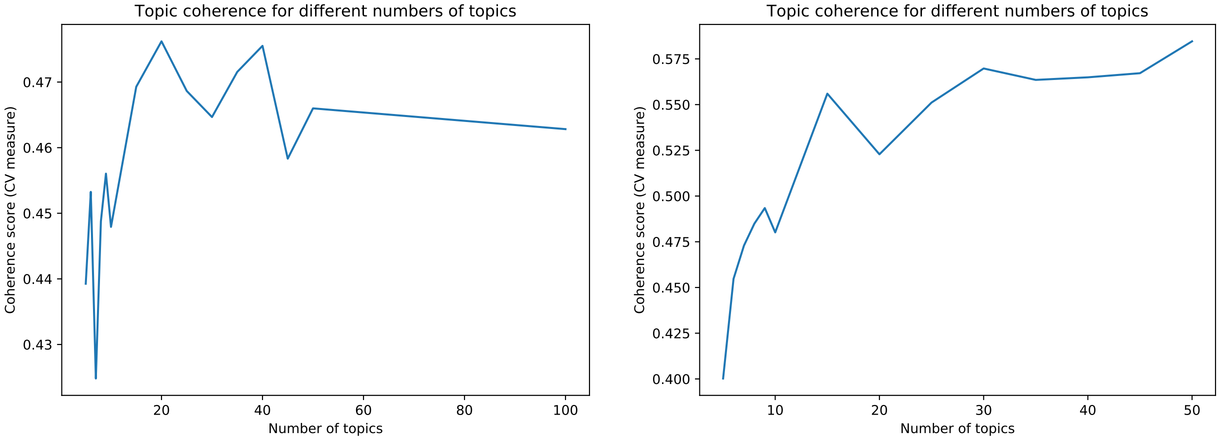
[4] In other languages, here are a few of the tokens that I found in the data: "kaisha" or "kk" in Japanese, "spa" in Italian, "gesellschaft" or "gmbh" or "ag" or "kg" in German, "bv" or "nv" in Dutch, "sa" or "sarl" in French, "ab" in Swedish, "oy" in Finnish, "rt" in Hungarian.



(a) Patents: 20 Topics

(b) Articles: 15 Topics

Figure B2: Topic Coherence Scores

Table B1: Top Twenty Words for Topics in Patents

Topic 1		Topic 2		Topic 3		Topic 4		Topic 5		Topic 6		Topic 7	
Words	Prob	Words	Prob	Words	Prob	Words	Prob	Words	Prob	Words	Prob	Words	Prob
polymer	0.0161	metal	0.0084	formula	0.0118	agent	0.0147	ester	0.0127	formula	0.0245	catalyst	0.0262
catalyst	0.0123	membrane	0.0082	carbon	0.0092	composition	0.0112	methyl	0.0085	atom	0.0243	metal	0.0117
carbon	0.0095	solution	0.0071	atom	0.0088	active	0.0064	titanium	0.0078	carbon	0.0214	hydrocarbon	0.0093
weight	0.0094	particle	0.0067	substitute	0.0086	weight	0.0062	catalyst	0.0060	represent	0.0175	hydrogen	0.0083
atom	0.0087	surface	0.0065	amine	0.0077	water	0.0052	solvent	0.0059	methyl	0.0128	water	0.0077
polymerization	0.0082	polymer	0.0064	metal	0.0076	solution	0.0050	ethyl	0.0056	hydrogen	0.0098	liquid	0.0074
metal	0.0065	water	0.0053	ester	0.0070	effect	0.0046	virus	0.0047	alpha	0.0094	carbon	0.0073
composition	0.0057	catalyst	0.0052	butyl	0.0070	tissue	0.0044	accord	0.0047	substitute	0.0094	component	0.0068
formula	0.0056	protein	0.0050	solvent	0.0069	formulation	0.0042	formula	0.0046	amino	0.0090	pressure	0.0068
solution	0.0056	electrode	0.0045	ether	0.0067	treatment	0.0039	agent	0.0046	radical	0.0083	oxide	0.0063
aromatic	0.0053	sample	0.0042	hydrogen	0.0066	patient	0.0039	polymerization	0.0046	general	0.0072	solvent	0.0062
prepare	0.0053	antibody	0.0039	methyl	0.0065	effective	0.0037	solution	0.0042	phenyl	0.0057	phase	0.0059
radical	0.0052	bind	0.0038	catalyst	0.0064	pharmaceutical	0.0037	active	0.0041	alkoxy	0.0056	stream	0.0057
range	0.0052	cecc	0.0038	weight	0.0060	release	0.0036	water	0.0039	halogen	0.0055	range	0.0053
component	0.0051	liquid	0.0037	phenyl	0.0060	substance	0.0036	weight	0.0039	agent	0.0054	reactor	0.0051
solvent	0.0051	enzyme	0.0036	organic	0.0058	polymer	0.0035	ether	0.0038	hydroxy	0.0054	weight	0.0049
water	0.0050	concentration	0.0035	composition	0.0056	solvent	0.0034	chloride	0.0038	derivative	0.0053	solution	0.0047
prefer	0.0047	solid	0.0033	acid	0.0053	administration	0.0034	hydrocarbon	0.0037	ethyl	0.0050	oxygen	0.0043
molecular	0.0047	electrolyte	0.0032	agent	0.0051	preparation	0.0032	solid	0.0037	solvent	0.0049	organic	0.0042
organic	0.0039	range	0.0032	radical	0.0046	ingredient	0.0031	component	0.0037	alkyl	0.0049	condition	0.0041

Topic 8		Topic 9		Topic 10		Topic 11		Topic 12		Topic 13		Topic 14	
Words	Prob	Words	Prob	Words	Prob	Words	Prob	Words	Prob	Words	Prob	Words	Prob
formula	0.0288	layer	0.0265	paper	0.0145	composition	0.0170	composition	0.0127	water	0.0221	solvent	0.0185
substitute	0.0137	image	0.0200	color	0.0144	weight	0.0129	metal	0.0088	solution	0.0140	formula	0.0147
hydrogen	0.0112	silver	0.0165	pigment	0.0115	surfactant	0.0124	formula	0.0087	composition	0.0117	water	0.0078
low	0.0112	color	0.0107	solvent	0.0097	carbon	0.0096	ester	0.0079	aqueous	0.0088	methyl	0.0077
methyl	0.0095	halide	0.0105	print	0.0080	alcohol	0.0092	peptide	0.0072	metal	0.0088	solution	0.0069
phenyl	0.0088	light	0.0101	water	0.0068	water	0.0091	agent	0.0056	agent	0.0082	active	0.0068
amino	0.0078	photographic	0.0091	sheet	0.0065	agent	0.0087	carbon	0.0056	weight	0.0080	polymer	0.0063
represent	0.0075	sensitive	0.0084	agent	0.0063	atom	0.0080	acid	0.0053	particle	0.0062	ethyl	0.0056
carbon	0.0074	emulsion	0.0083	formula	0.0059	polymer	0.0067	hydrogen	0.0053	sodium	0.0062	hydrogen	0.0053
solvent	0.0072	agent	0.0081	printing	0.0058	ester	0.0066	amino	0.0051	add	0.0050	weight	0.0052
radical	0.0064	represent	0.0079	composition	0.0057	oxide	0.0065	water	0.0051	soluble	0.0045	composition	0.0052
atom	0.0063	develop	0.0063	weight	0.0053	detergent	0.0060	catalyst	0.0051	organic	0.0043	agent	0.0050
salt	0.0061	formula	0.0061	organic	0.0049	glycol	0.0059	atom	0.0050	resin	0.0042	prepare	0.0047
alkoxy	0.0061	element	0.0061	carbon	0.0047	fatty	0.0058	solution	0.0050	solid	0.0041	carry	0.0047
derivative	0.0060	coupler	0.0058	methyl	0.0047	chain	0.0051	solvent	0.0049	surface	0.0040	chloride	0.0046
prepare	0.0057	charge	0.0053	liquid	0.0045	formula	0.0051	weight	0.0047	alkali	0.0039	organic	0.0044
agent	0.0056	solution	0.0052	ester	0.0040	prefer	0.0049	prepare	0.0046	concentration	0.0038	add	0.0043
optionaccy	0.0056	developer	0.0050	microcapsule	0.0036	methyl	0.0046	radical	0.0044	oxide	0.0038	prefer	0.0043
ethyl	0.0051	substitute	0.0049	metal	0.0035	ethylene	0.0045	organic	0.0043	range	0.0037	represent	0.0042
alkyl	0.0050	photosensitive	0.0049	aqueous	0.0035	ether	0.0045	salt	0.0043	calcium	0.0036	sodium	0.0041

Topic 15		Topic 16		Topic 17		Topic 18		Topic 19		Topic 20	
Words	Prob	Words	Prob	Words	Prob	Words	Prob	Words	Prob	Words	Prob
polycarbonate	0.0101	polymer	0.0229	layer	0.0227	sequence	0.0094	surface	0.0108	composition	0.0114
solution	0.0095	resin	0.0212	substrate	0.0132	cecc	0.0085	layer	0.0067	weight	0.0106
weight	0.0070	weight	0.0193	silicon	0.0099	protein	0.0075	mean	0.0062	polyester	0.0082
metal	0.0060	composition	0.0146	surface	0.0093	plant	0.0062	portion	0.0057	radical	0.0081
composition	0.0052	copolymer	0.0131	semiconductor	0.0092	amino	0.0055	member	0.0054	formula	0.0079
water	0.0050	monomer	0.0119	device	0.0091	activity	0.0053	second	0.0047	component	0.0077
alpha	0.0048	vinyl	0.0075	fiber	0.0083	growth	0.0053	sheet	0.0046	polyol	0.0075
hydroxyphenyl	0.0048	coating	0.0069	region	0.0072	enzyme	0.0052	pressure	0.0045	glycol	0.0072
acid	0.0045	agent	0.0068	oxide	0.0064	medium	0.0052	device	0.0044	isocyanate	0.0066
polymer	0.0044	polymerization	0.0061	crystal	0.0062	culture	0.0049	object	0.0043	agent	0.0065
prepare	0.0044	component	0.0060	electrode	0.0060	nucleic	0.0039	apparatus	0.0042	polymer	0.0062
atom	0.0041	rubber	0.0058	light	0.0058	microorganism	0.0038	metal	0.0039	carbon	0.0061
sodium	0.0041	acrylate	0.0057	liquid	0.0056	carbon	0.0034	fluid	0.0038	polyurethane	0.0061
catalyst	0.0040	property	0.0057	optical	0.0054	composition	0.0031	control	0.0035	atom	0.0060
methyl	0.0040	coat	0.0057	second	0.0054	prefer	0.0031	support	0.0035	catalyst	0.0059
ester	0.0039	layer	0.0056	metal	0.0054	acid	0.0031	plate	0.0034	aromatic	0.0059
solvent	0.0039	particle	0.0054	structure	0.0045	molecule	0.0031	position	0.0034	amine	0.0059
prefer	0.0038	surface	0.0054	etch	0.0044	strain	0.0030	chamber	0.0033	organic	0.0057
preparation	0.0038	solvent	0.0052	laser	0.0040	formula	0.0030	liquid	0.0032	ester	0.0056
effect	0.0037	part	0.0051	source	0.0039	peptide	0.0030	element	0.0032	molecular	0.0052

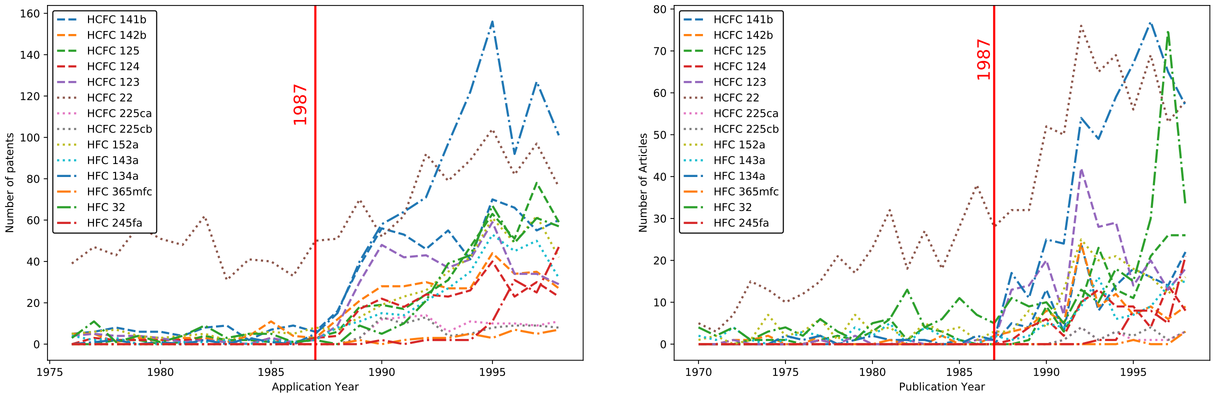
Table B2: Top Twenty Words for Topics in Articles

Topic 1		Topic 2		Topic 3		Topic 4		Topic 5	
Words	Prob	Words	Prob	Words	Prob	Words	Prob	Words	Prob
compound	0.0162	surface	0.0155	laser	0.0129	gifhttps	0.0351	complex	0.0584
extract	0.0072	material	0.0096	signal	0.0102	thumbnail	0.0282	ligand	0.0261
structure	0.0068	layer	0.0086	sample	0.0097	downsample	0.0270	metal	0.0187
product	0.0061	film	0.0075	pulse	0.0092	smlhttps	0.0190	spectra	0.0141
methyl	0.0056	process	0.0062	radical	0.0081	stripin	0.0175	structure	0.0080
spectrum	0.0051	growth	0.0057	light	0.0067	yield	0.0112	coordination	0.0069
carbon	0.0051	sample	0.0050	measurement	0.0065	smlsmlimage	0.0095	tran	0.0067
japan	0.0049	particle	0.0044	intensity	0.0065	product	0.0091	spectrum	0.0067
plant	0.0049	substrate	0.0043	spectra	0.0064	gifgifaltimg	0.0090	band	0.0064
signal	0.0048	energy	0.0042	flame	0.0060	gifsisi	0.0090	compound	0.0057
aromatic	0.0048	solid	0.0040	spectrum	0.0056	compound	0.0089	coordinate	0.0055
spectra	0.0045	accoy	0.0040	absorption	0.0053	mixture	0.0089	inorg	0.0053
degradation	0.0043	pressure	0.0039	experiment	0.0052	gifgifimage	0.0088	specie	0.0051
proton	0.0042	property	0.0038	radiation	0.0051	synthesis	0.0082	stretch	0.0050
isolate	0.0040	metal	0.0037	source	0.0050	smlgrgr	0.0072	bond	0.0050
presence	0.0040	phase	0.0036	optical	0.0049	gifgrgr	0.0065	copper	0.0049
fraction	0.0040	thickness	0.0035	concentration	0.0043	scheme	0.0058	raman	0.0045
natural	0.0032	electron	0.0034	measure	0.0042	add	0.0055	solid	0.0044
yield	0.0031	structure	0.0032	irradiation	0.0041	tetrahedron	0.0055	shift	0.0044
derivative	0.0031	silicon	0.0032	range	0.0039	methyl	0.0052	chemistry	0.0042

Topic 6		Topic 7		Topic 8		Topic 9		Topic 10	
Words	Prob	Words	Prob	Words	Prob	Words	Prob	Words	Prob
model	0.0144	state	0.0279	protein	0.0134	water	0.0075	protein	0.0250
energy	0.0086	energy	0.0245	amino	0.0110	plant	0.0062	activity	0.0222
function	0.0071	spectra	0.0126	peptide	0.0101	concentration	0.0060	enzyme	0.0214
phase	0.0071	electron	0.0119	acid	0.0077	sample	0.0051	bind	0.0173
equation	0.0069	fluorescence	0.0118	residue	0.0077	control	0.0051	concentration	0.0097
state	0.0067	molecule	0.0109	column	0.0066	level	0.0051	membrane	0.0083
parameter	0.0063	absorption	0.0098	chromatography	0.0063	production	0.0043	substrate	0.0078
field	0.0060	transition	0.0098	buffer	0.0057	total	0.0040	inhibitor	0.0067
calculate	0.0059	excitation	0.0083	enzyme	0.0057	organic	0.0037	receptor	0.0062
number	0.0059	transfer	0.0071	sequence	0.0055	treatment	0.0037	buffer	0.0057
constant	0.0056	spectrum	0.0070	fraction	0.0045	sediment	0.0036	inhibition	0.0051
point	0.0055	emission	0.0066	activity	0.0041	growth	0.0034	liver	0.0048
calculation	0.0053	intensity	0.0064	purification	0.0039	tissue	0.0032	assay	0.0045
order	0.0048	excited	0.0064	hydrolysis	0.0039	environmental	0.0032	biochem	0.0043
liquid	0.0045	electronic	0.0061	water	0.0038	marine	0.0029	phosphate	0.0042
large	0.0043	level	0.0061	extract	0.0035	biomass	0.0028	cytochrome	0.0039
theory	0.0041	molecular	0.0059	sample	0.0034	specie	0.0026	lipid	0.0039
measure	0.0040	orbital	0.0055	product	0.0034	research	0.0026	human	0.0039
frequency	0.0040	solvent	0.0050	sugar	0.0034	high	0.0024	presence	0.0037
interaction	0.0039	charge	0.0049	glucose	0.0034	waste	0.0024	cecc	0.0036

Topic 11		Topic 12		Topic 13		Topic 14		Topic 15	
Words	Prob	Words	Prob	Words	Prob	Words	Prob	Words	Prob
structure	0.0330	sample	0.0225	cecc	0.0292	polymer	0.0274	catalyst	0.0227
crystal	0.0148	concentration	0.0152	human	0.0102	membrane	0.0131	surface	0.0185
atom	0.0143	phase	0.0142	mutation	0.0092	water	0.0120	electrode	0.0130
compound	0.0121	column	0.0131	induce	0.0083	concentration	0.0088	oxidation	0.0107
angle	0.0109	water	0.0107	mutant	0.0074	phase	0.0082	potential	0.0092
molecule	0.0103	standard	0.0098	culture	0.0071	surface	0.0079	adsorption	0.0091
bond	0.0099	chromatogr	0.0093	strain	0.0071	chain	0.0075	carbon	0.0076
hydrogen	0.0095	determination	0.0092	cancer	0.0060	weight	0.0067	oxygen	0.0072
distance	0.0085	extraction	0.0087	assay	0.0053	particle	0.0065	hydrogen	0.0069
molecular	0.0079	separation	0.0086	expression	0.0051	molecular	0.0063	concentration	0.0065
conformation	0.0059	detection	0.0081	tumor	0.0047	sample	0.0062	catal	0.0064
structural	0.0052	liquid	0.0068	damage	0.0044	polym	0.0060	reduction	0.0064
interaction	0.0052	plasma	0.0067	sequence	0.0043	property	0.0058	metal	0.0064
energy	0.0047	chromatography	0.0066	treatment	0.0043	copolymer	0.0056	support	0.0063
chemistry	0.0047	compound	0.0059	repair	0.0042	figure	0.0053	catalytic	0.0062
length	0.0046	capiccary	0.0050	control	0.0040	solvent	0.0052	oxide	0.0061
electron	0.0045	analytical	0.0050	agent	0.0036	polymerization	0.0046	process	0.0059
carbon	0.0044	retention	0.0049	clone	0.0034	blend	0.0046	specie	0.0059
diffraction	0.0044	range	0.0045	plasmid	0.0034	monomer	0.0044	activity	0.0058
parameter	0.0044	solvent	0.0045	genetic	0.0034	surfactant	0.0043	zeolite	0.0057

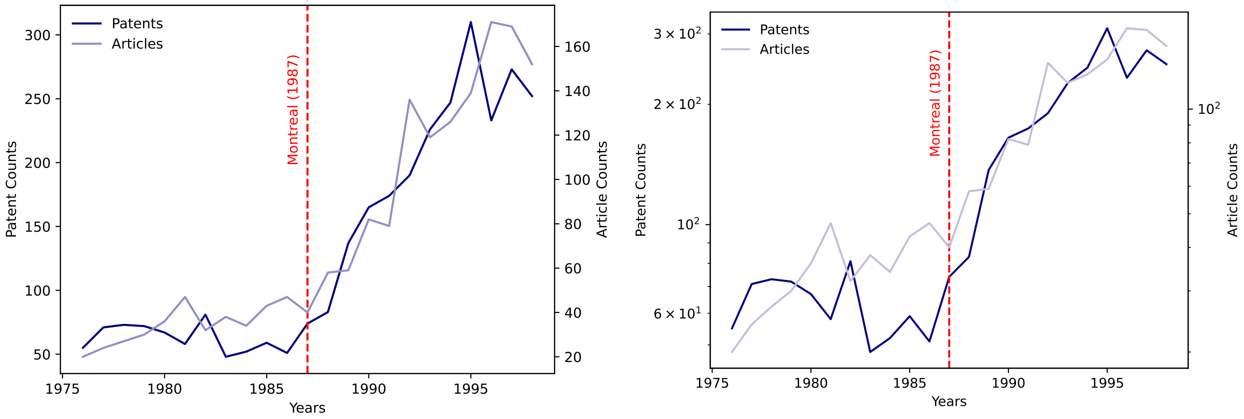
C Time Series and First Difference



(a) Patents

(b) Articles

Figure C1: Document Counts for Individual CFC Substitutes



(a) Linear Scale

(b) Log Scale

Figure C2: Counts of Patents and Articles Mentioning CFC Substitutes

Table C1: First Differences Results

	(1) Patents	(2) Patents	(3) Articles	(4) Articles
Post 1987	29.51	6.10	13.02	2.11
	(2.11)	(2.63)	(1.07)	(1.58)
Post 1987 x Years		3.95		1.44
		(0.44)		(0.28)
Years		-0.03		0.16
		(0.25)		(0.06)
Molecule FEs	Yes	Yes	Yes	Yes
Bootstraped SE	Yes	Yes	Yes	Yes
R-squared	0.64	0.74	0.58	0.63
Observations	322	322	406	406

Standard errors in parentheses. Variable ’Years’ is relative to 1987.

Time period: 1976-1998 for patents; 1970-1998 for articles

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

D Comparing HAPs and CFC Substitutes

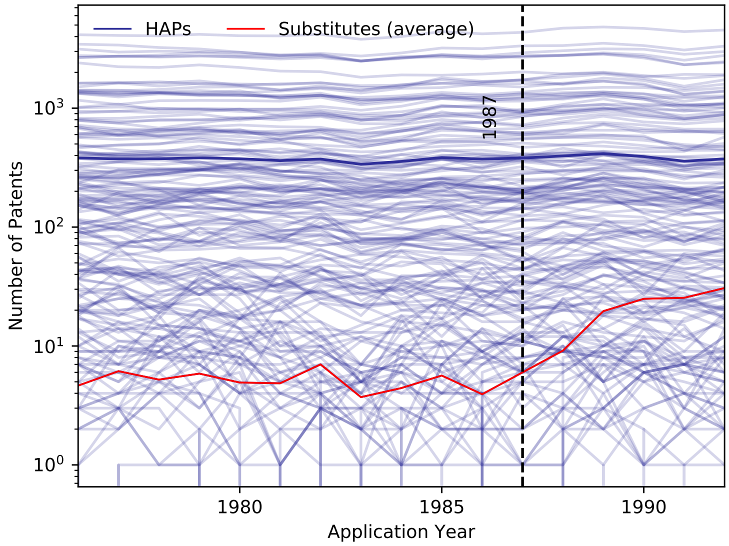


Figure D1: Patent Counts for Each HAP and for the Average CFC Substitute

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

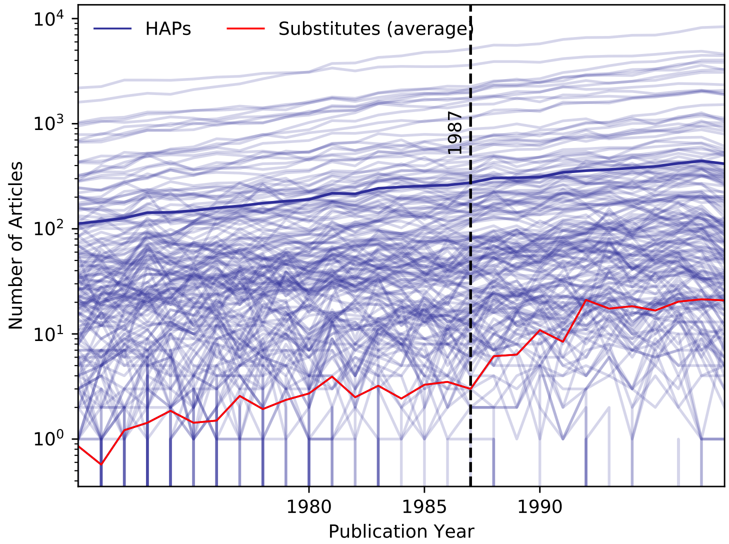


Figure D2: Articles Counts for Each HAP and for the Average CFC Substitute

Note: The grap shows article counts for each HAP (thin lines), for HAPs on average (thick line labeled "HAPs') and for CFC substitutes on average. The graph illustrates that HAPs are a diverse group of molecules. In particular, some of them have counts much higher than the average CFC substitute.

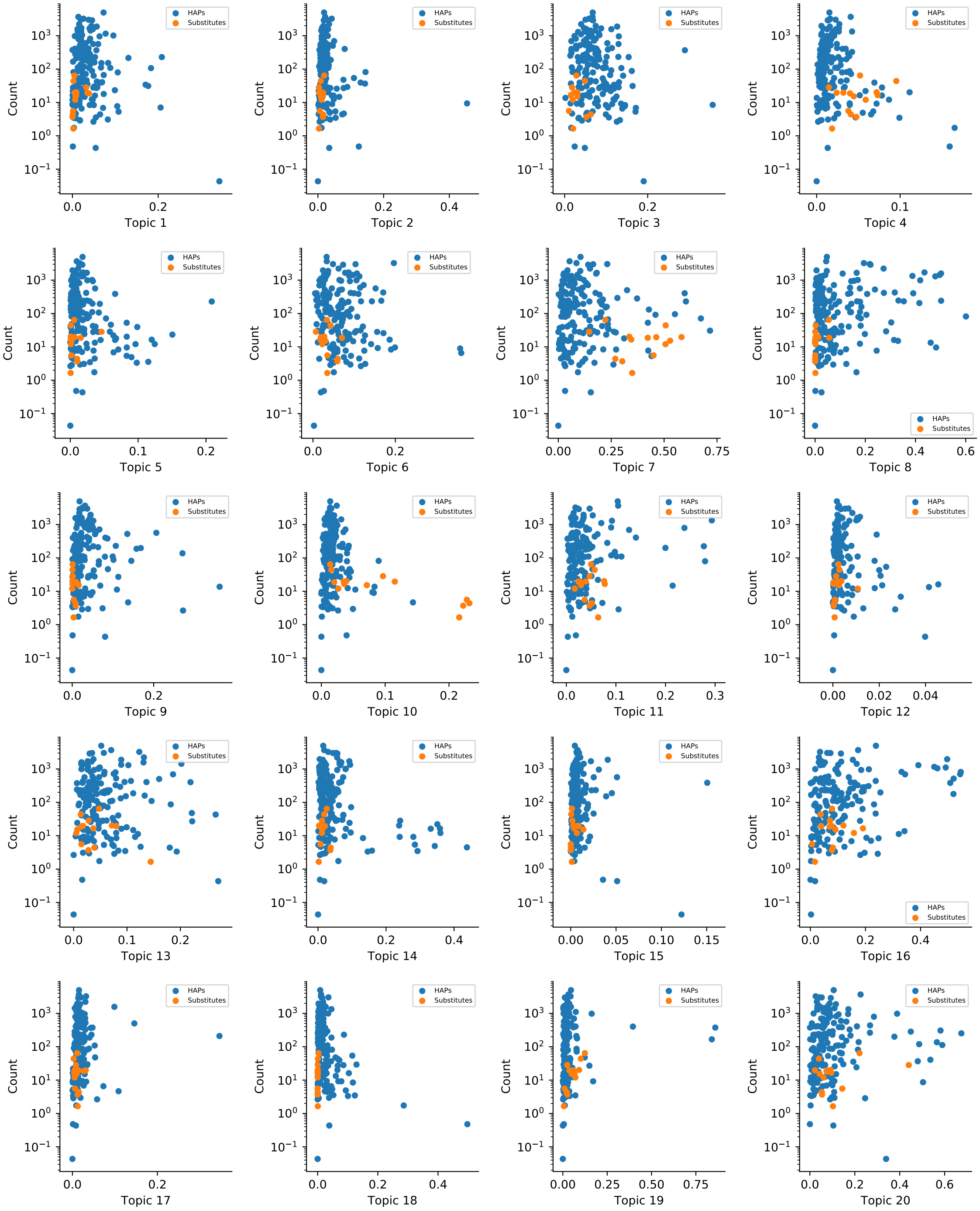


Figure D3: Scatterplot of Topics Proportion and Count for Patents.

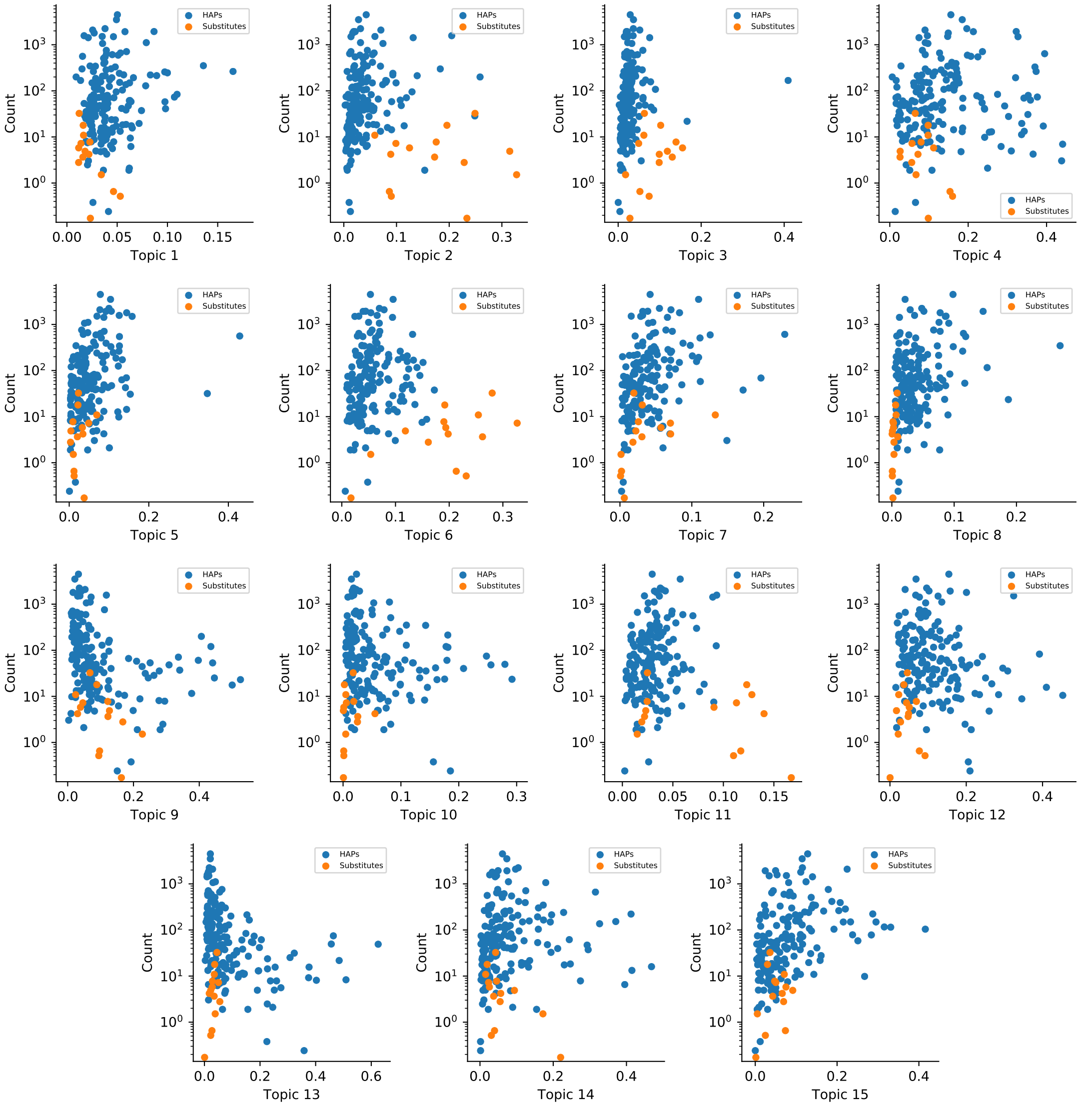


Figure D4: Scatterplot of Topics Proportion and Count for Articles.

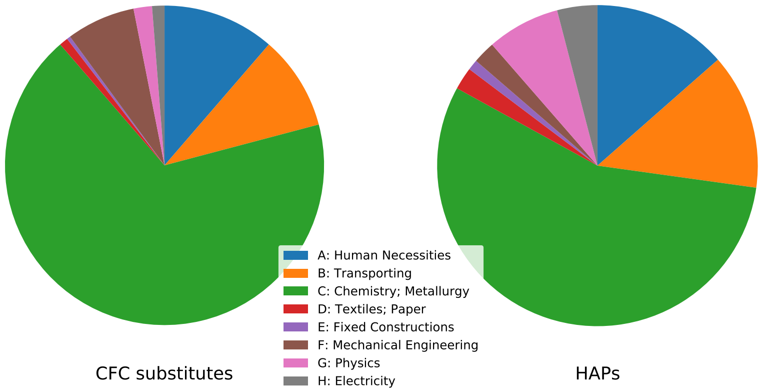


Figure D5: Top Level Patent Codes for CFC Substitutes and HAPs

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

Table D1: Similarity Between the Aggregate Subtitute and the Different HAPs included in the DiD Control Group and the SCM Donor Pool

HAPs	IPC Codes	NACE Codes	Unweighted Topics	Weighted Topics	DiD Control	SCM Donor
m-Cresol	0.82	0.99	0.84	0.88		Yes
1,2-Diphenylhydrazine	0.52	0.90	0.74	0.88	Yes	
Allyl chloride	0.53	0.99	0.77	0.88		Yes
Ethylidene dichloride	0.85	0.99	0.89	0.87		Yes
2-Nitropropane	0.67	0.99	0.80	0.86	Yes	
o-Cresol	0.78	0.99	0.77	0.85		Yes
m-Xylenes	0.59	1.00	0.66	0.84		Yes
p-Xylenes	0.52	1.00	0.62	0.83		Yes
Methyl isocyanate	0.56	0.83	0.69	0.82		Yes
Propylene dichloride	0.61	0.99	0.69	0.82		Yes
2,4-Dinitrotoluene	0.40	0.99	0.54	0.81	Yes	
Polychlorinated biphenyls	0.52	0.96	0.65	0.80	Yes	Yes
Ethyl chloride	0.63	0.99	0.65	0.80		Yes
1,1,2-Trichloroethane	0.62	0.97	0.61	0.79		Yes
Carbonyl sulfide	0.32	0.98	0.46	0.77		Yes
o-Xylenes	0.47	0.99	0.47	0.77		Yes
p-Cresol	0.73	0.99	0.68	0.75		Yes
1,4-Dichlorobenzene	0.85	1.00	0.57	0.75		Yes
Ethylene dibromide	0.52	0.92	0.55	0.70		Yes
Methyl bromide	0.50	0.86	0.45	0.65		Yes
Dimethyl phthalate	0.62	0.98	0.71	0.65		Yes
N-Nitrosomorpholine	0.38	0.98	0.48	0.65	Yes	
Benzotrichloride	0.43	0.99	0.42	0.65	Yes	
Dibenzofurans	0.43	0.82	0.38	0.62	Yes	
Ethylene imine	0.46	0.78	0.57	0.62		Yes
2,4-Toluene diamine	0.87	0.99	0.87	0.62		Yes
Bromoform	0.41	0.96	0.51	0.61	Yes	Yes
Calcium cyanamide	0.45	0.98	0.65	0.61		Yes
1,2-Dibromo-3-chloropropane	0.31	0.90	0.42	0.57	Yes	
3,3-Dimethoxybenzidine	0.81	0.99	0.86	0.56		Yes
1,2,4-Trichlorobenzene	0.71	0.99	0.43	0.56	Yes	Yes
Benzidine	0.77	0.97	0.86	0.55		Yes
beta-Propiolactone	0.73	0.93	0.79	0.51		Yes
N-Nitroso-N-methylurea	0.27	0.41	0.33	0.49	Yes	
Pentachlorophenol	0.49	0.85	0.38	0.48		Yes
2,4,6-Trichlorophenol	0.59	0.99	0.48	0.46	Yes	
Dimethyl aminoazobenzene	0.28	0.87	0.38	0.43	Yes	
4-Nitrobiphenyl	0.57	0.83	0.50	0.42	Yes	
2,4-Dinitrophenol	0.40	0.60	0.27	0.42		Yes
Diethyl sulfate	0.42	0.71	0.37	0.40		Yes
Ethylene thiourea	0.39	0.91	0.43	0.39	Yes	
4-Nitrophenol	0.52	0.71	0.31	0.37	Yes	Yes
1,3-Dichloropropene	0.40	0.84	0.29	0.33	Yes	
o-Anisidine	0.32	0.87	0.25	0.32	Yes	
Methoxychlor	0.17	0.45	0.27	0.30	Yes	
Chloramben	0.33	0.74	0.22	0.27	Yes	
Chlorobenzilate	0.27	0.67	0.23	0.26	Yes	
Propoxur	0.25	0.52	0.23	0.26	Yes	
4-Aminobiphenyl	0.33	0.99	0.18	0.25	Yes	
2-Acetylaminofluorene	0.15	0.15	0.17	0.24	Yes	
Dichlorvos	0.34	0.63	0.19	0.24	Yes	
Toxaphene	0.17	0.38	0.29	0.23	Yes	
3,3'-Dimethyl benzidine	0.05	0.26	0.15	0.14	Yes	

Note: The first three columns display the cosine similarity measure in the space of weighted topics, unweighted topics, and 4-digit IPC codes, respectively. In the pre-period, 65% of CFC substitute patents correspond to NACE code 20.1 (Manufacture of Basic Chemicals, Fertilisers and Nitrogen Compounds, Plastics, and Synthetic Rubber in Primary Forms); 10% NACE code 21 (Manufacture of Basic Pharmaceutical Products and Pharmaceutical Preparations); 5% NACE code 28.29 (Manufacture of Other General-Purpose Machinery). The rest is scattered across many codes.

Table D2: Similarity Summary Statistics for HAPs in Difference in Difference

	IPC Codes	NACE Codes	Unweighted Topics	Weighted Topics
count	27.00	27.00	27.00	27.00
mean	0.38	0.77	0.38	0.46
std	0.16	0.25	0.17	0.22
min	0.05	0.15	0.15	0.14
25%	0.28	0.65	0.24	0.26
50%	0.38	0.87	0.38	0.42
75%	0.47	0.97	0.48	0.62
max	0.71	0.99	0.80	0.88

Table D3: Similarity Summary Statistics for HAPs in the SCM

	IPC Codes	NACE Codes	Unweighted Topics	Weighted Topics
count	30.00	30.00	30.00	30.00
mean	0.60	0.93	0.62	0.68
std	0.16	0.10	0.17	0.15
min	0.32	0.60	0.27	0.37
25%	0.49	0.92	0.48	0.57
50%	0.57	0.98	0.65	0.72
75%	0.73	0.99	0.75	0.82
max	0.87	1.00	0.89	0.88

E Difference-in-Differences

Table E1: Pre-Period Balance Table Between CFC Substitutes and HAPs

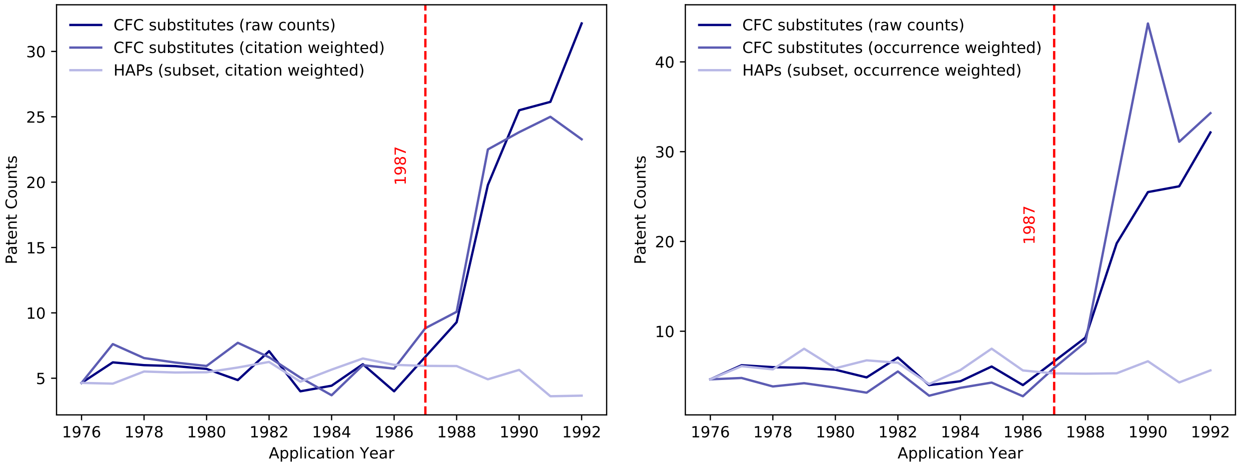
(a) Patents

	HAPs	CFC substitutes	Difference	T-stat
Counts	10.88	5.36	5.52***	(4.47)
Counts (occurrence weighted)	11.75	4.19	7.56***	(5.27)
Counts (citation weighted)	15.53	9.15	6.38***	(3.44)
Counts (3-year citation weighted)	11.47	4.15	7.32***	(4.90)
Topic 1 (w. mean)	0.03	0.02	0.01	(0.98)
Topic 2 (w. mean)	0.04	0.01	0.03*	(2.56)
Topic 3 (w. mean)	0.10	0.02	0.08***	(6.91)
Topic 4 (w. mean)	0.03	0.04	-0.01	(-0.95)
Topic 5 (w. mean)	0.04	0.01	0.03**	(3.21)
Topic 6 (w. mean)	0.11	0.03	0.08***	(5.16)
Topic 7 (w. mean)	0.11	0.37	-0.26***	(-10.41)
Topic 8 (w. mean)	0.08	0.02	0.05***	(3.95)
Topic 9 (w. mean)	0.04	0.01	0.04***	(3.77)
Topic 10 (w. mean)	0.03	0.04	-0.01	(-1.16)
Topic 11 (w. mean)	0.02	0.04	-0.03***	(-3.67)
Topic 12 (w. mean)	0.01	0.01	0.00	(0.80)
Topic 13 (w. mean)	0.06	0.05	0.00	(0.06)
Topic 14 (w. mean)	0.12	0.02	0.10***	(5.41)
Topic 15 (w. mean)	0.01	0.01	-0.00	(-0.40)
Topic 16 (w. mean)	0.06	0.10	-0.03*	(-2.14)
Topic 17 (w. mean)	0.02	0.01	0.00	(0.38)
Topic 18 (w. mean)	0.04	0.00	0.03**	(3.22)
Topic 19 (w. mean)	0.02	0.07	-0.05***	(-7.30)
Topic 20 (w. mean)	0.04	0.12	-0.07***	(-4.86)

(b) Articles

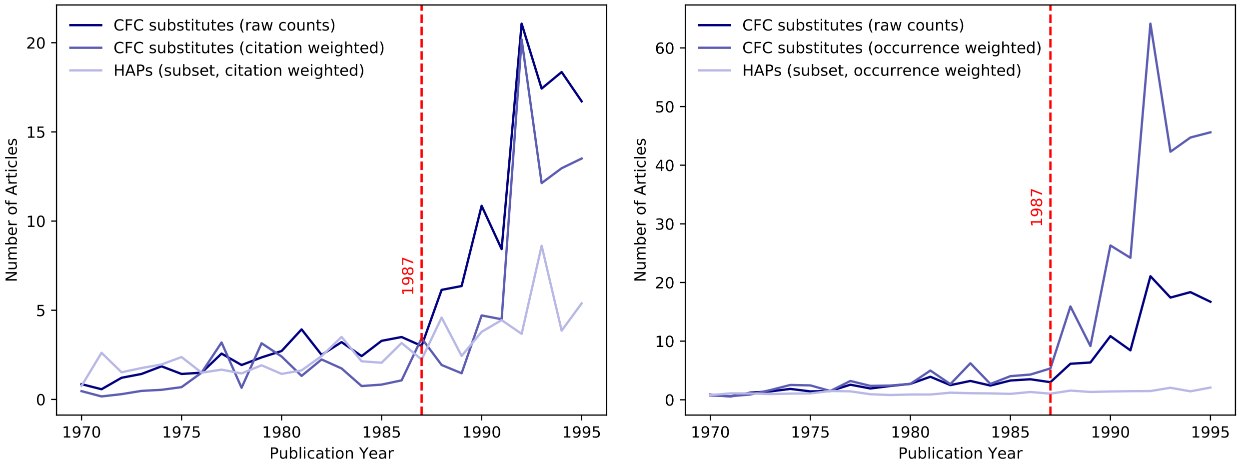
	HAPs	CFC substitutes	Difference	T-stat
Count	5.98	2.19	3.79***	(8.48)
Counts (occurrence weighted)	6.17	1.18	4.99***	(9.56)
Counts (citation weigh)	5.39	2.17	3.22***	(3.79)
Topic 1 (w. mean)	0.03	0.01	0.02***	(4.50)
Topic 2 (w. mean)	0.02	0.07	-0.04***	(-4.97)
Topic 3 (w. mean)	0.02	0.10	-0.08***	(-8.67)
Topic 4 (w. mean)	0.13	0.11	0.03	(1.36)
Topic 5 (w. mean)	0.05	0.06	-0.01	(-0.89)
Topic 6 (w. mean)	0.04	0.18	-0.13***	(-11.95)
Topic 7 (w. mean)	0.04	0.09	-0.05***	(-4.28)
Topic 8 (w. mean)	0.03	0.01	0.02***	(3.94)
Topic 9 (w. mean)	0.19	0.05	0.14***	(5.71)
Topic 10 (w. mean)	0.07	0.03	0.04***	(3.44)
Topic 11 (w. mean)	0.03	0.14	-0.11***	(-11.35)
Topic 12 (w. mean)	0.14	0.03	0.11***	(6.61)
Topic 13 (w. mean)	0.13	0.03	0.10***	(5.14)
Topic 14 (w. mean)	0.02	0.03	-0.01	(-1.19)
Topic 15 (w. mean)	0.05	0.07	-0.02*	(-2.01)

Note: The table displays the pre-period mean of outcome variables and topic proportions for patents and articles for CFC substitutes and for HAPs selected in the DiD sample.



(a) Patent Citation Weighted Counts

(b) Patent Occurrence Weighted Counts



(c) Article Citation Weighted Counts

(d) Article Occurrence Weighted Counts

Figure E1: Time Series of Citation- and Occurrence-Weighted Counts

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

Table E2: Difference-in-Differences Robustness Checks

(a) Patents

	(1) Count	(2) Count	(3) Cit	(4) Occ	(5) Cit-Occ
Post 1987 x Substitutes	21.12 (2.06)	13.00 (1.71)	29.85 (3.38)	33.45 (3.79)	44.91 (6.70)
Count (lag 1)		0.39 (0.07)			
Count (lag 2)		0.27 (0.07)			
Year FE	Yes	Yes	Yes	Yes	Yes
Molecule FE	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	Yes	Yes	Yes	Yes	Yes
Bootstraped	Yes	Yes	Yes	Yes	Yes
R-squared	0.86	0.90	0.78	0.70	0.66
Observations	595	528	595	595	595

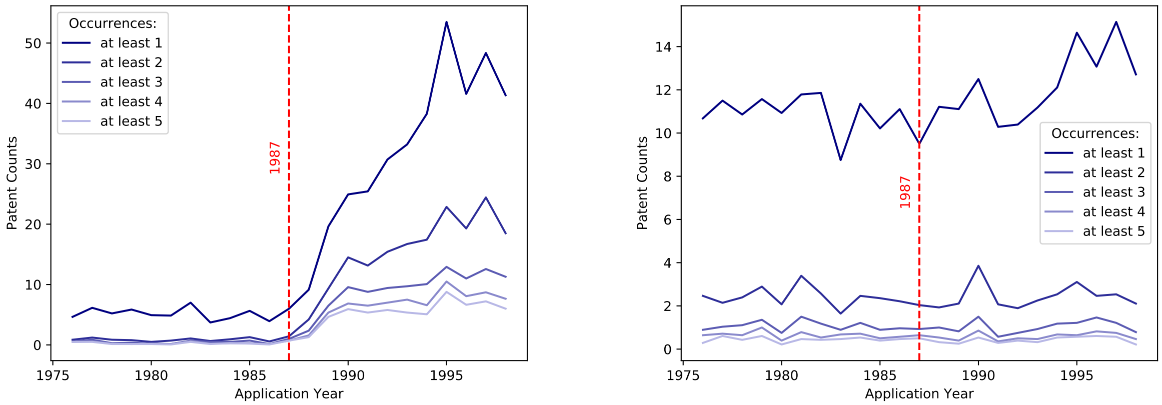
Bootstrapped standard errors in parentheses. Time period: 1976 to 1992

(b) Articles

	(1) Count	(2) Count	(3) Cit	(4) Occ	(5) Cit-Occ
Post 1987 x Substitutes	12.63 (1.69)	5.10 (1.25)	12.22 (3.38)	17.62 (2.71)	18.11 (4.43)
Count (lag 1)		0.34 (0.05)			
Count (lag 2)		0.34 (0.08)			
Year FE	Yes	Yes	Yes	Yes	Yes
Molecule FE	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	Yes	Yes	Yes	Yes	Yes
Bootstraped	Yes	Yes	Yes	Yes	Yes
R-squared	0.64	0.75	0.34	0.49	0.37
Observations	846	790	846	846	846

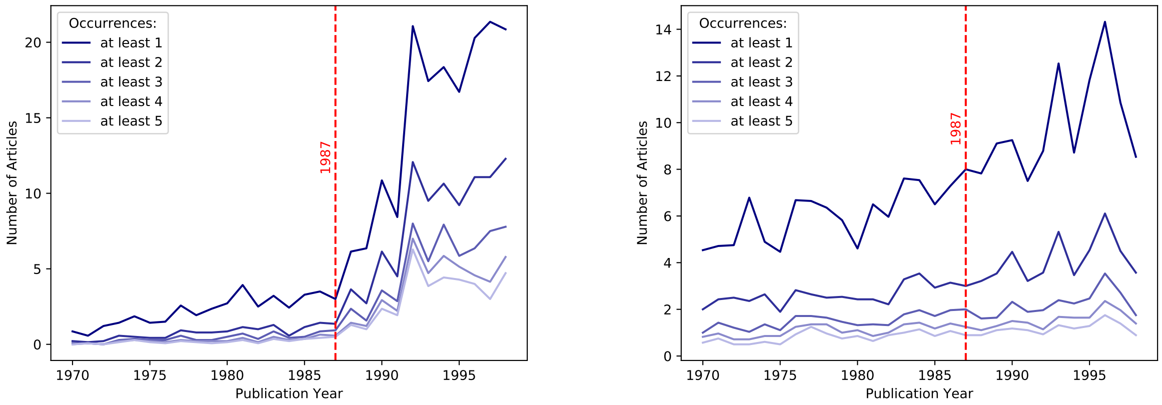
Standard errors in parentheses. Time period: 1970 to 1995

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



(a) Patents - CFC Substitutes

(b) Patents - HAPs



(c) Articles - CFC Substitutes

(d) Articles - HAPs

Figure E2: Robustness Check: Counts with Several Thresholds of Molecule Occurrences

Note: The graphs illustrate that the differential trends CFC substitutes and HAPs are not affected by adopting more stringent definition of what constitutes a document “about CFC substitutes”.

Table E3: Difference-in-Differences with Triadic Patents Only

	(1)	(2)
Post 1987 x Substitutes	9.47	3.37
	(1.13)	(1.99)
Post 1987 x Substitutes x Years		2.81
		(0.64)
Substitutes x Years		-0.28
		(0.12)
Years		0.58
		(0.06)
Post 1987		-1.56
		(0.55)
Year FE	Yes	No
Molecule FE	Yes	Yes
R-squared	0.71	0.72
Observations	714	714

Standard errors in parentheses.
Dependent variable: Number of Triadic Patents.
Variable ’Years’ is relative to 1987.
Time period: 1976 to 1992

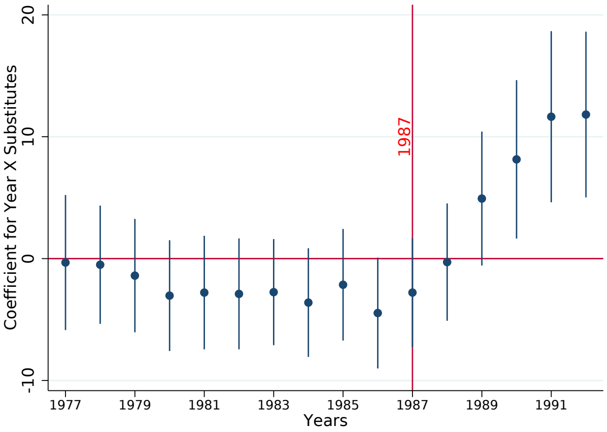


Table E4: Difference-in-Differences with PPML Regressions

(a) Patents

	(1) Count	(2) Count	(3) Count	(4) Count	(5) Count	(6) Cit	(7) Occ	(8) Cit-Occ
Post 1987 x Substitutes	1.37	1.22	0.57	0.48	0.96	1.22	1.70	1.74
	(0.13)	(0.12)	(0.24)	(0.20)	(0.12)	(0.13)	(0.15)	(0.16)
Post 1987 x Substitutes x Years			0.24	0.25				
			(0.06)	(0.05)				
Substitutes x Years			0.00	-0.01				
			(0.03)	(0.02)				
Years			-0.01	-0.01				
			(0.01)	(0.01)				
Post 1987			0.11	0.07				
			(0.06)	(0.07)				
Count (lag 1)					0.01			
					(0.00)			
Count (lag 2)					0.01			
					(0.00)			
Topics (weighted)	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Av. Marginal Effects	14.82	15.91	2.61	3.25	12.78	22.51	23.58	33.04
	(1.50)	(1.61)	(0.66)	(0.64)	(1.59)	(2.44)	(2.20)	(3.47)
Molecule FEs	X	X	X	X	X	X	X	X
Year FEs	X	X			X	X	X	X
Pseudo R-squared	0.71	0.68	0.71	0.68	0.69	0.65	0.70	0.66
Observations	714	594	714	594	527	594	594	594

Poisson pseudo-maximum likelihood.
Robust standard errors in parentheses.
Dependent variable: Number of Patents.
Time period: 1976 to 1992

(b) Articles

	(1) Count	(2) Count	(3) Count	(4) Count	(5) Count	(6) Cit	(7) Occ	(8) Cit-Occ
Post 1987 x Substitutes	1.33	0.85	0.41	0.08	0.52	0.62	1.49	1.16
	(0.12)	(0.11)	(0.21)	(0.19)	(0.12)	(0.23)	(0.14)	(0.24)
Post 1987 x Substitutes x Years			0.08	0.09				
			(0.03)	(0.03)				
Substitutes x Years			0.04	0.03				
			(0.02)	(0.01)				
Years			0.03	0.03				
			(0.00)	(0.01)				
Post 1987			0.07	0.07				
			(0.06)	(0.06)				
Count (lag 1)					0.01			
					(0.00)			
Count (lag 2)					0.01			
					(0.00)			
Topics (weighted)	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Av. Marginal Effects	8.82	7.29	0.55	0.78	4.60	5.57	12.64	10.38
	(0.79)	(0.96)	(0.21)	(0.24)	(1.03)	(2.11)	(1.24)	(2.17)
Molecule FEs	X	X	X	X	X	X	X	X
Year FEs	X	X			X	X	X	X
Pseudo R-squared	0.58	0.49	0.58	0.48	0.49	0.43	0.49	0.46
Observations	1092	846	1092	846	790	846	846	846

Poisson pseudo-maximum likelihood.
Robust standard errors in parentheses.
Dependent variable: Number of Articles.
Time period: 1976 to 1995

Table E5: Difference-in-Differences Results Using All HAPs (log)

	(1) Patents	(2) Patents	(3) Patents	(4) Patents	(5) Patents	(6) Articles	(7) Articles	(8) Articles	(9) Articles	(10) Articles
Post 1987 x Substitutes	1.49	1.52	1.54	0.34	0.70	0.70	0.74	0.59	0.33	0.10
	(0.11)	(0.09)	(0.09)	(0.22)	(0.14)	(0.10)	(0.10)	(0.11)	(0.16)	(0.22)
Post 1987 x Substitutes x Years				0.35	0.27				0.19	0.18
				(0.07)	(0.04)				(0.04)	(0.03)
Substitutes x Years				0.01	0.00				-0.03	-0.02
				(0.01)	(0.01)				(0.01)	(0.01)
Years				-0.01	-0.01				0.05	0.05
				(0.00)	(0.00)				(0.00)	(0.00)
Post 1987				0.15	0.14				-0.05	-0.01
				(0.02)	(0.02)				(0.02)	(0.02)
Year FEs	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	No
Molecule FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	No	No	Yes	No	Yes	No	No	Yes	No	Yes
Bootstraped SE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.97	0.98	0.98	0.98	0.98	0.96	0.96	0.96	0.96	0.96
Observations	3145	3018	3018	3145	3018	4625	4359	4359	4625	4359

Standard errors in parentheses. Variable 'Years' is relative to 1987.
Time period: 1976-1992 for patents; 1970-1995 for articles

Note: The table presents OLS regression results for difference-in-difference specifications using all HAPs in the control (171 HAPs in total). The outcome variable is the log of Count + 1.

Table E6: Difference-in-Differences Results Using All HAPs (PPML)

	(1) Patents	(2) Patents	(3) Patents	(4) Articles	(5) Articles	(6) Articles
Post 1987 x Substitutes	1.36	1.21	1.22	1.14	0.82	0.70
	(0.13)	(0.12)	(0.13)	(0.11)	(0.10)	(0.10)
Topics (weighted)	No	No	Yes	No	No	Yes
Molecule FEs	X	X	X	X	X	X
Year FEs	X	X	X	X	X	X
Pseudo R-squared	0.99	0.99	0.99	0.98	0.98	0.98
Observations	3145	3017	3017	4625	4358	4358

Poisson pseudo-maximum likelihood.
Robust standard errors in parentheses.
Time period: 1976-1992 for patents; 1970-1995 for articles

Note: The table presents PPML regression results for difference-in-difference specifications using all HAPs in the control (171 HAPs in total)

Table E7: Patents - Difference-in-Differences - By Consumer Exposure

	(1) Counts	(2) Counts	(3) Counts	(4) Counts	(5) Counts	(6) Counts
Post 1987 x Substitutes	16.54 (1.74)	21.12 (2.06)	28.42 (3.78)	30.57 (5.21)	24.60 (3.30)	29.45 (5.09)
Post 1987 x Substitutes x Exposed					7.63 (3.63)	1.65 (3.60)
Exposed					3.17 (2.66)	24.91 (8.20)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Molecule FE	Yes	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	No	Yes	No	Yes	No	Yes
Bootstraped	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.84	0.86	0.84	0.88	0.85	0.88
Observations	714	595	204	148	204	148

Standard errors in parentheses
Bootstrapped standard errors in parentheses.
Dependent variable: Number of Patents.
Variable 'Years' is relative to 1987.
Time period: 1976 to 1992

Note: The table presents Difference-in-Differences regression results with an interaction term to examine heterogeneity based on whether the CFC substitute was consumer exposed or not. Columns 1 and 2 reproduce the results from the main table in the paper (Table 2). Columns 3 and 4 replicate the same specifications but exclude two CFC substitutes which could not be classified with certainty as either exposed or not exposed (HCFC 141b and HFC 245fa). Columns 5 and 6 use the same sample as Columns 3 and 4 but include an interaction term with the binary variable "Exposed," where 1 indicates CFC substitutes with uses targeting applications exposed to consumers, and 0 indicates those that do not. Column 5 shows that the coefficient for the interaction is positive and statistically significant, suggesting that the induced innovation response was stronger for consumer-exposed CFC substitutes. However, after controlling for topic modeling, the coefficient becomes insignificant, indicating that other molecule-level characteristics (possibly the types of industrial applications, or the thermodynamic or safety profiles) may explain why consumer-exposed molecules show a stronger response. Since there is no quasi-random variation in the assignment of consumer exposure status, a causal interpretation for the interaction with the binary variable "Exposed" is not feasible.

F Synthetic Control Method

F1 Theoretical Foundations

Here, I briefly summarize the theoretical underpinnings of the synthetic control method. 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 1 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 synthetic control method allows the effects of confounding unobserved characteristics to vary with time; taking time differences would not get us rid of μ_i.

$$Y_{it}^N = \delta_t + \theta_t Z_i + \lambda_t \mu_i + \varepsilon_{it} \tag{1}$$

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} ... Y_{1T_0} is a way of indirectly 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.

F2 Figures and Tables

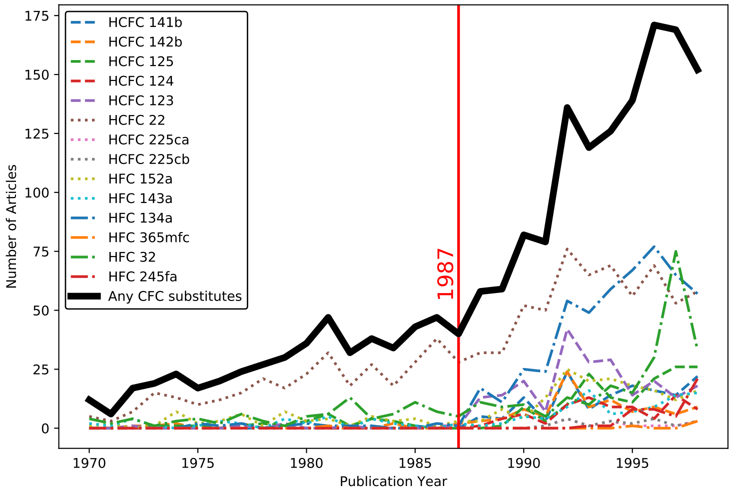


Figure F1: Article Counts for CFC Substitute, Individually and Aggregated

Note: The graph illustrates the difference between considering the 14 molecules independently and considering them as one treated molecule. The thick line called ”Any CFC substitutes” corresponds to the number of articles mentioning any of the 14 CFC substitutes.

Table F1: Synthetic Control Method Extrapolation Check

(a) Patents

Variables (pre-1986 average)	Substitutes	HAPs Mean	HAPs Min	HAPs Max	HAPs Std.Dev.
Count	34.36	59	36.45	87.55	19.19
Topic 1 (weighted mean)	0.01	0.04	0.01	0.1	0.03
Topic 2 (weighted mean)	0.14	0.04	0	0.19	0.05
Topic 3 (weighted mean)	0.07	0.08	0.01	0.18	0.04
Topic 4 (weighted mean)	0.08	0.01	0	0.03	0.01
Topic 5 (weighted mean)	0.03	0.02	0	0.08	0.02
Topic 6 (weighted mean)	0.26	0.06	0.01	0.14	0.04
Topic 7 (weighted mean)	0.07	0.19	0.01	0.74	0.21
Topic 8 (weighted mean)	0.01	0.09	0	0.33	0.09
Topic 9 (weighted mean)	0.05	0.03	0	0.09	0.03
Topic 10 (weighted mean)	0.02	0.02	0	0.1	0.02
Topic 11 (weighted mean)	0.09	0.04	0	0.2	0.04
Topic 12 (weighted mean)	0.04	0.01	0	0.03	0.01
Topic 13 (weighted mean)	0.04	0.06	0.01	0.3	0.07
Topic 14 (weighted mean)	0.04	0.04	0.01	0.11	0.03
Topic 15 (weighted mean)	0.04	0.01	0	0.04	0.01
Topic 16 (weighted mean)	NaN	0.08	0.02	0.23	0.06
Topic 17 (weighted mean)	NaN	0.01	0	0.02	0.01
Topic 18 (weighted mean)	NaN	0.02	0	0.07	0.02
Topic 19 (weighted mean)	NaN	0.02	0	0.07	0.02
Topic 20 (weighted mean)	NaN	0.14	0.02	0.57	0.16

(b) Articles

Variables (pre-1986 average)	Substitutes	HAPs Mean	HAPs Min	HAPs Max	HAPs Std.Dev.
Count	34.36	31.38	22.27	41.82	4.85
Topic 1 (weighted mean)	0.01	0.04	0.01	0.11	0.03
Topic 2 (weighted mean)	0.14	0.03	0.01	0.07	0.02
Topic 3 (weighted mean)	0.07	0.02	0	0.1	0.02
Topic 4 (weighted mean)	0.08	0.1	0.02	0.31	0.08
Topic 5 (weighted mean)	0.03	0.04	0	0.13	0.04
Topic 6 (weighted mean)	0.26	0.05	0.01	0.18	0.05
Topic 7 (weighted mean)	0.07	0.04	0	0.24	0.05
Topic 8 (weighted mean)	0.01	0.03	0	0.08	0.02
Topic 9 (weighted mean)	0.05	0.13	0.03	0.45	0.13
Topic 10 (weighted mean)	0.02	0.08	0.01	0.25	0.07
Topic 11 (weighted mean)	0.09	0.03	0	0.08	0.02
Topic 12 (weighted mean)	0.04	0.13	0.04	0.32	0.07
Topic 13 (weighted mean)	0.04	0.16	0.01	0.49	0.15
Topic 14 (weighted mean)	0.04	0.06	0.01	0.29	0.07
Topic 15 (weighted mean)	0.04	0.05	0	0.14	0.04

Note: The table displays summary statistics for the aggregated CFC substitutes and HAPs for patents. We note that the range of values displayed by the HAPs always contains the value for CFC substitutes. Hence, the constraints that weights must sum to 1 and be non-negative does not seem to be an issue. Such constraint is imposed by the synthetic control method algorithm to avoid extrapolation.

Table F2: HAPs Contributing to the Synthetic Control

(a) Patents

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

(b) Articles

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

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

Table F3: Variable Weights Used in the Construction of the Synthetic Control

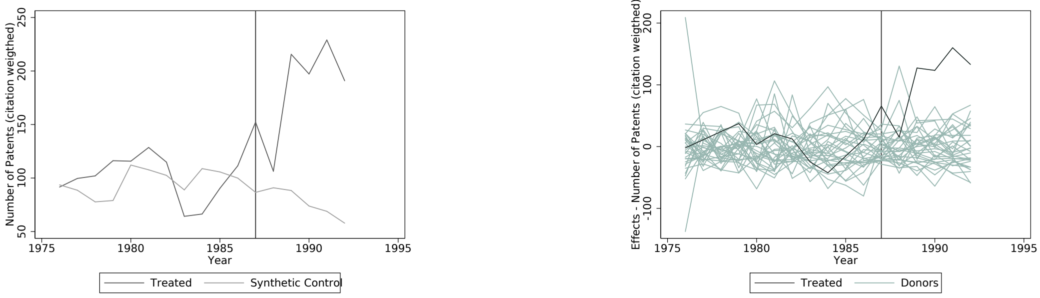
(a) Patents

	Variable Weight
Topic 1	0.02
Topic 2	0.04
Topic 3	0.05
Topic 4	0.10
Topic 5	0.03
Topic 6	0.02
Topic 7	0.10
Topic 8	0.04
Topic 9	0.01
Topic 10	0.03
Topic 11	0.01
Topic 12	0.04
Topic 13	0.03
Topic 14	0.04
Topic 15	0.02
Topic 16	0.01
Topic 17	0.02
Topic 18	0.08
Topic 19	0.27
Topic 20	0.01
Count	0.02

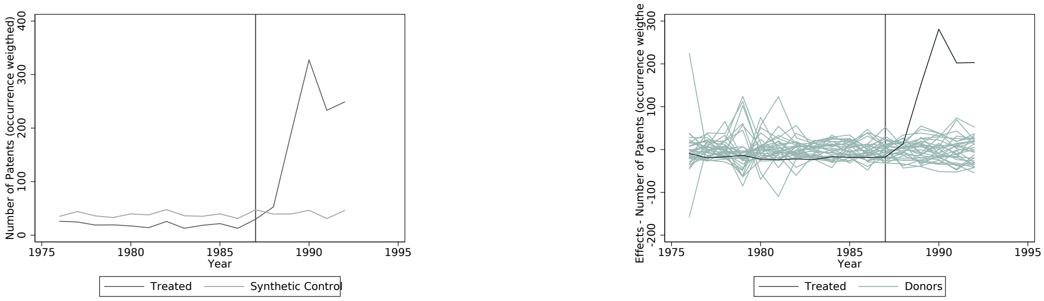
(b) Articles

	Variable Weight
Topic 1	0.06
Topic 2	0.06
Topic 3	0.07
Topic 4	0.07
Topic 5	0.06
Topic 6	0.07
Topic 7	0.02
Topic 8	0.05
Topic 9	0.02
Topic 10	0.07
Topic 11	0.13
Topic 12	0.05
Topic 13	0.12
Topic 14	0.04
Topic 15	0.07
Count	0.05

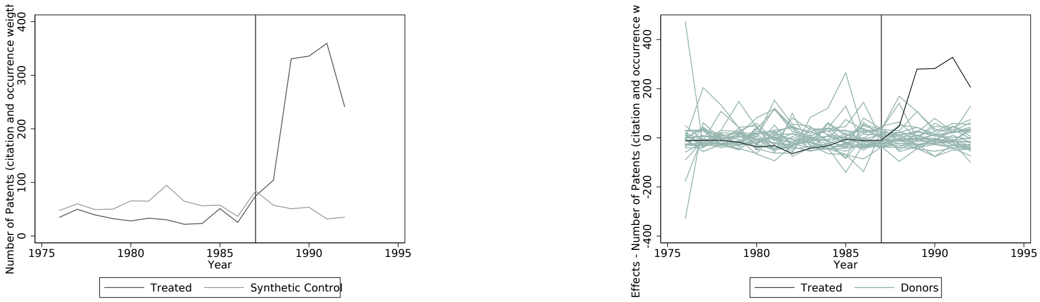
Note: The table displays the value of each variable's contribution to the synthetic control. We note that topic 19, 4 and 7 contribute the most for patents, and topic 11 and 13 for articles. This indicate that these topics had the highest correlations with the outcome variable. In the Stata *synth* package, these weights are determined according to the amount of predictive power that each variable has over the outcome.



(a) Citation Weighted



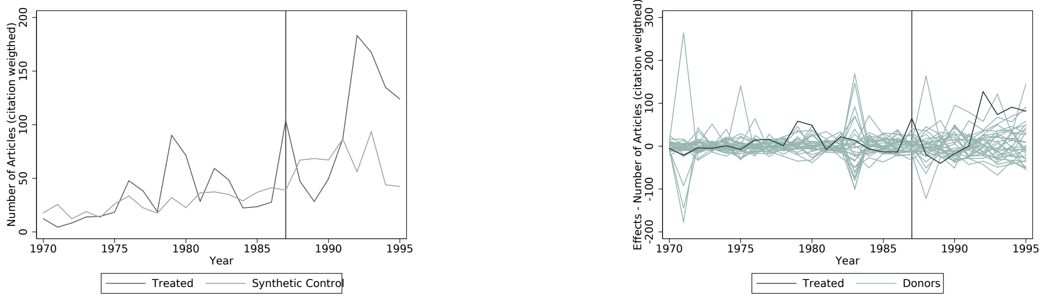
(b) Occurrence Weighted



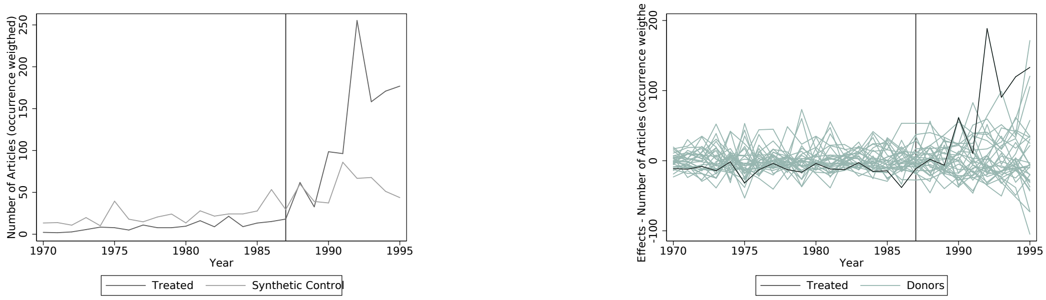
(c) Occurrence and Citation Weighted

Figure F2: Robustness Check for Patents: Synthetic Control Method with Counts Weighted by Occurrences and Citations

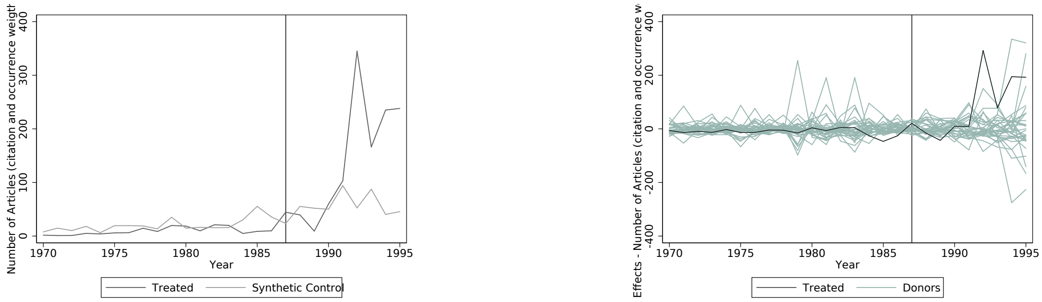
Note: These figures show that implementing the synthetic Control method using patent counts weighted by molecule occurences and patent citation does not alter the main conclusions.



(a) Citation Weighted



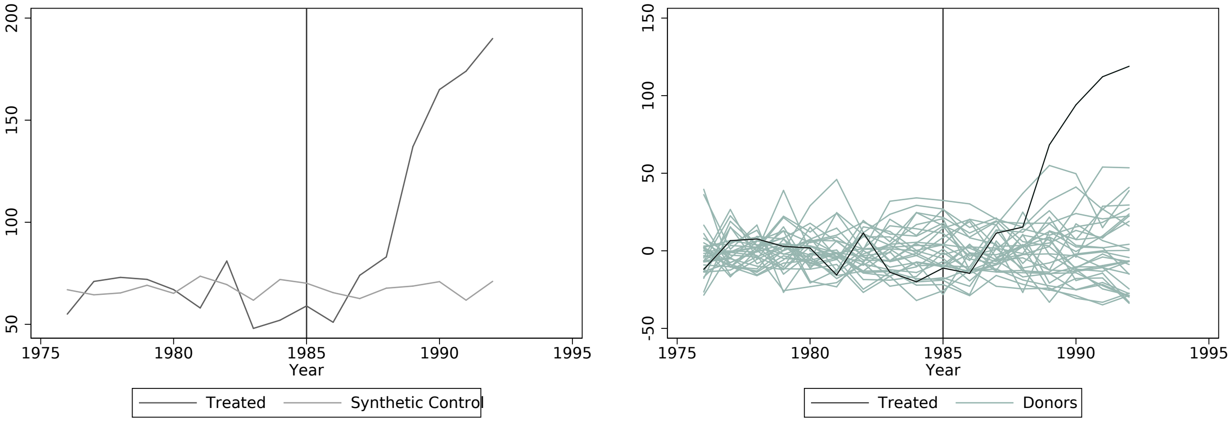
(b) Occurrence Weighted



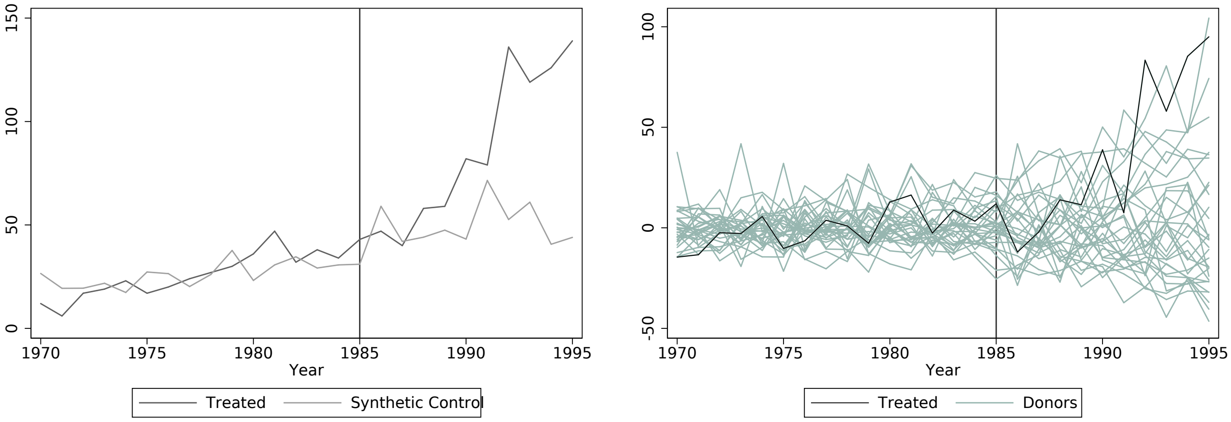
(c) Occurrence and Citation Weighted

Figure F3: Robustness Check for Patents: Synthetic Control Method with Counts Weighted by Occurrences and Citations

Note: These figures show that implementing the synthetic sontrol method using article counts weighted by molecule occurences and article citation does not alter the main conclusions.



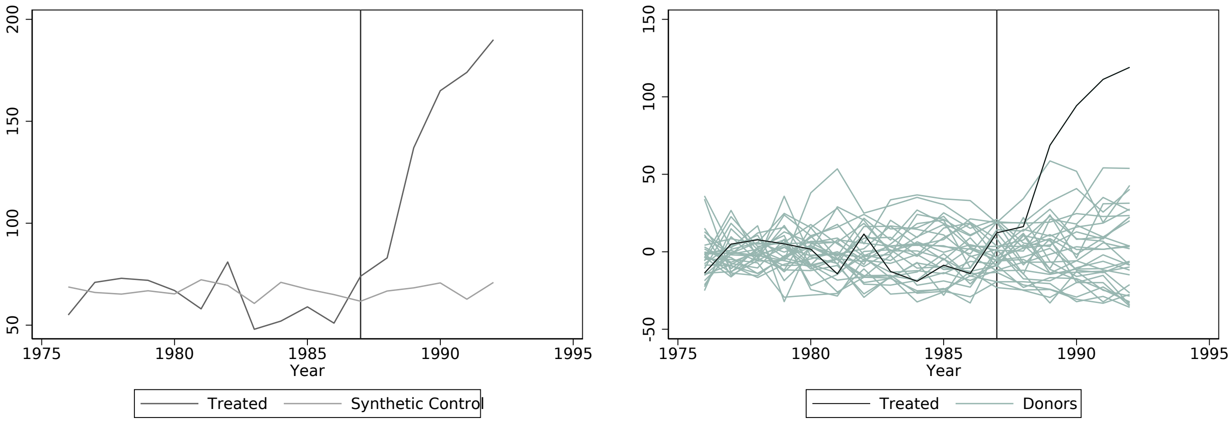
(a) Patents: Raw Effect (left) and Placebo Tests (right)



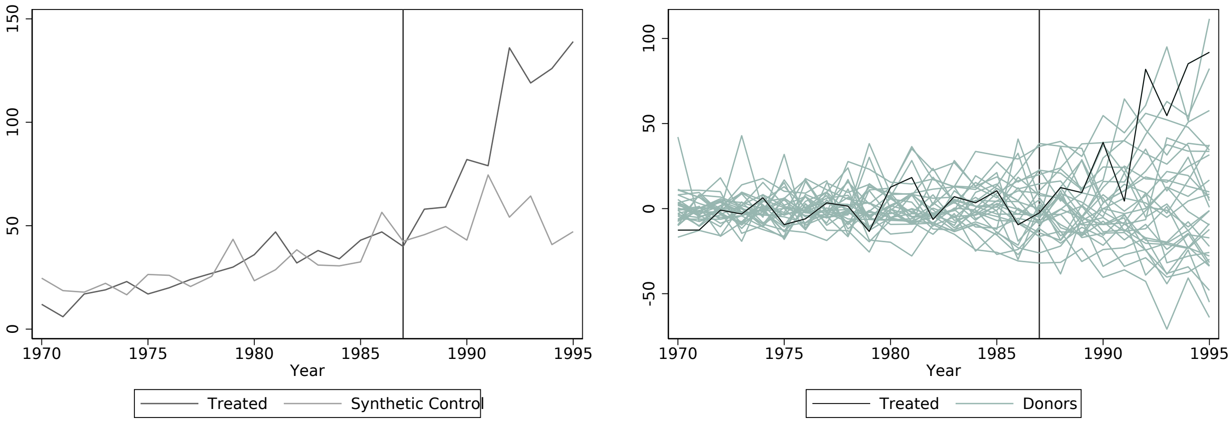
(b) Articles: Raw Effect (left) and Placebo Tests (right)

Figure F4: Synthetic Control Method Graphs for CFC Substitutes Assuming Anticipation

Note: These figures show that implementing the synthetic control method using years only up to 1982 does not alter the main conclusions.



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



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

Figure F5: Synthetic Control Method Graphs for CFC Substitutes Using Only First Part of Pre-Period

Note: These figures show that implementing the synthetic control method using years only up to 1980 for aptents and 1978 for articles does not alter the main conclusions.

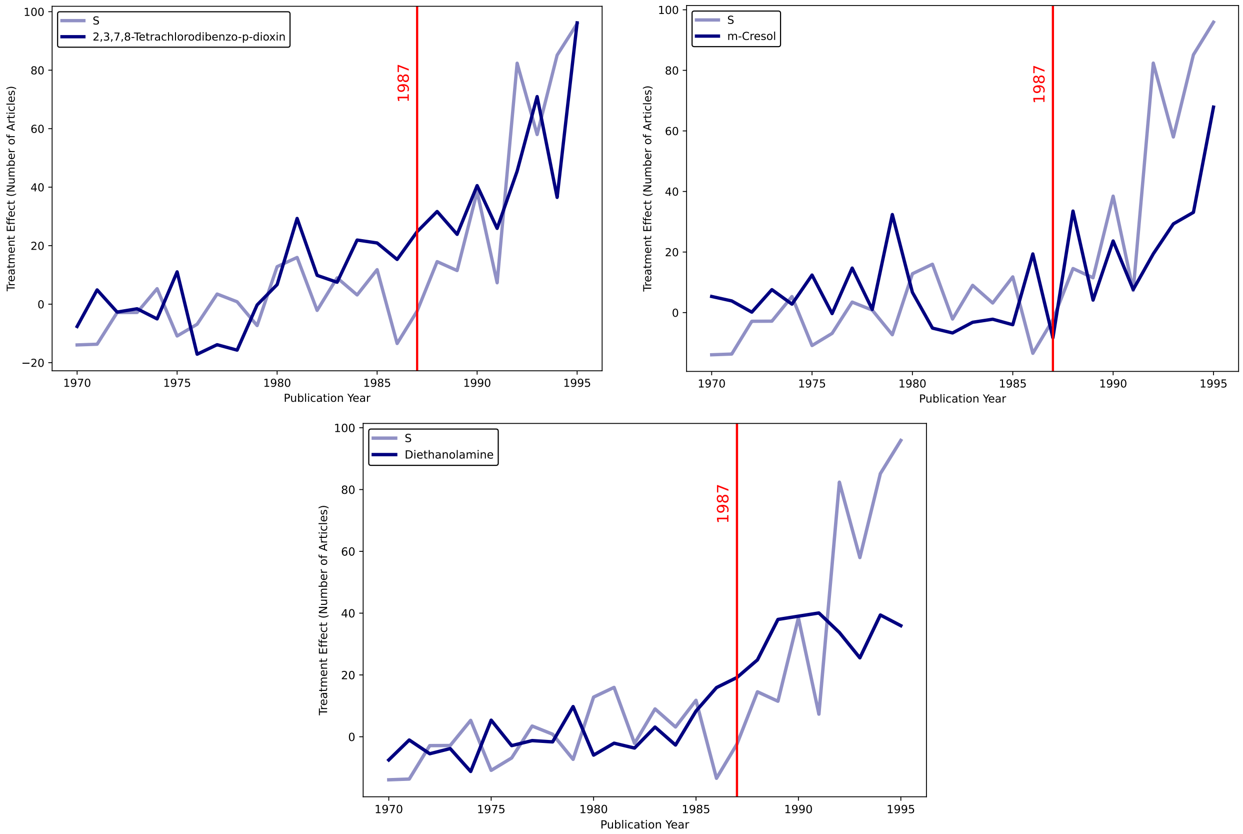


Figure F6: HAPs with High Placebo Treatment Effects

Note: More information about each of these HAPs is provided below.

2,3,7,8-Tetrachlorodibenzo-p-dioxin (a.k.a. TCDD). This is the HAP that stands out the most. TCDD has quite a high post-1990 increase but also quite a substantial pre-trend. The number of articles seems to increase throughout the 1980s and 1990s; it does not look like something specific to 1987.

TCDD is a highly toxic dioxin that can be found in some herbicides, which were banned in the U.S. in 1985 due to their harmful effects. This chemical is a by-product of the herbicide synthesis process and has been linked to a range of health problems in humans and animals, including cancer, reproductive and developmental issues, and immune system dysfunction. In addition, TCDD is infamous for being the key toxic contaminant in Agent Orange, a herbicide used by the U.S. military during the Vietnam War to defoliate forests and crops.

The United States Department of Agriculture stopped the use of TCDD on all food crops except rice in 1970, and in 1985 the EPA banned all remaining use and manufacture in the U.S. The 1998 Rotterdam Convention also restricts international trade of TCDD.

Due to the highly toxic and persistent nature of TCDD, contamination and exposure incidents have been reported over the years, with lasting impacts. This may explain why there is a higher trend in research publications on TCDD compared to other HAPs.

One of the most significant TCDD-related incidents was the Seveso disaster in Italy in 1976. This disaster occurred when a reactor at a chemical plant in the town of Seveso overheated, releasing a cloud of toxic gas that contaminated a large area and affected the health of thousands of people, causing significant environmental damage.

Another well-known incident is the Times Beach incident in Missouri, USA. In 1971, the town of Times Beach was contaminated with TCDD after waste oil sprayed on its dirt roads was found to be contaminated with the chemical. The town was evacuated, and the contaminated soil was incinerated.

m-Cresol. The treatment effect in article counts for m-Cresol seems to increase significantly after 1992. M-cresol is a toxic compound typically present at low concentrations in various environmental media, including air, car exhaust, wood, and coal. It was first registered as a pesticide in the U.S. in 1980 and is also used as an intermediate for producing many products. It has also seen an increasing number of niche applications, and its market size is still growing.

Exposure to m-cresol can be harmful to human health, especially if it occurs at high levels. Inhalation of m-cresol vapors can cause respiratory irritation while ingesting the compound can cause nausea, vomiting, and abdominal pain. In addition, long-term exposure to m-cresol has been associated with kidney and liver damage, skin irritation and sensitization.

Diethanolamine (DEA). The trend for DEA starts around 1985. This may not be a coincidence since concerns about DEA's potential health risks began to emerge in the 1980s. In 1984, the International Agency for Research on Cancer classified DEA as a Group 2B carcinogen. Following this classification, there was increased scrutiny of the use of DEA in personal care products, and some companies began to reformulate their products to remove DEA and other potentially harmful ingredients.

G Descriptives and Mechanisms

G1 Describing CFC Substitutes Patents and Articles

Table G1: Five Most Common Patent Codes for Patents Mentioning CFC Substitutes

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

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

Table G2: Titles of the Five Most Cited Patents Mentioning CFC Substitutes

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

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

G2 Firm-Level Descriptives

Table G3: Titles of the Five Most Cited Articles Mentioning CFC Substitutes

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

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

Table G4: Summary Statistics for Documents Mentioning CFC substitutes

(a) Patents

	count	mean	sd	min	max
Occurrences	3437	6.17	11.32	1.00	187.00
Citations	3273	9.25	13.23	0.00	153.00
USA	3179	0.59	0.49	0.00	1.00
UK	3179	0.05	0.22	0.00	1.00
Japan	3179	0.19	0.39	0.00	1.00
Canada	3179	0.00	0.07	0.00	1.00
France	3179	0.03	0.17	0.00	1.00
Germany	3179	0.09	0.28	0.00	1.00
Italy	3179	0.01	0.11	0.00	1.00
Europe	3179	0.21	0.41	0.00	1.00
Education	3140	0.03	0.16	0.00	1.00
Company	3140	0.96	0.19	0.00	1.00
Government	3140	0.00	0.07	0.00	1.00
Facilities	3140	0.00	0.07	0.00	1.00
Non Profit	3140	0.00	0.00	0.00	0.00
Healthcare	3140	0.00	0.00	0.00	0.00

(b) Articles

	count	mean	sd	min	max
Occurrences	1926	7.18	16.53	1.00	222.00
Citations	926	31.74	70.58	0.00	1298.00
USA	892	0.37	0.48	0.00	1.00
Japan	892	0.09	0.29	0.00	1.00
UK	892	0.10	0.31	0.00	1.00
Germany	892	0.08	0.28	0.00	1.00
France	892	0.05	0.22	0.00	1.00
Italy	892	0.05	0.22	0.00	1.00
Canada	892	0.05	0.22	0.00	1.00
India	892	0.03	0.17	0.00	1.00
Netherlands	892	0.04	0.19	0.00	1.00
Spain	892	0.01	0.11	0.00	1.00
Europe	892	0.38	0.49	0.00	1.00
Education	893	0.68	0.47	0.00	1.00
Company	893	0.13	0.34	0.00	1.00
Government	893	0.09	0.29	0.00	1.00
Facilities	893	0.15	0.36	0.00	1.00
Non Profit	893	0.04	0.19	0.00	1.00
Healthcare	893	0.02	0.14	0.00	1.00

Note: "Occurrences" capture the number of time any relevant molecule is mentioned in the document. "Facilities" encompass building or facilities researching specific areas and usually containing specific equipment (e.g., a nuclear plant). "Healthcare" corresponds to institutions were patients are treated (e.g. hospitals). See Section 3 for more details about country and affiliation data.

Table G5: Summary Statistics for Documents Mentioning CFC Substitutes Before and After 1987

(a) Patents

	Before	After	Difference	T-stat
Occurrences	1.87	7.66	-5.80***	(-13.46)
Citations	14.99	7.59	7.40***	(13.74)
USA	0.59	0.59	0.00	(0.09)
UK	0.02	0.06	-0.04***	(-4.46)
Japan	0.12	0.21	-0.09***	(-5.55)
Canada	0.01	0.00	0.00	(0.95)
France	0.04	0.03	0.01	(1.30)
Germany	0.19	0.05	0.14***	(12.12)
Italy	0.01	0.02	-0.01*	(-2.24)
Europe	0.27	0.19	0.08***	(4.78)
Education	0.02	0.03	-0.01	(-1.86)
Company	0.97	0.96	0.01	(0.77)
Government	0.01	0.00	0.01***	(4.41)
Facilities	0.00	0.01	-0.01*	(-2.14)
Non Profit	0.00	0.00	0.00	(.)
Healthcare	0.00	0.00	0.00	(.)

(b) Articles

	Before	After	Difference	T-stat
Occurrences	2.41	8.91	-6.50***	(-7.74)
Citations	31.80	31.71	0.09	(0.02)
USA	0.43	0.34	0.09**	(2.69)
Japan	0.04	0.12	-0.08***	(-3.99)
UK	0.13	0.09	0.04	(1.84)
Germany	0.06	0.10	-0.04*	(-2.17)
France	0.07	0.04	0.02	(1.58)
Italy	0.02	0.06	-0.04**	(-2.66)
Canada	0.08	0.03	0.05***	(3.55)
India	0.04	0.02	0.01	(1.02)
Netherlands	0.04	0.04	-0.01	(-0.38)
Spain	0.00	0.02	-0.02*	(-2.31)
Europe	0.37	0.39	-0.02	(-0.53)
Education	0.67	0.69	-0.02	(-0.61)
Company	0.10	0.15	-0.05	(-1.91)
Government	0.06	0.10	-0.04*	(-2.10)
Facilities	0.17	0.15	0.02	(0.89)
Non Profit	0.05	0.03	0.02	(1.22)
Healthcare	0.02	0.02	0.01	(0.60)

Note: "Occurrences" capture the number of time any relevant molecule is mentioned in the document. "Facilities" encompass building or facilities researching specific areas and usually containing specific equipment (e.g., a nuclear plant). "Healthcare" corresponds to institutions were patients are treated (e.g. hospitals). See Section 3 for more details about country and affiliation data.

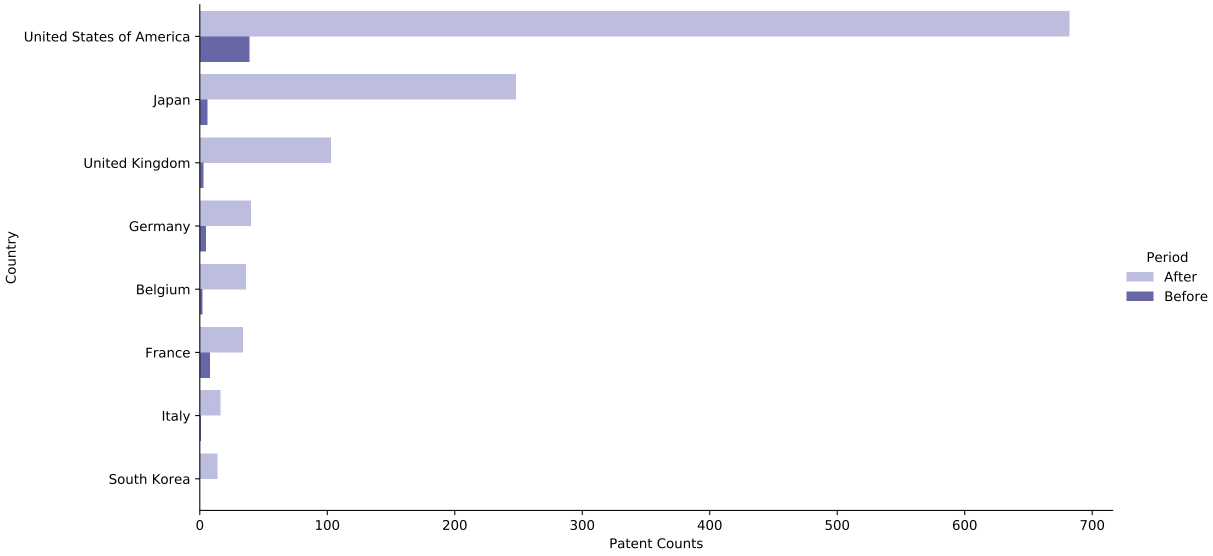


Figure G1: Patent Counts by Country Before and After 1987

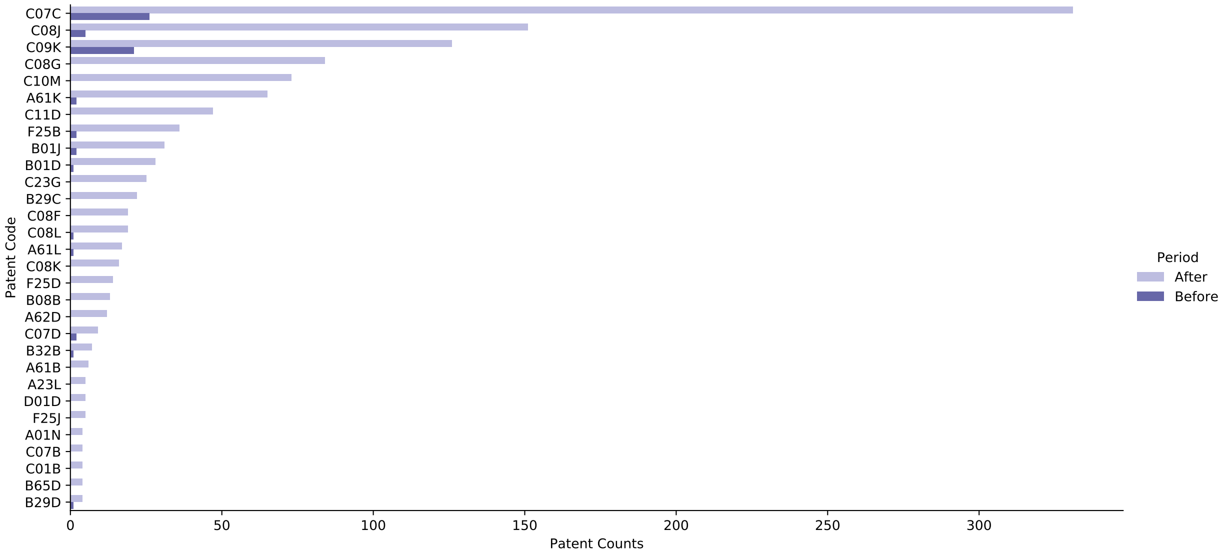
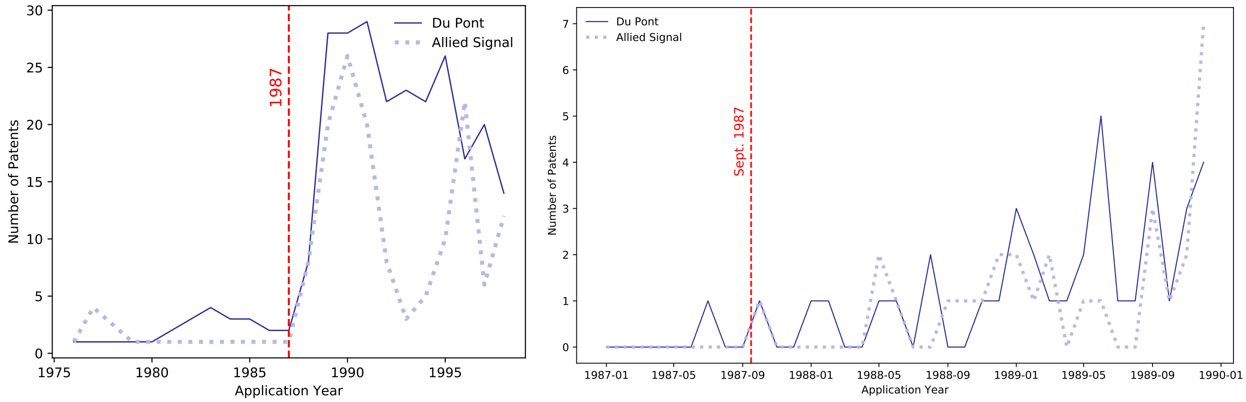


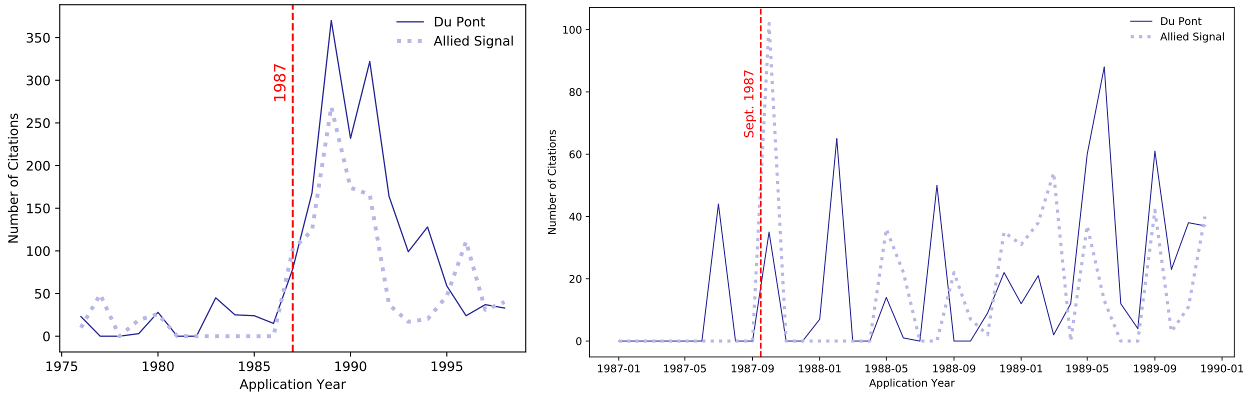
Figure G2: Most Frequent Codes for Patents Mentioning CFC Susbtitutes Before and After 1987

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



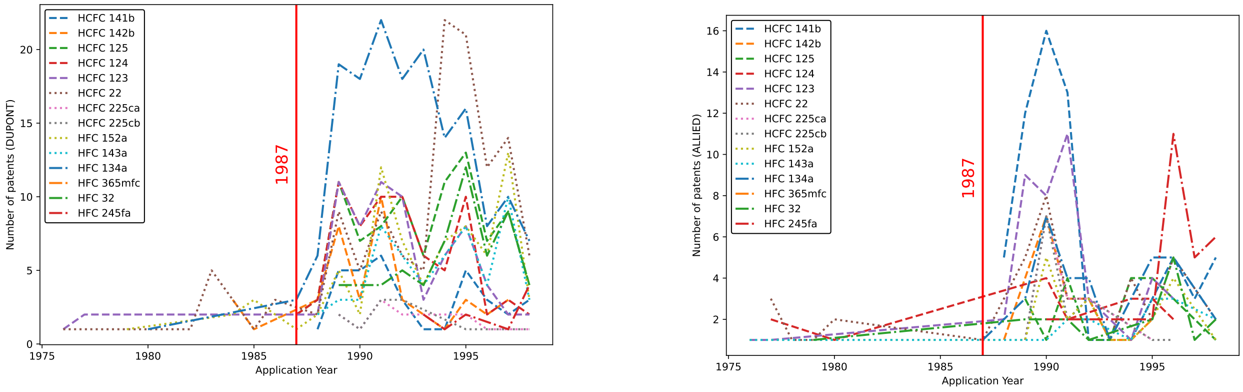
(a) Yearly Counts

(b) Monthly Counts



(c) Yearly Citation Weighted Counts

(d) Monthly Citation Weighted Counts



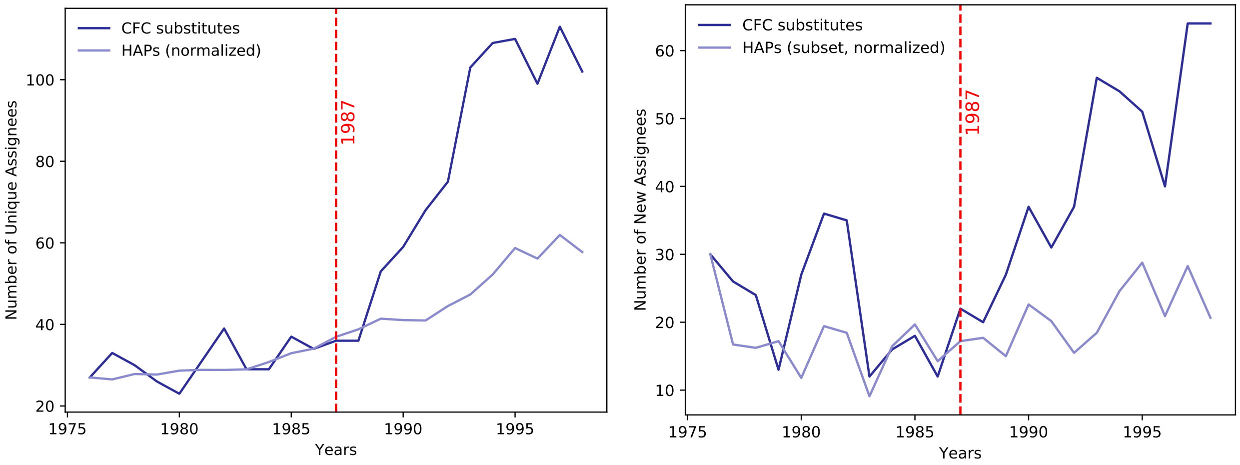
(e) DuPont's Yearly Counts for Different Substitutes

(f) Allied's Yearly Counts for Different Substitutes

b

Figure G3: Patenting Activity of DuPont and Allied

Note: Figure G3a shows that most patents granted to DuPont and Allied were applied for after 1989. Figure G3b shows that there is no sudden peak patenting right after Montreal. Instead, we observe a gradual ramping up of patenting activity. Figure G3c illustrates that the patents granted to DuPont and Allied, which received the highest number of citations, mostly originate from 1989 to 1991. Figure G3d indicates, however, that, in the weeks that followed Montreal, both DuPont and Allied applied for patents that would go on receiving a high number of citations. Only patents with at least three occurrences of a molecule are retained in the sample.

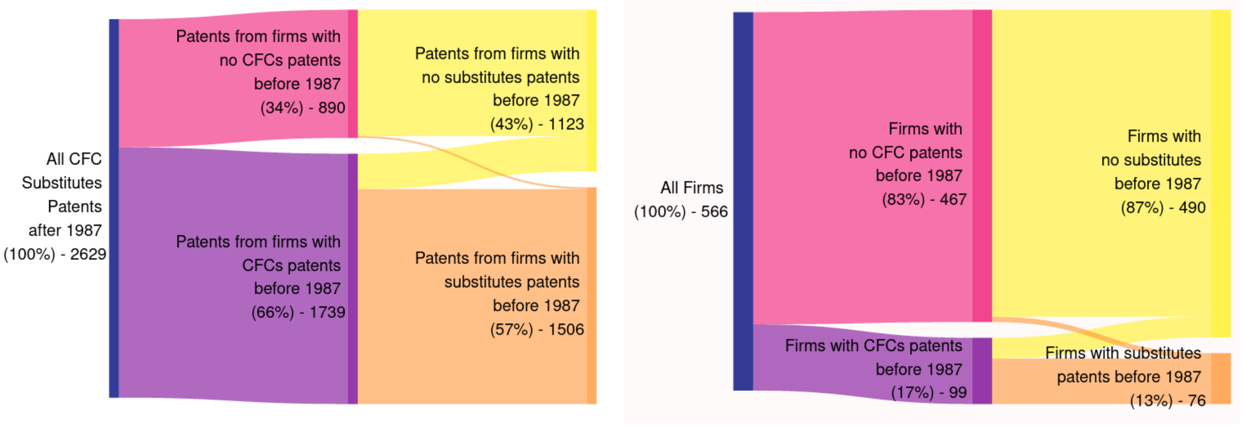


(a) Number of Assignees

(b) Number of “New” Assignees

Figure G4: Number of Patent Assignees Over Time

Note: Figure G4a displays the number of assignees that patent on CFC substitutes or HAPs in any given year. Figure G4b displays the number of assignees that are “new” (i.e., they apply for a patent on CFC substitutes or HAPs for the first time). The figure shows that, after 1987, many firms with no prior experience on CFC substitutes begin patenting. The data for HAPs is normalized such that y-axis values are equal to those of CFC substitutes in 1976. To limit noise, the sample used to generate the table contains only documents with at least three occurrences of CFC substitutes.



(a) By Number of Patents

(b) By Number of Firms

Figure G5: Composition of CFC Substitutes Patenting

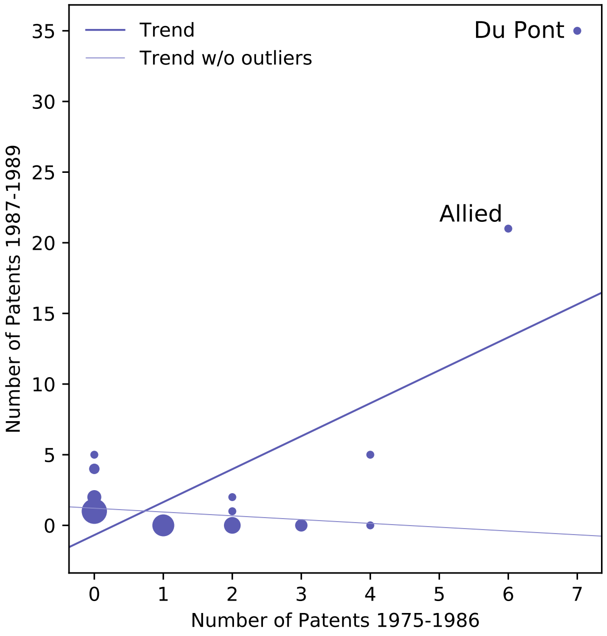
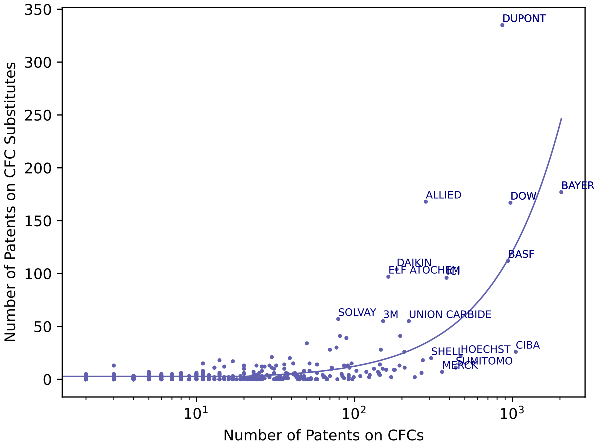
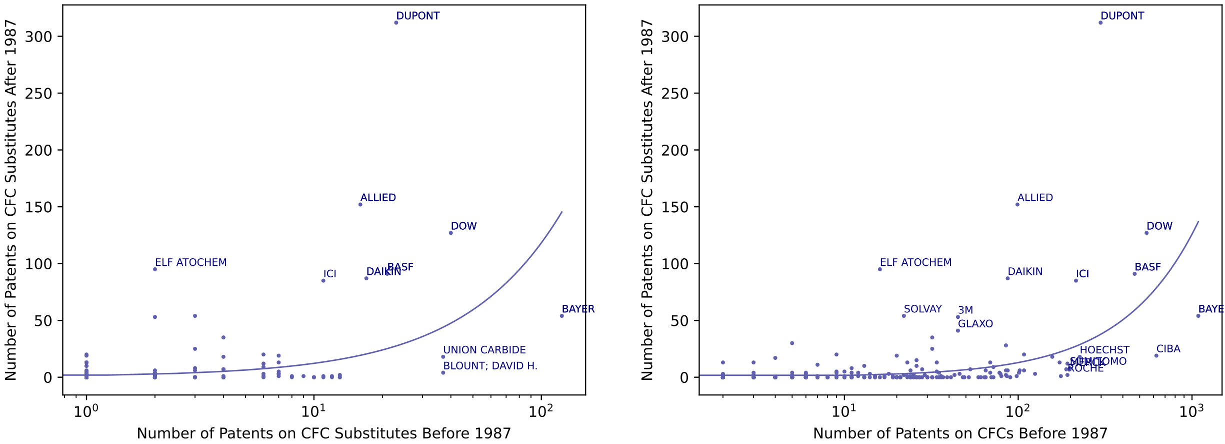


Figure G6: Patenting Before 1987 as a Predictor to Patenting After 1987

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



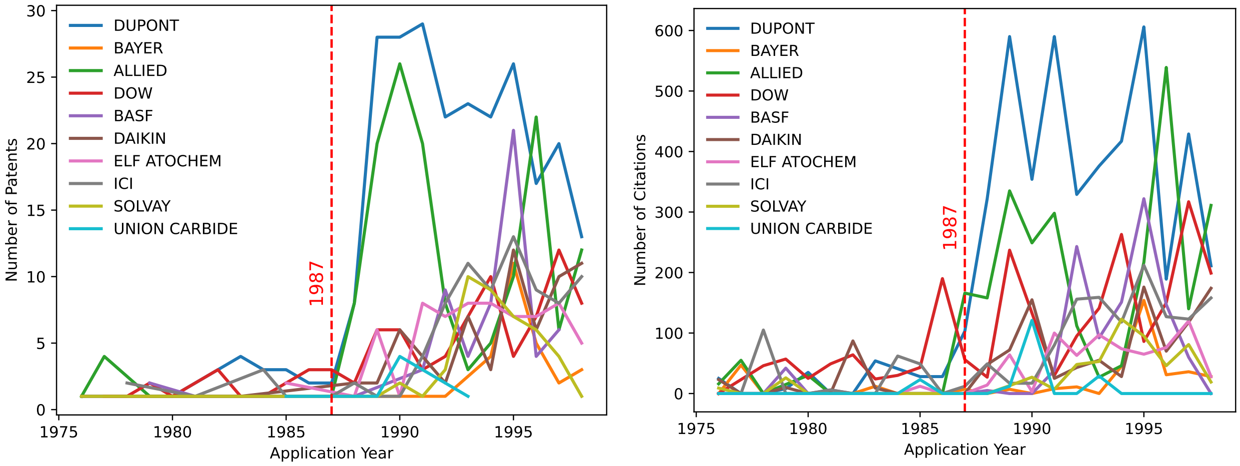
(a) CFCs vs CFC Substitutes (in 1974-2000)



(b) Substitutes Before vs After

(c) Substitutes After vs CFCs Before

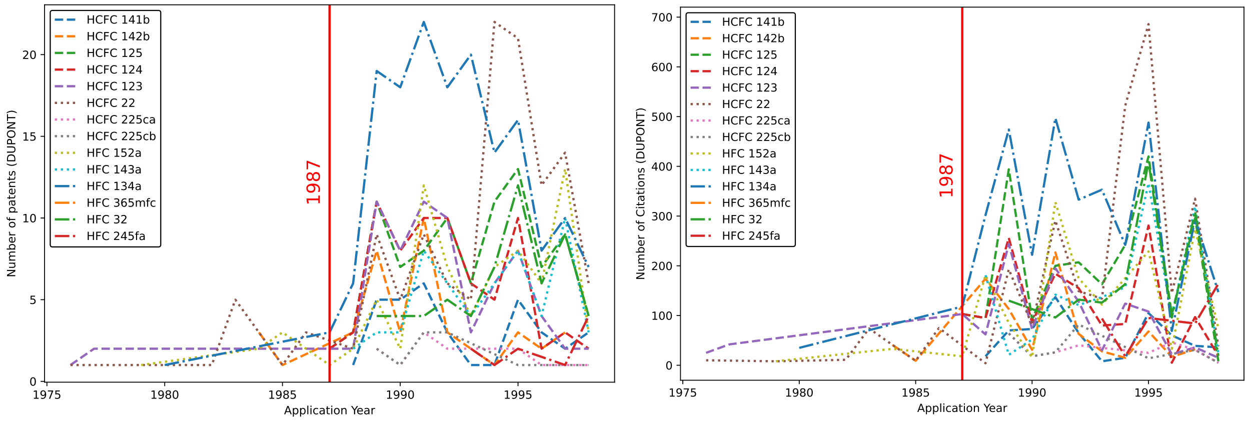
Figure G7: Scatterplots of Firm-Level Patenting



(a) Patent Counts

(b) Patent Counts Weighted by Citations

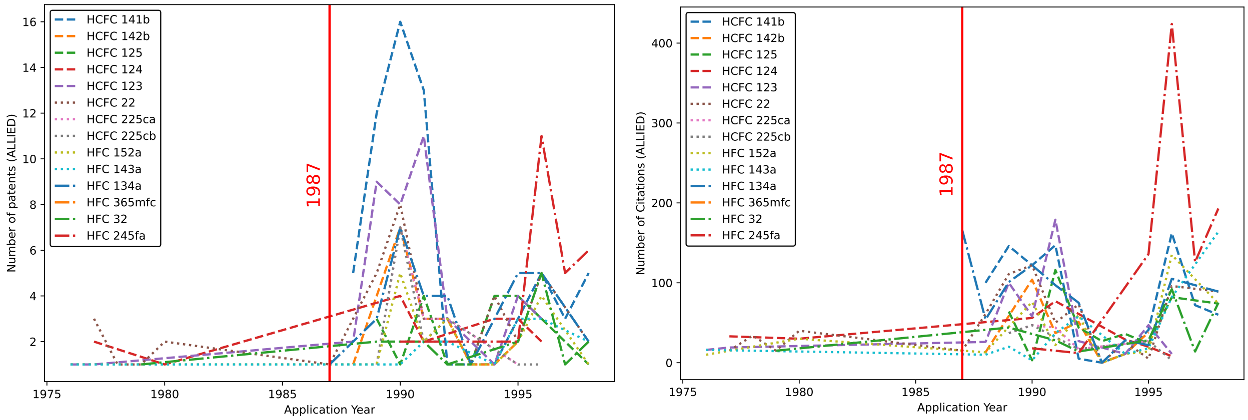
Figure G8: Time-series of Firm-Level Patenting



(a) Patent Counts

(b) Patent Counts Weighted by Citations

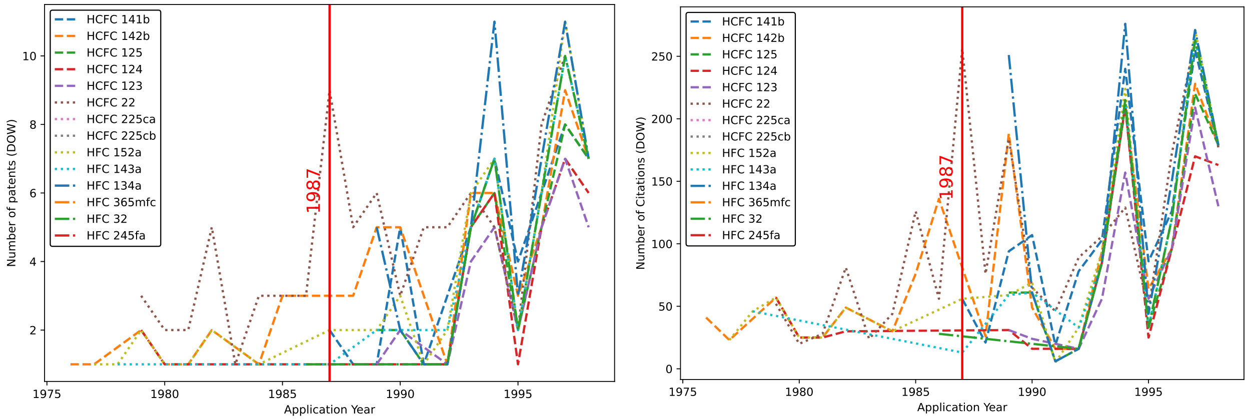
Figure G9: Patenting Time-series for DuPont



(a) Patent Counts

(b) Patent Counts Weighted by Citations

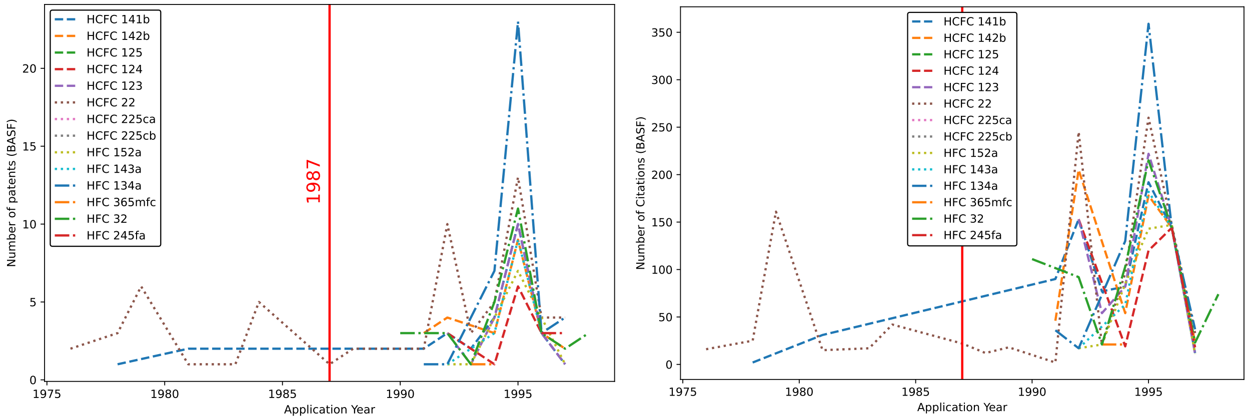
Figure G10: Patenting Time-series for Allied



(a) Patent Counts

(b) Patent Counts Weighted by Citations

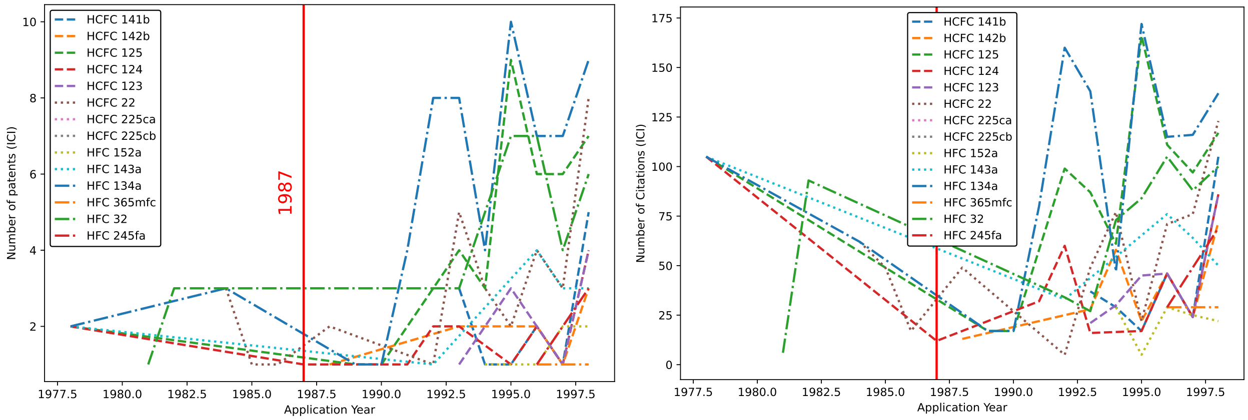
Figure G11: Patenting Time-series for Dow



(a) Patent Counts

(b) Patent Counts Weighted by Citations

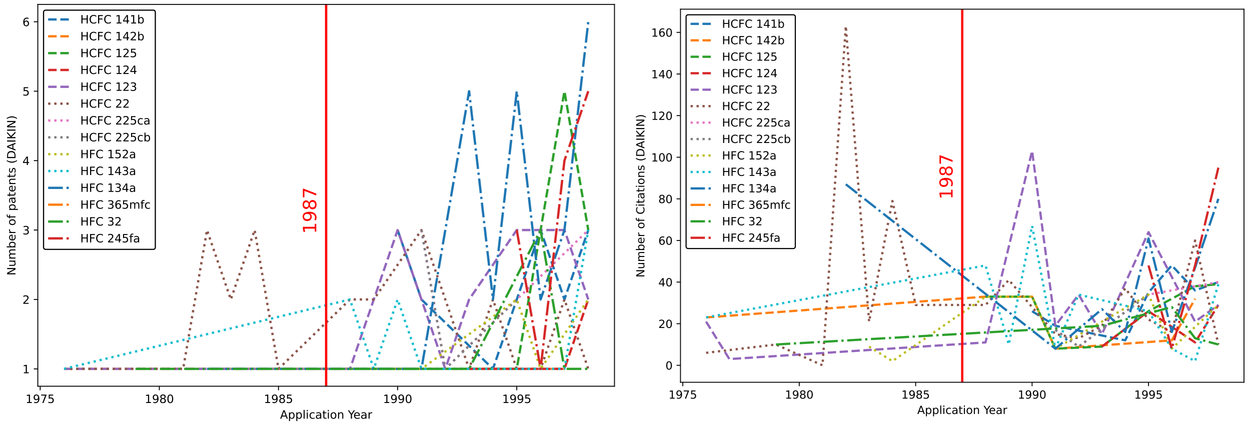
Figure G12: Patenting Time-series for BASF



(a) Patent Counts

(b) Patent Counts Weighted by Citations

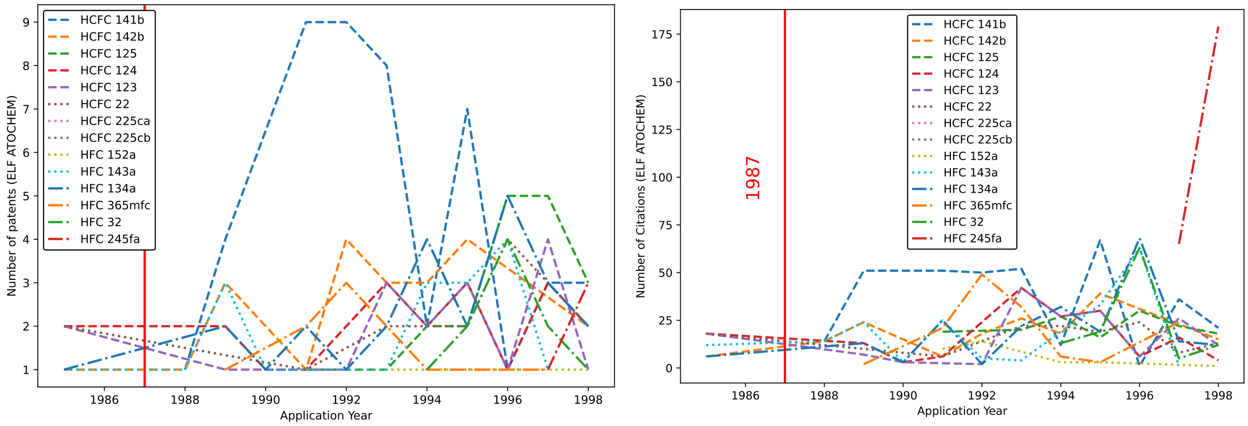
Figure G13: Patenting Time-series for ICI



(a) Patent Counts

(b) Patent Counts Weighted by Citations

Figure G14: Patenting Time-series for DAIKIN

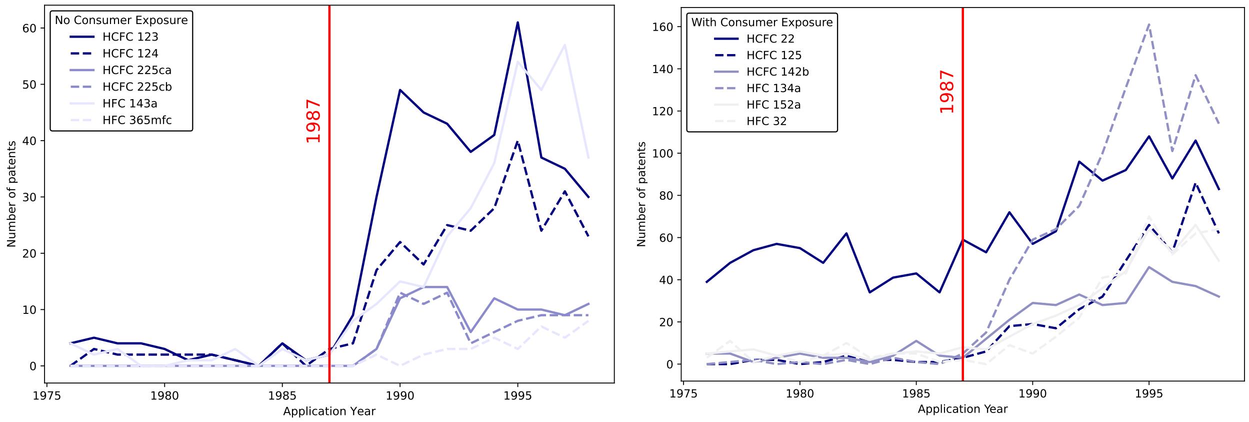


(a) Patent Counts

(b) Patent Counts Weighted by Citations

Figure G15: Patenting Time-series for ELF ATOCHEM

G3 Consumer Exposure



(a) CFC Substitutes not Exposed to Consumers

(b) CFC Substitutes Exposed to Consumers

Figure G16: Consumer Exposure and Patent Counts for CFC Substitutes

Note: The plot shows the number of patents mentioning CFC substitutes that were (or were not) exposed to consumers. We observe that, for most of them, including those not exposed, the number of patents increased sharply after 1987. This indicates that consumer pressure and public opinion did not play an essential role in driving innovation after the Montreal Protocol.

Table G6: Patents - Difference-in-Differences - With or without Consumer Exposure

	(1) Counts	(2) Counts	(3) Counts	(4) Counts	(5) Counts	(6) Counts
Post 1987 x Substitutes	16.54	21.12	28.42	30.57	24.60	29.45
	(1.74)	(2.06)	(3.78)	(5.21)	(3.30)	(5.09)
Post 1987 x Substitutes x Exposed					7.63	1.65
					(3.63)	(3.60)
Exposed					3.17	24.91
					(2.66)	(8.20)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Molecule FE	Yes	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	No	Yes	No	Yes	No	Yes
Bootstraped	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.84	0.86	0.84	0.88	0.85	0.88
Observations	714	595	204	148	204	148

Standard errors in parentheses

Bootstrapped standard errors in parentheses.

Dependent variable: Number of Patents.

Variable 'Years' is relative to 1987.

Time period: 1976 to 1992

Note: The table presents Difference-in-Differences regression results with an interaction term to examine heterogeneity based on whether or not the CFC substitute was consumer exposed. Columns 1 and 2 reproduce the results from the main table in the paper (Table 2). Columns 3 and 4 replicate the same specifications but exclude two CFC substitutes that could not be classified with certainty as either exposed or not exposed (HCFC 141b and HFC 245fa). Finally, Columns 5 and 6 use the same sample as Columns 3 and 4 but include an interaction term with the binary variable "Exposed," where 1 indicates CFC substitutes with uses targeting applications exposed to consumers, and 0 indicates those that do not. Column 5 shows that the coefficient for the interaction is positive and statistically significant, suggesting that the induced innovation response was stronger for consumer-exposed CFC substitutes. However, after controlling for topic modeling, the coefficient becomes insignificant, indicating that other molecule-level characteristics (possibly the types of industrial applications or the thermodynamic or safety profiles) may explain why consumer-exposed molecules show a stronger response. Since there is no quasi-random variation in the assignment of consumer exposure status, a causal interpretation for the interaction with the binary variable "Exposed" is not feasible.

H Theoretical Model

H1 Overview

Conceptualizing agreements as a vehicle for inducing innovation bears important implications for how we interpret the theory of international agreements. To make my argument, I use a stylized model of international environmental agreement and model induced innovation as a small learning rate. In the basic setup, N countries pollute and can decide to pay for pollution abatement. The costs are incurred by each country separately while the benefits of abatement accrue to all. Free-riding incentives, therefore, arise: countries would be better off if all were to abate a high amount of emissions (the cooperative level), but the Nash equilibrium of the game leaves all countries at a lower amount of abatement (the non-cooperative level).

As explained in Barrett (1994), the marginal costs of abatement and the marginal benefits from abatement determine the magnitude of the gains from cooperation, that is, how much better off countries would be if all were abating at the cooperative level rather than staying at the non-cooperative one. As illustrated on Figure H1a, cooperation gains are high when both marginal costs and marginal benefits are large. This area corresponds to where cooperation provides the most additional welfare compared to the non-cooperative equilibrium. Barrett (1994) showed that this area is, unfortunately, the least likely to support successful self-enforcing agreements. The Montreal Protocol can be interpreted as an agreement located in the area of low cooperation gains, i.e. the darker area on Figure H1a. On the other hand, the targets negotiated in 1990 and 1992 (London and Copenhagen) would be located, from the perspective of 1987, in the area of higher cooperation gains because, in 1987, the London and Copenhagen targets were seen too costly to be part of the agreement.

I build on this simple model by assuming that countries make their abatement decisions over several time periods and by endogenizing innovation. Now, the marginal costs of abatement in period t depends on the amount of abatement done in period $t-1$:

$$c_t(q_t) = c_{t-1}(1-r)^{q_{t-1}} \tag{2}$$

c_t stands for the marginal cost of abatement in period t, q_t for the amount of abatement done in period t and r is a constant between 0 and 1 that can be interpreted as a learning rate. Abatement in period $t-1$, therefore, leads to reductions in the abatement costs in period t.[5]

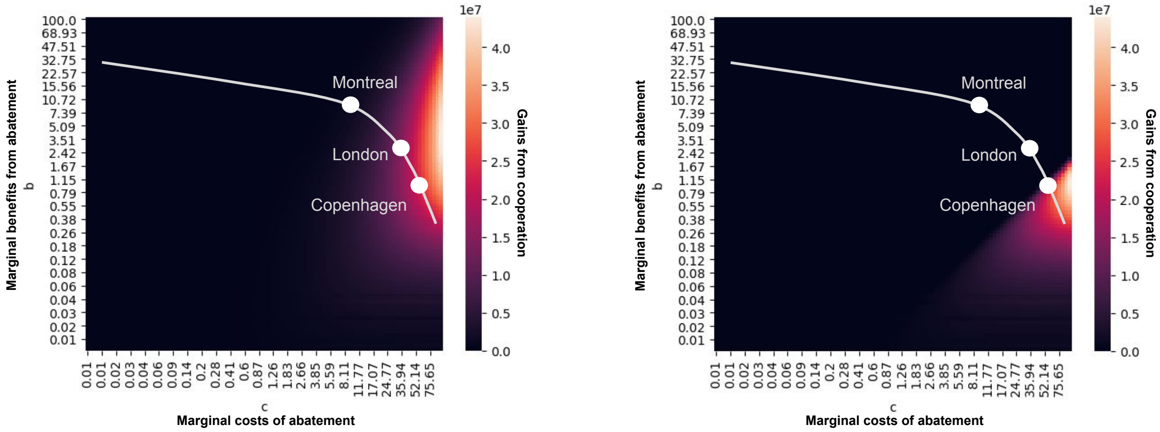
This models the effect of induced innovation: by enforcing q_t emission reduction in period t, the agreement forces firm to do new things, to experiment, to develop new or improve old technologies. These processes pave the way for lowering the marginal cost of abatement in the next period.

Over several time periods, the area of high cooperation gains becomes smaller, indicating that allocations that used to be difficult to achieve are now within reach.[6] In turn, the level of abatement

---

[5] Note that abatement costs increase with the amount of abatement undertaken to reflect that the more costly steps are usually done after exhausting the cheaper ones. As a result, induced innovation leads to abatement costs being lower than what they would have been for a particular quantity of abatement. Furthermore, in this simple model where induced innovation is modeled to decrease the slope of the abatement cost curve, any rate r strictly positive will lead to the cost of the first unit abated in the next period to be lower than the cost of the last unit abated in the previous period.

[6] See Online Appendix Figure H3 for more details.



(a) Initial Period (e.g., 1987)

(b) After Induced Innovation (e.g., 1992)

Figure H1: Gains from Cooperation and Induced Innovation

Note: The figure interprets the success of the Montreal protocol in light of the theory of international environmental agreements. The x-axis represents the scale of the costs of abating one more unit of CFC emissions. The y-axis represents the scale of the benefits arising from the avoided ozone depletion due to one more unit of abated emissions. Units should be interpreted as units of welfare (e.g., in dollars). Following Barrett (1994), areas where cooperation gains are high are the least likely to support self-enforcing agreements. Figure H1a represents the locations of targets agreed in Montreal, London and Copenhagen from the vantage point of 1987. In the 1987, the London and Copenhagen targets were out of reach. Figure H1b illustrates that induced innovation increases the set of negotiable outcomes. Note that the numbers are not calibrated to specific values and so the quantitative exercise is for illustration only.

in the non-cooperative equilibrium increases. Concretely, more abatement is undertaken by all countries even in the absence of cooperation. As a result, for any point on Figure H1b, the gains from cooperation are lower compared to Figure H1a. In 1987, the London and Copenhagen targets were too expensive, but induced innovation made then within reach of an agreement a few years later.

H2 Standard Model

Suppose N countries, all identical and indexed by i. Each country emits a pollutant that damages a shared environmental resource but can also abate an amount q_i of pollution. The benefits from abatement depends on the total amount abated by all countries:

$$B_i(Q) = \frac{b}{N}(aQ - \frac{Q^2}{2}) \tag{3}$$

where $Q = \sum q_i$ and a, b, and c are positive constants.

The costs of abatement only depend on each country's own abatement:

$$C_i(q_i) = \frac{c}{2}q_i^2 \tag{4}$$

At the uncooperative equilibrium, countries abate up to the point where the marignal costs equal the marginal benefits for country i. Hence, we obtain the expression below for q_N, the amount country i abates in the noncooperative equilirbium:

$$MC_i = MB_i \Leftrightarrow cq_i = \frac{b}{N}(a - Q) \Leftrightarrow q_N = \frac{1}{N}\frac{a}{1+\frac{c}{b}} \tag{5}$$

At the cooperative, countries abate up to the point where the marignal costs equal the global marginal benefits. Hence, we obtain the expression below for q_C, the amount country i abates in the cooperative equilirbium:

$$MC_i = \sum_i MB \Leftrightarrow cq_i = N * \frac{b}{N}(a - Q) \Leftrightarrow q_C = \frac{a}{N + \frac{c}{b}} \tag{6}$$

Define the net benefits Π as the difference benefits and costs. The gains from cooeperation are:

$$CooperationGains = \Pi_C - \Pi_N = N * \Big(B_i(q_C) - C_i(q_C)\Big) - N * \Big(B_i(q_N) - C_i(q_N)\Big) \tag{7}$$

Figure H2 illustrates the size of cooperation gains for specific value of b and c (and N set at 100). We note that cooperation gains are highest when c and b are both large. As Barrett (1994) showed, the area when cooperation gains are the highest are is the area where it is the most difficult to sustain a self-enforcing coalition.

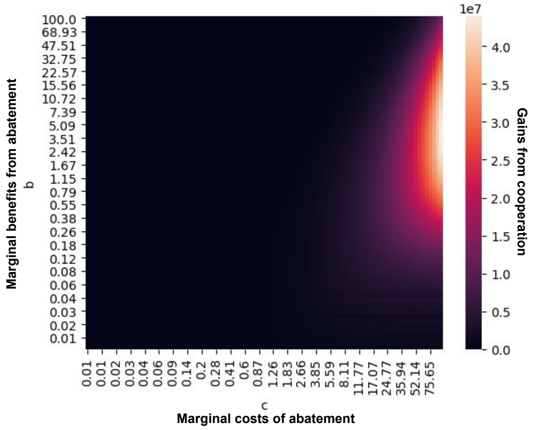


Figure H2: Gains from Cooperation

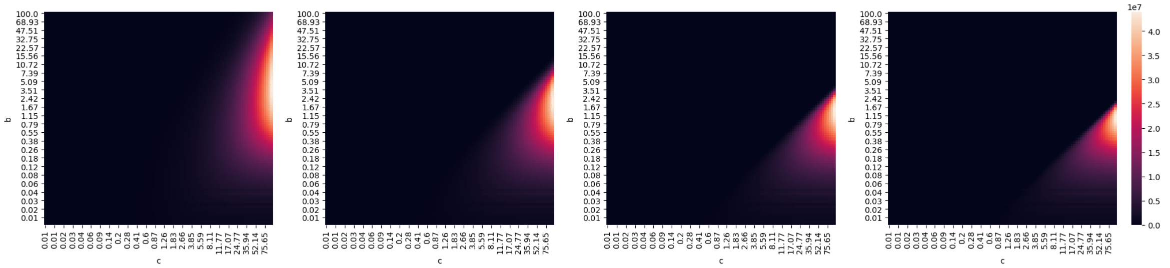
Note: Note that the numbers are not calibrated to specific values and so the quantitative exercise is for illustration only.

H3 Endogeneizing Innovation

Next, I extend this simple model by assuming that countries make their abatement decisions over several time periods and endogenize innovation. The parameter c now is replaced by a function c of the amount of abatement in the previous period:

$$c_t(q_t) = c_0(1 - r)^{q_{t-1}} \tag{8}$$

, where c is a constant controlling how costly abatement is, and r a constant between 0 and 1 that can be interpreted as a learning rate. The higher the amount of abatement in period $t - 1$ and the lower the marginal cost of abatement in the next period. As Figure H3 illustrates, over several time periods, the area of high gain from cooperation reduces indicating that allocations that used to be difficult to achieve are now within reach.

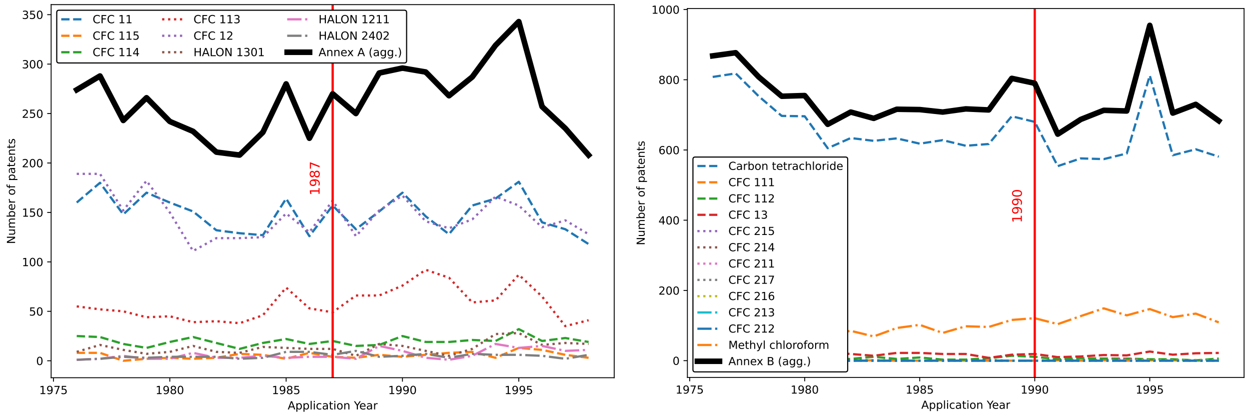


(a) Period 1 (b) Period 2 (c) Period 3 (d) Period 4

Figure H3: Gains from Cooperation and Induced Innovation

Note: Note that the numbers are not calibrated to specific values and so the quantitative exercise is for illustration only.

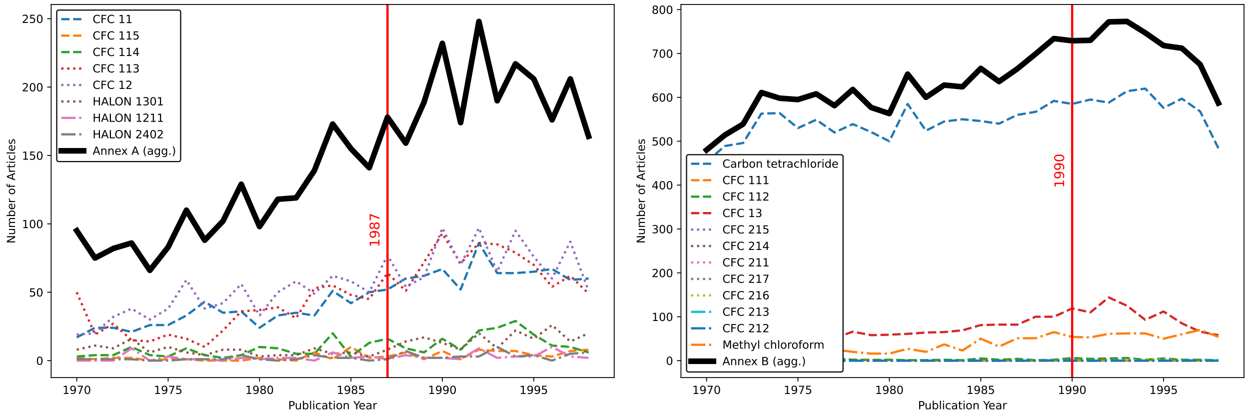
I Annex A and B Compounds



(a) Annex A

(b) Annex B

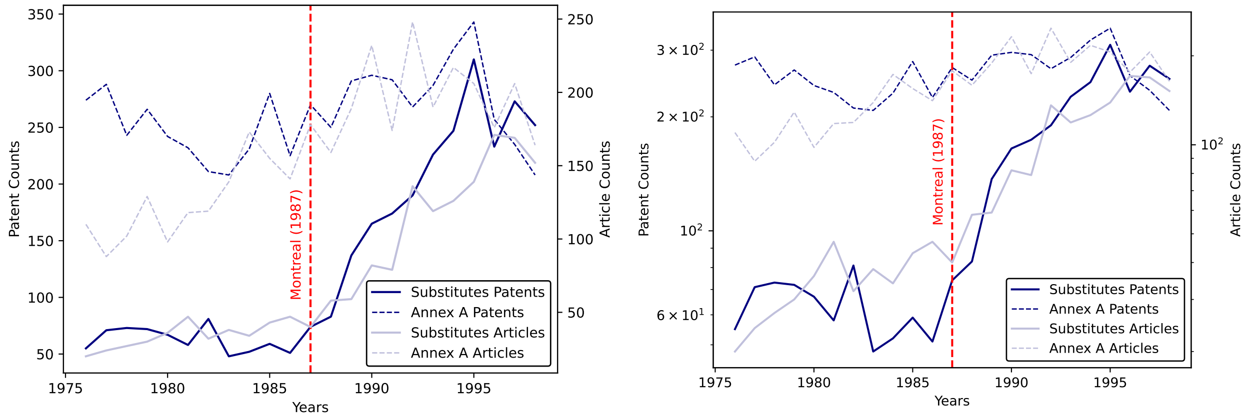
Figure I1: Patents Counts for Each Annex A/B Compound and for the "Aggregate" Annex A/B Compound



(a) Annex A

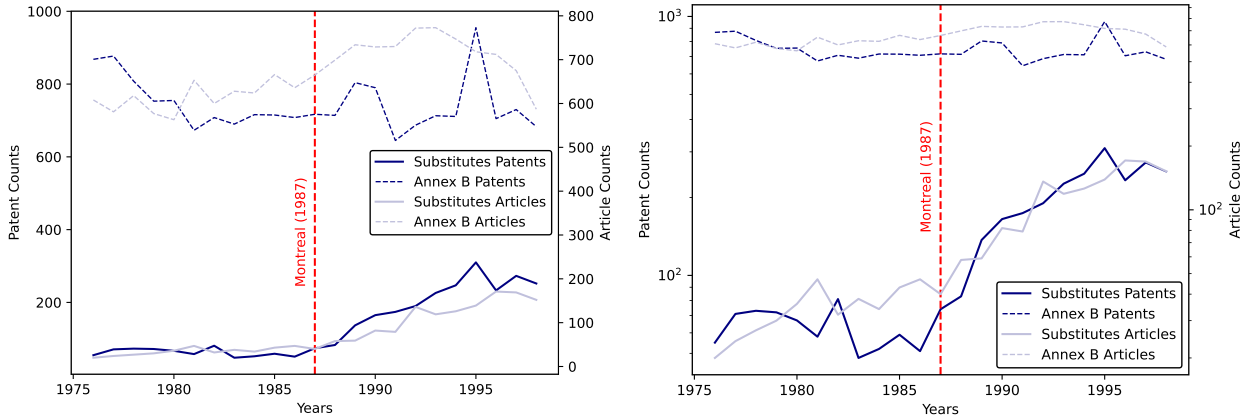
(b) Annex B

Figure I2: Article Counts for Each Annex A/B Compound and for the "Aggregate" Annex A/B Compound



(a) With Annex A - Linear Scale

(b) With Annex A - Log Scale

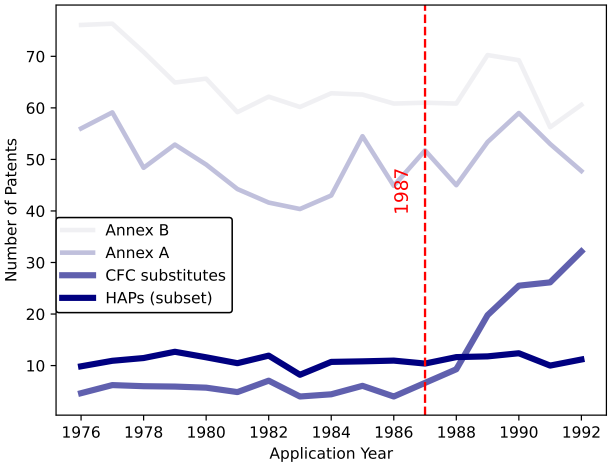


(c) With Annex B - Linear Scale

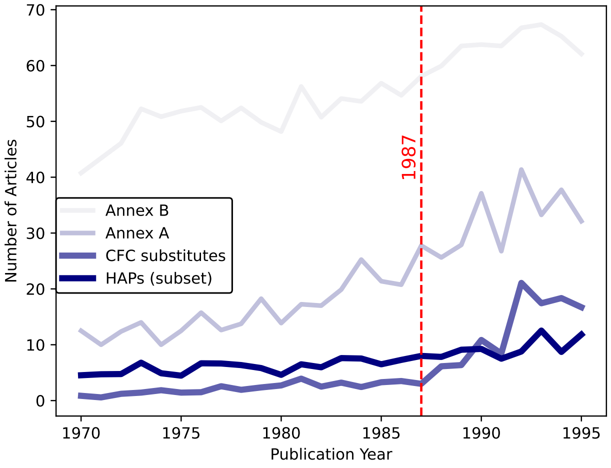
(d) With Annex B - Log Scale

Figure I3: Similar to Figure 1 but with Trends for Annex A and B Compounds

Note: There were a total of 8 compounds regulated in 1987 (referred to as Annex A compounds) and an additional set of 12 regulated in 1990 (referred to as Annex B compounds). Montreal did not impose a full ban, but rather a freeze and progressive phase-out. Concretely, this meant that CFCs would still be used for a short period of time, even in high-income countries (in low- and middle-income countries, their use was not yet regulated). The announcement of the freeze and progressive phase-out would probably have encouraged firms to cease developing new applications for CFCs. However, it may also have prompted them to develop more efficient ways of using CFCs or methods for recycling, which could translate into new patents and articles. Furthermore, some CFCs had much lower ozone-depleting potential compared to others, and those were at some point considered as potential substitutes, and so more research on these could have been induced. Therefore, the impact of the Montreal Protocol on patenting related to Annex A and B compounds is inherently uncertain. It may have led to more patents for certain applications and fewer for others, making it challenging to establish a strong prior on the net effect.



(a) Patent Counts



(b) Article Counts

Figure I4: Similar to Figure 3a but with Trends for Annex A and B Compounds

Note: There were a total of 8 compounds regulated in 1987 (referred to as Annex A compounds) and an additional set of 12 regulated in 1990 (referred to as Annex B compounds). Figure 3a showed the pre-trends for the treated group (CFC substitutes) and the control group constructed using a subset of the HAP molecules with counts and pre-trends closest to the average CFC substitutes. Here, I add similar trends for Annex A and B compounds. Note that Montreal did not impose a full ban, but rather a freeze and progressive phase-out. Concretely, this meant that CFCs would still be used for a short period of time, even in high-income countries (in low- and middle-income countries, their use was not yet regulated). The announcement of the freeze and progressive phase-out would probably have encouraged firms to cease developing new applications for CFCs. However, it may also have prompted them to develop more efficient ways of using CFCs or methods for recycling, which could translate into new patents and articles. Furthermore, some CFCs had much lower ozone-depleting potential compared to others, and those were at some point considered as potential substitutes, and so more research on these could have been induced. Therefore, the impact of the Montreal Protocol on patenting related to Annex A and B compounds is inherently uncertain. It may have led to more patents for certain applications and fewer for others, making it challenging to establish a strong prior on the net effect.

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