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Political, economic and research disintegration: The impact of geopolitical uncertainty on cross-border R&D collaborations and innovation

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Abstract

Uncertainty regarding the policy environment could be particularly detrimental for innovation, as it requires high-risk investment, and long-term commitments with scientists and research partners. This paper focuses on the effects of geopolitical uncertainty on cross-border R&D collaborations and patenting activity, exploiting the UK exit from the EU as a quasi-natural experiment in a Difference-in-Difference (DiD) analysis. Our results reveal a significant disruption in cross-border research collaborations of UK organisations after the Brexit referendum, as EU based inventors were replaced by UK ones. This has resulted in a shift in the field of technologies patented, and in a decrease in inventions patented overseas. Overall, the disruption has negatively affected the innovations of UK based organisations, reducing both the number and quality of patents.

JEL Codes: F15; O30; O34; O36; D80.

Keywords: Economic policy uncertainty; Brexit; Innovation; Patents; International research collaborations.

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1 Introduction

Technological progress and innovation are at the heart of human development, long-term economic growth and competitive advantage, and they have been the focus of extensive economic analysis since the seminal works of Schumpeter (1942) and Solow (1957). A vast strand of the literature on the economics of innovation analyses the drivers and determinants of innovation, not only focusing on the role of research and development (R&D) investments (Crepon et al., 1998; OECD, 2009; Hall et al., 2010), but also considering other important inputs as human capital (Romer, 1990; Squicciarini and Voigtländer, 2015; Diodato et al., 2021), the role played by government policies in addressing market failures (Zúñiga-Vicente et al., 2014; Vanino et al., 2019; Bloom et al., 2019a), and of intellectual property rights to protect firms' incentives to innovate (Trajtenberg et al., 1997; Jaffe and Trajtenberg, 2002; Jaffe and de Rassenfosse, 2017). Previous studies have also realised that innovation is not an isolated activity but rather a result of complex interactions between various actors and institutions, studying the complex interactions between researchers, firms, universities, research institutes, and government agencies, and their integration within innovation ecosystems and international collaborative networks (Teece, 1986; Chesbrough, 2003; Cassiman and Veugelers, 2006). However, still little is known about how R&D and innovation activities are impacted by political crises, unexpected changes in public policies, and uncertainty about future policy arrangements. This is an important gap in the knowledge base, as public policies shape the economic and regulatory framework in which innovative organisations operate, which ultimately affects a country's innovation and economic performance. Uncertainty regarding the policy environment could be particularly detrimental for innovation, as it requires especially long-term investment with significantly higher risks regarding the future outcomes generated (Bhattacharya et al., 2017).

In this paper, we investigate the impact of mounting policy uncertainty and economic disintegration on international R&D collaborations and consequent innovation outcomes, by analysing the impact of the economic policy uncertainty induced by the exit of the United Kingdom from the European Union (the Brexit process) on UK organisations international collaborations and patenting activity over the period 2013-2019. This is an ideal setting for our analysis for several reasons. First, the UK is one of the world leaders in innovation and R&D, ranking among the top countries in the Global Innovation Index[1], in particular thanks to its research-intensive universities contributing to more than 23% of the country's R&D investment in 2019, and part of an extensive network of publicly funded collaborative research projects with private and public organizations around the world (PolicyLinks, 2022).[2] Secondly, the UK has been experiencing one of the most unexpected policy uncertainty shocks since the June 2016 Brexit referendum, going through a long negotiation period resulting in the UK formally leaving the EU in January 2020. During this period there has been a large amount of speculation and uncertainty regarding the shape and the scope of the future economic and political relationships between the UK and the EU, which ultimately resulted in the exit of the UK from the EU single market, customs union, and from most policy partnerships. Many studies have evaluated the impact of the Brexit uncertainty and process on several aspects of the UK economy, including foreign direct investment (Breinlich et al., 2020), gross domestic product (Born et al., 2019), living standards (Dhingra et al., 2016; Breinlich et al., 2022), trade activity (Graziano et al., 2020; Crowley et al., 2020; Douch and Edwards, 2021, 2022; Douch et al., 2022), firm productivity (Bloom et al., 2019b), and labour markets (Javorcik et al., 2019). Nevertheless, none of the previous studies looked at the impact on innovation.

The exit of the UK from the EU have impacted UK organizations' innovativeness in several ways. First, uncertainty about the UK's participation in Horizon Europe, the EU's 95.5 billion research and innovation fund, has been one of the biggest issues in the fractious post-Brexit UK-EU relationship. The temporary exclusion from the Horizon programme not only prevented UK research organizations from accessing an important source of funding, but also made it harder for them to recruit the best international scientists, and possibly reduced collaboration between UK and EU research organizations (Meyers and Springford, 2022). Secondly, exiting the EU single market also has detrimental effects on the UK innovation. Foremost, Brexit has ended EU's free movement of labour and capital, hindering the supply of skilled European workers in the science, technology, engineering, and medicine (STEM) fields, and also limiting access to investment from the

[1] https://www.great.gov.uk/international/content/investment/why-invest-in-the-uk/uk-innovation/

[2] Overall, the UK spends 1.74% of GDP in R&D, below the 2.5% OECD average, although the UK government has committed to increase its contribution from the current 6.6% of R&D investing £22 billion in R&D by 2026/27. Compared to other countries, it is in particular the business sector in the UK that contributes less to R&D funding, funding around 55% of R&D lower than comparative countries such as Germany, Korea and Japan, with very few firms headquartered in the UK among the global leaders in R&D investment and patent applications (PolicyLinks, 2022).

EU, with large negative effects on the development of technology and its diffusion across the economy (Society, 2019). Third, it has ended the free circulation of goods and services across borders with the rest of the EU markets. This has made UK products in the EU market less competitive, ending the automatic reciprocal recognition of product standards and certificates. Although intellectual property rights (IPR) have not been affected so far, and the system of patent protection obtained through the UK Intellectual Property Office (UKIPO) or the European Patent Office has remained unchanged, there is uncertainty about future divergence in the EU and UK IPR framework.[3] For instance, a new European patent regime called the Unified Patent Court is being planned, enabling proprietors of inventions to apply for a single, pan-European Unitary Patent (UP) covering most of Europe, and with a single Unified Patent Court (UPC) to hear and determine patent disputes on a pan-European basis.[4] As a result of Brexit, the UK will not form part of the UPC system and a UP will not cover the UK. All of these issues have caused increased uncertainty for British research intensive organizations, causing delays and stagnation of investment in these key sectors for the economy.

Several studies show that policy uncertainty adversely affects investment since, as they are often characterised by sunk costs not fully reversible, economic agents become cautious and hold back on investment in the face of uncertainty, increasing the value of the option to wait (Bernanke, 1983; Alesina and Perotti, 1996; Bloom, 2009, 2014). The value of the option to wait is particularly important for investments in research and development (R&D), given the exploratory nature of innovation, and the high uncertainty regarding future commercialization and profitability of innovations (Holmstrom, 1989; Aghion and Tirole, 1994; Manso, 2011; Ferreira et al., 2014). In addition, it is unclear how policy uncertainty influences R&D investment and innovation strategies, as the economic factors affecting innovation are different from those that affect regular investment, including the availability of highly-skilled human capital, tangible and intangible assets, access to public and private funding, collaborations with a range of for- and non-for-profit partners, and the presence of a regulatory framework protecting the outcomes of the investment.

The impact of policy uncertainty on innovation could be one of the key aspects to consider in the future (Archibugi and Filippetti, 2015), as in order to maintain a com-

[3] The Law Society (2021): https://www.lawsociety.org.uk/topics/brexit/intellectual-property-after-brexit

[4] For more information see: https://www.nortonrosefulbright.com/en/knowledge/publications/01b81fec/impact-of-brexit-on-intellectual-property

petitive advantage and promote economic growth, governments and firms will need to consistently innovate to maintain their market shares, improve production efficiency, and compete in the international markets (Baldwin and Johnson, 1996; Martín-de Castro et al., 2013; Tidd and Bessant, 2020). This is becoming even more important recently, in an evolving geopolitical context of increasing international tensions, with political and economic disintegration between countries. This has led to the emergence of "technological sovereignty" strategies carried out by several governments to strengthen domestic technological capabilities, and reduce the dependence on foreign third parties and international research collaborations (Filippetti and Vezzani, 2022; Edler et al., 2023).

However, only few previous studies have started analysing how policy uncertainty can affect innovation (Padilla and Garrido, 2018; Di Cataldo, 2017). For instance, (Bhattacharya et al., 2017) using a panel of more than 40 countries show that patenting activity drops significantly during times of policy uncertainty, measured by national elections with close presidential elections and ethnic fractionalisation, in particular for influential innovations driven by a decrease in patenting inventors. Furthermore, Liu and Ma (2020) have reported that businesses tend to delay investing in innovation processes when they are not certain about future trade policy, by analysing an increase in Chinese patent filings after the reduction of trade policy uncertainty following China's accession to the World Trade Organization (WTO) in 2001, as predicted by the real option theory where firms have the ability to wait for uncertainty to diminish before proceeding in high sunk costs investment as R&D. On the contrary, Pertuze et al. (2019) examine the differential effects of two sources of uncertainty, leaders' education levels and political regimes, on patent applications. The authors find that firms react to political uncertainty caused by the unexpected departure of a national leader by investing in patents, as an alternative growth option. This effect is amplified in the case of leaders with higher education and in presidential regimes. Similarly, Tajaddini and Gholipour (2020) using a panel of 20 countries show that higher levels of economic policy uncertainty are positively associated with higher R&D expenditure as well as innovation outputs. Finally, two recent studies have looked into the specific potential impact of Brexit on innovation. The first one (Garas et al., 2019) trying to predict the impact Brexit might have on transnational research collaborations in healthcare technologies using network simulation models, while the second one (Pichler and Pisera, 2024) estimates the change in UK firms' R&D investment following the Brexit referendum.

Our study contributes to the existing literature in the following way. First, using firm-patent level data for the UK and other EU countries we will be able to provide a micro-level analysis of the impact of policy uncertainty on R&D collaborations and innovation, while controlling for time-variant firm characteristics, countries' economic performance, and other macroeconomic shocks. Secondly, the use of detailed patent data, will give us the opportunity to explore some of the mechanisms through which policy uncertainty affects innovation, considering the impact on firms' patent quality, changes in their technological specialisation, the disruption of transnational research collaborations, and the availability of human capital. Third, by exploiting the Brexit policy uncertainty shock as a quasi-natural experiment, we will be able to address several endogeneity concerns that affected previous contributions, identifying in this way the causal effect of policy uncertainty on R&D collaborations and innovation outcomes.

Our results show that the policy uncertainty generated by the Brexit process has severely disrupted cross-border research collaborations between UK and EU based organisations, with a clear change in the composition of inventors in patents filed by UK organisations, as the share of EU based inventors decreases compensated by an increase in the number of UK based inventors. This is also reflected in the patenting strategy of UK organisations, as the number of patents filed overseas decreased, in particular at European patent offices, while no effect is found for patents at the domestic UK IPO. This is a possible indication that because of mounting policy uncertainty, UK organisations might have decided to refocus their innovation activity domestically, reorganizing and adapting their innovation processes to the changes in the geopolitical panorama. UK organisations have expanded the scope of patents as a consequence of Brexit, increasing the number of IPC sub-classes per patent, with a shift away from traditional operations and transport technologies towards applied physics technologies. However, this has not resulted in an improvement in UK patents' generality and originality, but has instead affected their quality. This evidence suggests that UK organizations have adopted a more inward-looking innovation strategy as a result of Brexit, severing international R&D collaborations with European inventors and partners in favor of developing new technological capabilities domestically. However, this shift toward a "technological sovereignty" approach appears to have hindered innovation, with both the quantity and quality of patented innovations declining due to growing scientific isolation.

The rest of the paper is organized as follows. The next section presents the data used providing some stylised statistics and discusses the identification strategy and the econometric methodology applied. Section 3 reports the main findings of the analysis, while section 4 discusses them, and section 5 concludes.

2 Data & Methodology

2.1 Data

This analysis makes use of the EPO PATSTAT Global database, which provides detailed bibliographical data relating to more than 100 million patent documents from most countries (Kang and Tarasconi, 2016). PATSTAT offers information regarding, among others, the patent's filing date and patent office, name and address of owners and inventors, technological classifications, backward and forward citations, as well as information about the patent family[5]. We focus on patents filed between January 2013 and December 2019, as full information for patents filed in later years is still incomplete and to avoid the Covid-19 pandemic that significantly disrupted patenting activity, by organisations based either in the UK or in the EU, including universities, private firms, and other public or non-for-profit research institutions.

For our analysis, we aggregate the data at the applicant and quarter level, generating several variables describing the patenting activity of all EU and UK organizations filing a patent during this period. This leaves us with around 987,000 observations, including around 470,000 European and 63,000 UK applicants. We consider several measures of innovation performance exploiting the richness of the PATSTAT data[6]. First, we look at the total number of patent families filed by an applicant in each quarter, and at their overall stock of patents filed until that point. Then we also consider where those patents have been filed, distinguishing between the UK Intellectual Property Office (IPO), patents filed at the European Patent Office or in other EU countries' national patent offices (EPO), at the United States Patent and Trademark Office (USPTO), at the World Intellectual Property Organization (WIPO), or at any other national patent office in the rest of the

[5] A patent family denotes a group of patents which relate to similar or identical purposes or inventions. The families are constructed, typically automatically, by the patent offices. Applicants may re-patent the same innovation numerous times across several patent offices, which would then be recorded as separate patents, however, patent families account for this by bringing together all patents that pertain to the same invention (Martinez, 2010).

[6] Summary statistics and definition of the main patent variables considered in our analysis are reported in Tables A1 and A2 respectively in the Appendix.

world (ROW). This will give us an indication of the overall patenting activity of organizations, and of their strategic decisions about where to protect their inventions, a signal of the importance of each specific market. Secondly, we consider several measures of patent quality. We start with the simple number of citations for each patent family, before building a measure of patent quality following Hall et al. (2001) measured as the relative number of citations by a patent with respect to all the other patents filed in the same quarter, and differentiating between the quality of patents filed at different patent offices. We also consider two measures of patents *generality* and *originality* as developed by Hall and Trajtenberg (2004). In summary, generality represents how diverse a patent's citations received are, derived by calculating the percentage of citations received that belong to the patent's own technological field. Originality is calculated in the same manner, however, it relates to citations made by the patent, as opposed to citations received. Third, we look at the different types of patented inventions, considering the International Patent Classification (IPC) of technologies[7]. This will allow us to identify if the patenting activity of UK organisations has significantly changed following a period of uncertainty for specific technologies rather than others. Finally, we consider the number of co-applicants and inventors listed in each patent, and their geographical location, distinguishing between co-applicants and inventors based in the UK, EU countries, the USA, or other countries (ROW). This will be important to analyse how policy uncertainty might disrupt in particular cross-border patenting collaborations, by making more difficult the flow of people, capital and services between countries.

To identify the impact of policy uncertainty on R&D collaborations and innovation, we will analyse the UK exit process from the European Union, commonly known as Brexit, from the referendum of June 2016 until the ratification of the withdrawal agreement in January 2020. Brexit has been used before as a quasi-natural experiment to analyse uncertainty, particularly in the Trade Policy Uncertainty (TPU) literature (Graziano et al., 2020; Crowley et al., 2020; Douch et al., 2022), given the unpredictable nature of the Brexit referendum outcome, and the fact that the consequences for the future typology of UK EU membership remained largely uncertain for years after the referendum. Figure 1 provides a graphical timeline of the events, including key dates and the primary sources of uncertainty, showing how the level of uncertainty has dramatically increased following the Brexit referendum. This reverberated through the entire economy, also affecting research-

[7]In this paper we use the IPC technological classification at the sub-class level. Our results are reported at the section level, from A to H, as listed in Table A1 in the Appendix.

intensive organisations, as shown in Figure 2 presenting the trends in Google searches in the UK about combinations of Brexit and other innovation related keywords since 2015. Searches about the post-Brexit research and innovation ecosystem jumped in the immediate aftermath of the Brexit referendum outcome shock, including searches about the European Research Council (ERC), the EU Horizon 2020 funding scheme, research grants and the consequences of a no deal scenario for innovation. These started increasing significantly again towards the end of 2018, when the UK Government struggled to secure a meaningful vote about the exit agreement with the EU, and had to reopen the negotiations at the very last moment in 2019.

[Figures 1 and 2 about here]

Figure 3 show how the patenting activity of UK and EU based organisations have changed over this period of high policy uncertainty. It is possible to notice that while EU-based organisations have shown a stable trend in terms of patent filing, quality and composition of inventors throughout the period of analysis, the patenting activity of UK based organisations have rapidly changed starting from 2016, showing a slower rate of patent filing, in particular at EU patent offices, with a significant reduction in patent quality, and in the share of inventors based in the EU.

[Figure 3 about here]

2.2 Methodology

The above statistics present some preliminary evidence of a possible impact on innovation of the policy uncertainty induced by Brexit. In order to test this relationship we implement a two-way fixed effects (TWFE) difference-in-differences (DID) estimation to compare the effect of Brexit uncertainty between the group of UK (treated) and EU based organisations (control) on several measures of patenting activity before and after the beginning of the Brexit process in June 2016, as specified in the following model:

$$y_{it} = \beta_0 + \beta_1 BXT_t \times UK_i + \beta_2 PS_{it} + \eta_t + \theta_{iy} + \epsilon_{it} \tag{1}$$

Here, y_{it} represents the different outcome variables measuring the patenting activity of each organisation i in quarter t, including as previously discussed the composition of patents co-applicants and co-inventors networks, the distribution of patents across different patent offices, the technological specialisation of patents, the number of new patents filed and other indicators of patents quality. The main coefficient of interest will be β_1, estimating the effect of the post-Brexit referendum uncertainty for UK organisations with respect to EU-based ones, by interacting BXT_t a dummy variable equal to 1 for quarters after 2016q2 and UK_i a dummy variable equal to 1 for UK based organisations and 0 for EU ones. We include quarter η_t fixed-effects to control for quarter-specific macro shocks, and organisation-year θ_{iy} fixed-effects to consider any idiosyncratic organisation-specific time-variant characteristics which could predict their patenting activity. In addition, we control for the organisation stock of patents filed overall until each quarter PS_{it}.

Starting from this baseline specification, we extend our analysis by modeling the Brexit-induced policy uncertainty as a dynamic process rather than as a single event. To do that we start by developing an event study analysis which allows us to check the validity of the pre-treatment parallel trend assumption, and to analyse the dynamic evolution of the impact of policy uncertainty on innovation starting from the Brexit referendum at the end of the second quarter of 2016 (Callaway and Sant'Anna, 2021). This method combines elements of inverse probability weighting (IPW) and ordinary least squares (OLS), offering a powerful framework for estimating causal effects in DiD settings. This doubly robust approach minimizes the risk of incorrect specification and offers more accurate estimates, particularly when considering a complex, evolving phenomenon like the impact of Brexit on R&D collaborations and innovation.

Finally, we perform several robustness tests to check the validity of our main results. First, we change the model in equation 1 by replacing the BXT_t dummy variable with a continuous and time-varying variable measuring changes in policy uncertainty. In this case, we make use of the time-varying Bank of England Brexit Uncertainty Index (BUI_t) developed by Bloom et al. (2019c) based on the Decision Makers Panel survey of around 3,000 firms responding every month, and representing the share of firms which rate Brexit as one of the three highest drivers of uncertainty for their business. Then, we re-estimate equation 1 with log-linearised dependent variables, given their very skewed distribution, and by using a count Poisson model for the variables with only integer values, as generally done in the related literature given the presence of many 0 values in patent data.

3 Results

We start in Table 1 by looking at the impact of policy uncertainty on the disruption of cross-border research collaborations by UK organisations. First, we can observe a significant reduction in the number of co-applicants in patents filed in by UK organisations. This could be a first evidence of disruption of research collaborations, however, it is not clear by which group of co-applicants this is driven, as none of the estimated coefficients are statistically significant when differentiating by applicant location. We observe a clear change in the composition of inventors in patents filed by UK organisations in respect to those filed by EU based applicants. In fact, following the Brexit referendum, UK organisations' patents have experienced on one side a significant reduction in the share of EU based inventors, while at the same time an increase in UK based inventors, with an overall zero sum effect in terms of the total number of inventors. This can be explained by two mechanisms. In fact, the disruption of cross-border research collaborations driven by the uncertainty about future UK-EU relations could result firstly from reduced access to the pool of EU-based inventors available for UK organisations, and secondly from a more general disruption of cross-border collaborations with EU-based institutions. Overall, this evidence suggests that UK organisations have adopted a more inward-looking innovation strategy as a result of Brexit, severing international R&D collaborations with European inventors and partners.

[Table 1 about here]

We then investigate in Table 2 how geopolitical uncertainty might have also affected UK organisations strategic decisions about where to file for patent protection. Our results show that while there is no significant effect for patents filed at the UK IPO, it is possible to observe a significant reduction across all other overseas patent offices after the Brexit referendum, with particularly negative effects for patents filed at European and US patent offices. This could be an indication that because of the mounting uncertainty UK based organisations have refocused their patenting strategy domestically, reducing patent filing at overseas offices, in particular those in European countries. This could be a signal of a lower importance of the EU single market for UK innovations, or also an isolationist strategy to keep the protection of intellectual properties in the home country jurisdiction (Hingley and Park, 2017).

[Table 2 about here]

We then investigate the heterogeneous impact of policy uncertainty on innovations across different technological fields. To do this, we consider in Table 3 the overall number of IPC sub-classes listed in each patent, and the breakdown by IPC classes. It is possible to notice an overall increase in the total number of IPC sub-classes per patent by UK organisations following the Brexit referendum, a possible sign of an increase in patent generality. This evidence could indicate that UK organisations have expanded the scope of patents as a consequence of Brexit, increasing the number of IPC sub-classes per patent. However, if we differentiate by IPC class, we can observe a significant decrease in patents for performing operations and transporting technologies (IPC B), one of the technologies in which the UK has a comparative advantage, and a contemporaneous increase of patents in physics related technologies (IPC G). This could be evidence of a shift away from technologies in which UK based organisations traditionally had a comparative advantage, towards new technologies not widely patented before. It can also be interpreted as an effort by UK organisations to develop new technological capabilities domestically, following a "technological sovereignty" approach (Edler et al., 2023).

[Table 3 about here]

Finally, we want to investigate the overall impact of these inward-looking, autarchic, technological sovereignty disruptive effects of policy uncertainty on the overall quantity and quality of UK organisations' patents. Column 1 in Table 4 shows a significant and sharp decrease in the number of patent families registered by UK organisations with respect to EU-based ones after the Brexit referendum. As discussed before, this could be jointly driven by a disruption in cross-border R&D collaborations, and all the consequent effects documented above, and by a delay in risky investment for R&D activities. It is possible to notice in the following column that uncertainty has also significantly affected not only the likelihood of filing new patent families, but also the quality of those filed in. In fact, those filed in by UK organisations following the Brexit referendum are significantly less likely to be cited by other patents, a general indicator of their quality. However, we do not observe any effect in terms of patents generality and originality (Hall and Trajtenberg, 2004). Further unreported results show that the quality of patents has decreased particularly for patent families filed at European patent offices, another indication that the uncertainty regarding the future UK-EU research and innovation relationships might have prevented UK organisations from patenting high-quality innovations in Europe.[8]

[Table 4 about here]

Results reported in Figure 4 corroborate our main findings by implementing an event-study analysis. We focus in this case on the most relevant results identified in the previous tables. In general, we can notice the absence of a statistical difference in patenting outcomes between UK and EU organisations before the Brexit referendum, evidence of the validity of the parallel trend assumption. From the top diagrams, we can observe that policy uncertainty has immediately affected the composition of UK organisations inventors teams after the Brexit referendum, with a sharp increase in the share of UK inventors and a consequent decrease in the share of EU-based inventors. The impact on the total number of filed patents is overall negative, although it is noisily estimated, while we can observe a sharp drop in the number of patents filed by UK organisation at European patent offices in diagram (d), in particular starting from 2019. This coincides with a rapid increase in policy uncertainty as shown in Figure 1, following the reopening of the Brexit negotiations between the UK and the EU, and the UK government announcement that UK organizations would no longer be able to access funding for Horizon 2020 projects after the 1st quarter of that year. The bottom diagrams confirm a sharp and immediate decline in UK organisations patents forward citations and overall quality following the Brexit referendum. This could also be a sign of the interruption of cross-border R&D collaborations between UK and EU organisations, as a more isolationist and technological-sovereign approach might have pushed EU organisations to stop citing UK patents.[9]

[Figure 4 about here]

4 Discussion

Through our analysis, it becomes clear that the ramifications of Brexit have pronouncedly affected the landscape of research and innovation within the UK. The reduction in the

[8] Results reported in Tables A3 and A4 in the Appendix are consistent when re-estimating the baseline specifications with log-linearised dependent variables or using a count Poisson model for the variables with only integer values.

[9] Results reported in Table A5 in the Appendix are consistent when considering a continuous and time-varying measure of policy uncertainty using the Bank of England Brexit Uncertainty Index.

number of co-applicants from EU countries in patents filed by UK companies suggests a fragmented collaborative environment. Such collaborations traditionally drive both the quantity and quality of outputs, indicating a disruption that could threaten the UK's standing as a global innovation economy, in line with existing studies highlighting the importance of international cooperation (Squicciarini and Voigtländer, 2015; Diodato et al., 2021).

The strategic shift towards more domestic-centric patent filings, as evidenced by diminished activities in EU and US patent offices, likely represents a defensive move against uncertainties over intellectual property management post-Brexit. This inward-looking pivot, while protective, might reduce the exposure and influence of UK innovations in international markets (Hingley and Park, 2017). Moreover, such trends potentially signal a broader withdrawal from the collaborative and open innovation model that has characterised global research and development in recent decades, highlighting potential concerns about the UK's future role in the international innovation landscape (Chesbrough, 2003). Their disruption can greatly impact organisational output and strategic planning (Cassiman and Veugelers, 2006).

Furthermore, our findings regarding the technological shifts in patent filings post-Brexit highlight not just a diversification strategy, but potentially a deeper recalibration of UK innovation towards domains perceived as more secure and controllable at a national level. This inclination towards "technological sovereignty" might be symptomatic of wider geopolitical shifts towards nationalism and has significant implications for policy (Edler et al., 2023). Although diversifying technology portfolios could be a strategic hedge, moving away from established areas of comparative advantage could dilute the UK's competitive edge in global tech arenas.

This recalibration has unfolded alongside an evident decline in the quality of UK patents, particularly those filed in Europe. This degradation, as evidenced by fewer citations, suggests a diminishing recognition of UK innovations, which is problematic given the strong correlation between citation metrics and innovation impact (Hall and Trajtenberg, 2004). The decrease in patent quality and quantity following the Brexit referendum suggests a potential erosion of R&D productivity which could have long-lasting repercussions on economic growth and competitiveness (Schumpeter, 1942; Solow, 1957).

UK policymakers must address these issues by developing new policy strategies to promote domestic innovation and help foster new international collaborations. Initiatives could include refocusing some of the current innovation public support, such as the R&D tax credit provided by HMRC and the UKRI research funding, to incentivise UK organisations to form new international partnerships beyond the EU, to partially counterbalance the loss of EU collaborations. Establishing bilateral R&D agreements with other global innovation leaders could be particularly advantageous. Additionally, ensuring policy clarity and stability is urgent to diminish the uncertainty that might curtail R&D investment. An environment characterised by clear, stable, and strategic policies could enhance investor confidence and innovation activities. Furthermore, adapting to new technological frontiers by promoting industries and academia around emerging tech sectors could pivot the UK towards future-ready areas of innovation, ensuring that the UK remains a competitive player on the global stage.

5 Conclusion

Uncertainty regarding the geopolitical environment could be particularly detrimental for innovation, as it requires high-risk investment, and long-term commitments with scientists and research partners scattered across different countries. This paper has focused on the effects of political and economic disintegration on cross-border patent collaborations and innovation, exploiting the UK exit from the EU as a quasi-natural experiment in a two-way fixed-effects difference-in-difference analysis. Our results reveal a disruption of cross-border research collaborations, as EU based inventors are replaced by UK ones in UK organisations' patents, and by a shift in the technological fields patented. This has resulted in a significant decrease in the number and quality of patents applications after the Brexit referendum for UK organisations in respect to EU ones, affecting in particular applications at European patent offices.

The results from this study highlight the significant impact of geopolitical uncertainty on cross-border research collaborations and innovation. The analysis reveals that political and economic disintegration can disrupt international research networks, with adverse consequences for patenting activity and technological progress. This is evidence that the recent evolution of technological sovereignty and geopolitical tensions could have dire consequences for science and technology, as innovation is inherently global, requiring cross-border collaborations to pool resources, knowledge, and expertise (Verspagen et al., 2005;

LaBelle et al., 2023). Our findings suggest that the disruption of these collaborations can significantly hinder the innovation capacity of organisations, especially in knowledge-intensive sectors that rely on international networks of scientists. This mirrors earlier studies on the impact of political instability on international R&D collaboration and the role of institutional stability in fostering innovation (Charpin et al., 2024).

Moreover, the shift in patenting activity and the decline in patent quality, as observed in this paper, reflects a broader phenomenon where uncertainty over geopolitical events increases the perceived risks associated with long-term innovation investments. As innovation involves significant upfront investment in research, often with uncertain and delayed returns, the disruption of stable institutional environments—whether through trade barriers, regulatory divergence, or political fragmentation—can reduce the incentive for organisations and researchers to engage in cross-border collaborations (Bloom, 2009, 2014). Policymakers must therefore be proactive in mitigating the risks associated with geopolitical instability in an increasingly multipolar world, fostering cross-border collaborations and mutual trust to ensure continued technological progress.

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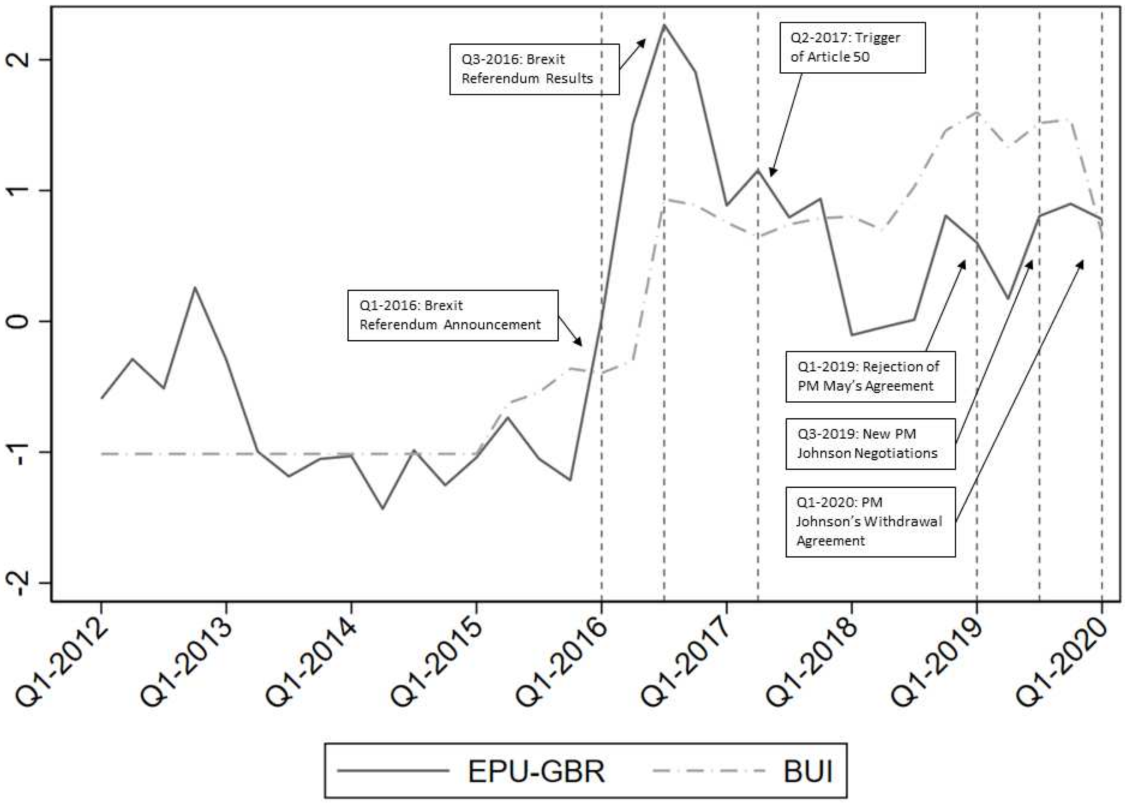
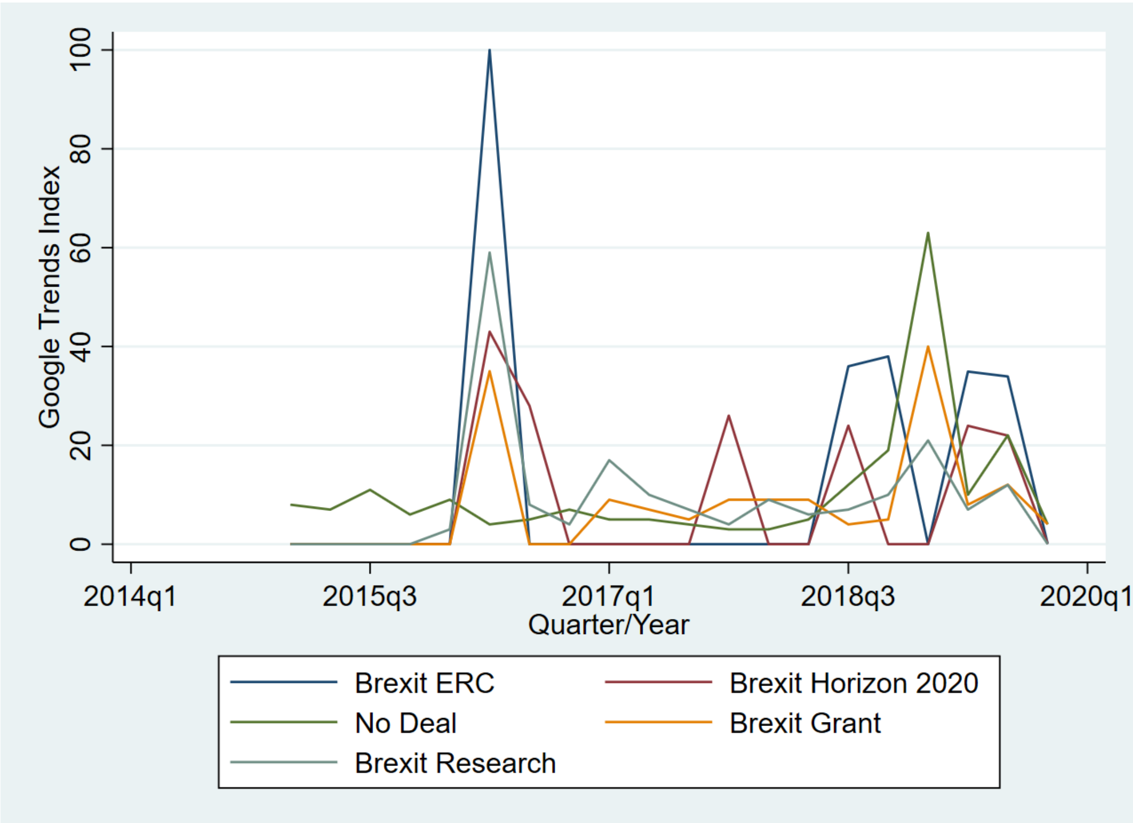
Tables and Figures

Figure 1: Brexit events timeline and quarterly changes in uncertainty indexes 2012-2020.



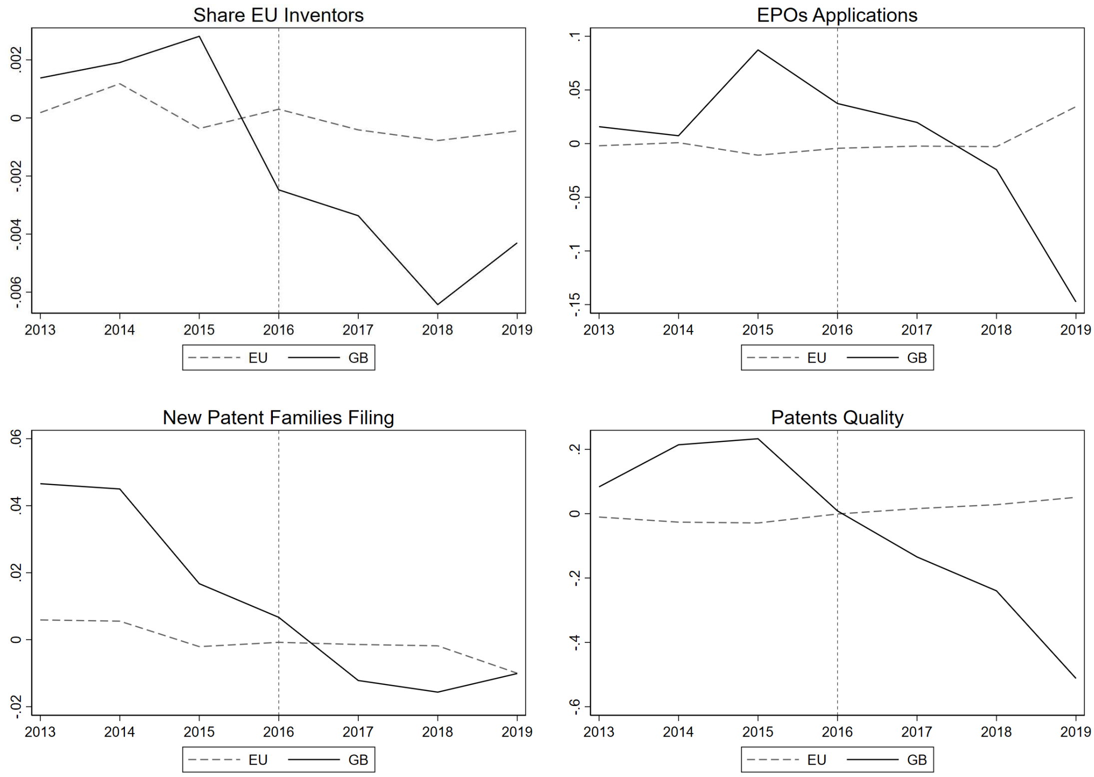
Note: Time series of the Bank of England Brexit Uncertainty Index (BUI) (Bloom et al., 2019c), and of the Economic Policy Uncertainty (EPU) index (Baker et al., 2016) for each quarter between 2012-Q1 and 2020-Q1. Key dates and events important to explain uncertainty indicated with reference lines.

Figure 2: Google searches in the UK about Brexit and other innovation related keywords.



Note: Time series of Google Trends indexes summarising Google searches in the UK about Brexit and other innovation related keywords since 2015.

Figure 3: Patenting activity of UK and EU based organisations over the period of analysis.



Note: Statistics using PATSTAT data over the period 2013-2019. Yearly mean values for UK and EU based organisations after controlling for quarter seasonality and country specific effects.

Table 1: Impact of policy uncertainty on cross-border patenting collaborations.

	No. Coapp.	UK Coapp.	EU Coapp.	ROW Coapp.	US Coapp.
$BXT_t \times UK_i$	-0.0265***	0.00140	-0.000547	-0.000723	-0.000130
	(0.00905)	(0.00259)	(0.00162)	(0.00148)	(0.00175)
Observations	340,807	340,807	340,807	340,807	340,807
R-squared	0.810	0.993	0.983	0.885	0.882
	No. Invent.	UK Invent.	EU Invent.	ROW Invent.	US Invent.
$BXT_t \times UK_i$	0.0361	0.0139**	-0.0121***	0.000839	-0.00264
	(0.0463)	(0.00575)	(0.00427)	(0.00376)	(0.00396)
Observations	340,466	340,466	340,466	340,466	340,466
R-squared	0.692	0.945	0.889	0.760	0.758

Notes: Estimates from a panel two-way fixed effects (TWFE) difference-in-differences (DID) model using PATSTAT data at the applicant-quarter level for the period 2013-2019. Quarter and applicant-year fixed-effects included in all estimations. Robust standard errors clustered at the applicant-quarter level reported in parenthesis. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2: Impact of policy uncertainty on patent filing across offices.

	(1)	(2)	(3)	(4)	(5)
	UK PTO	EU PTO	US PTO	WIPO	ROW PTO
$BXT_t \times UK_i$	-0.0507	-0.243***	-0.296***	-0.169**	-0.202***
	(0.0526)	(0.0819)	(0.0845)	(0.0718)	(0.0572)
Observations	351,795	351,795	351,795	351,795	351,795
R-squared	0.826	0.958	0.929	0.935	0.880

Notes: Estimates from a panel two-way fixed effects (TWFE) difference-in-differences (DID) model using PATSTAT data at the applicant-quarter level for the period 2013-2019. Quarter and applicant-year fixed-effects included in all estimations. Robust standard errors clustered at the applicant-quarter level reported in parenthesis. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 3: Impact of policy uncertainty on patents technological scope.

	Tot. IPC	IPC A	IPC B	IPC D	IPC D
$BXT_t \times UK_i$	0.143***	0.00137	-0.0271***	0.00522	0.000289
	(0.0538)	(0.00654)	(0.00633)	(0.00584)	(0.00166)
Observations	344,664	344,664	344,664	344,664	344,664
R-squared	0.584	0.835	0.796	0.771	0.786
		IPC E	IPC F	IPC G	IPC H
$BXT_t \times UK_i$		-0.00169	0.00507	0.0150**	0.00179
		(0.00306)	(0.00442)	(0.00714)	(0.00640)
Observations		344,664	344,664	344,664	344,664
R-squared		0.846	0.794	0.751	0.803

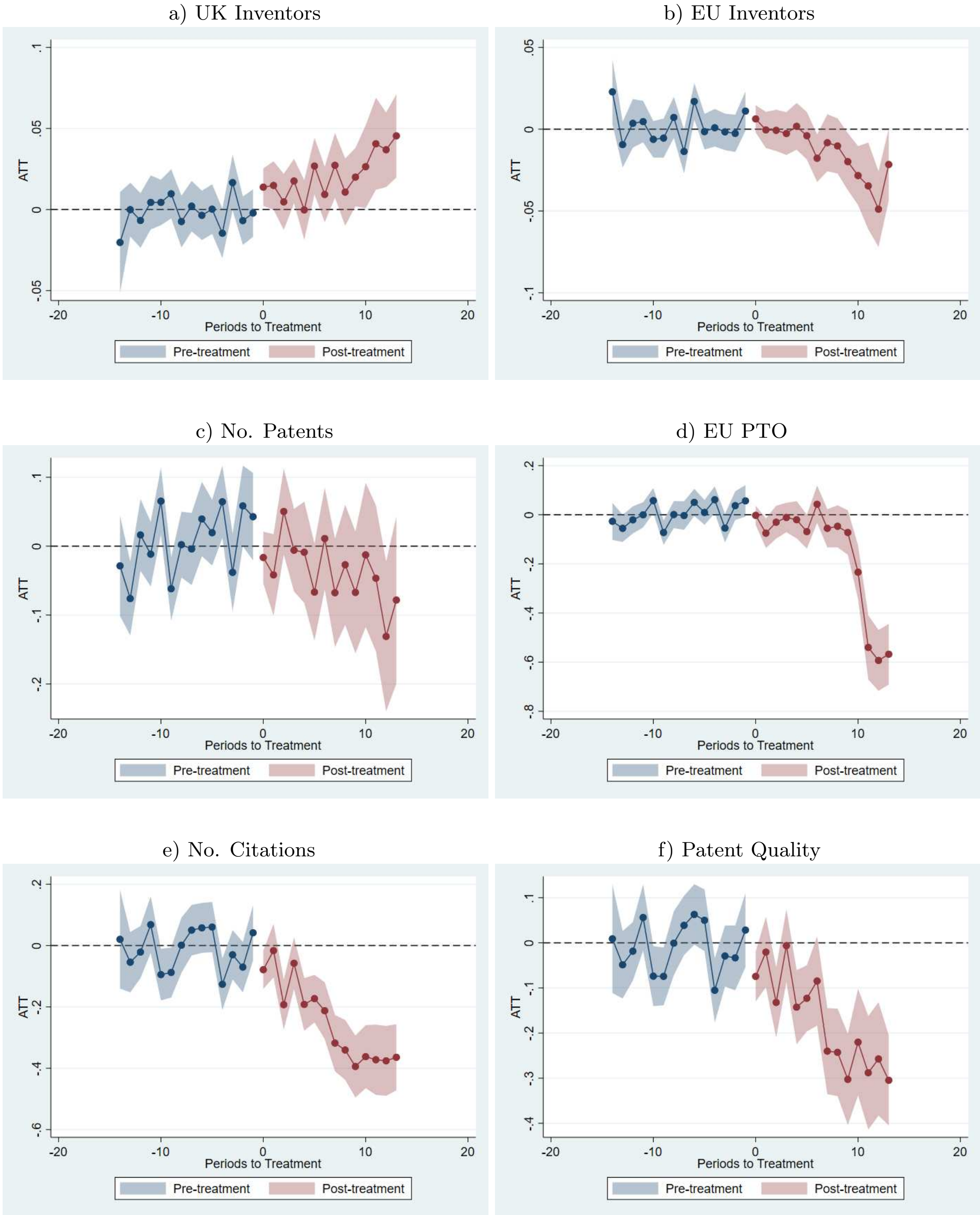
Notes: Estimates from a panel two-way fixed effects (TWFE) difference-in-differences (DID) model using PATSTAT data at the applicant-quarter level for the period 2013-2019. Quarter and applicant-year fixed-effects included in all estimations. Robust standard errors clustered at the applicant-quarter level reported in parenthesis. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 4: Impact of policy uncertainty on patents number and quality.

	(1) Number	(2) Citations	(3) Quality	(4) Generality	(5) Originality
$BXT_t \times UK_i$	-0.213**	-0.906***	-0.671***	-0.0101	0.00917
	(0.105)	(0.149)	(0.110)	(0.00830)	(0.00584)
Observations	351,795	351,795	351,795	196,463	317,109
R-squared	0.957	0.706	0.679	0.560	0.605

Notes: Estimates from a panel two-way fixed effects (TWFE) difference-in-differences (DID) model using PATSTAT data at the applicant-quarter level for the period 2013-2019. Quarter and applicant-year fixed-effects included in all estimations. Robust standard errors clustered at the applicant-quarter level reported in parenthesis. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Figure 4: Dynamic impact of policy uncertainty on UK organisations patenting activities.



Note: Estimates from an event study analysis using PATSTAT data at the applicant-quarter level for the period 2013-2019. Quarter and applicant-year fixed-effects included in all estimations. Robust standard errors clustered at the applicant-quarter level reported in parenthesis. Confidence intervals at the 95% significance level reported.

A Appendix

Table A1: Patent variables definitions.

Variable	Definition
No. Patent Families	Number of new patent families filed in quarter q by applicant i.
Patents Stock	Total number of patent families filed in by applicant i up to quarter q.
No. UK PTO Filings	Number of patents filed in at the UK Patent Office in quarter q by applicant i.
No. EU PTOs Filings	Number of patents filed in at the EPO and other EU countries national patent offices in quarter q by applicant i.
No. US PTO Filings	Number of patents filed in at the US Patent Office in quarter q by applicant i.
No. WIPO Filings	Number of patents filed in at the International Patent Office in quarter q by applicant i.
No. ROW PTOs Filings	Number of patents filed in at other countries' Patent Offices in quarter q by applicant i.
No. Citations	Average number of citations for patent families filed in quarter q by applicant i.
Generality	Average generality measure estimated following Hall and Trajtenberg (2004) for patent families filed in quarter q by applicant i.
Originality	Average originality measure estimated following Hall and Trajtenberg (2004) for patent families filed in quarter q by applicant i.
Patent Quality	Average quality based on relative number of citations in respect to other patents filed in the same quarter for patent families filed in quarter q by applicant i.
No. IPC Classes	Average number of IPC technological classifications at the sub-class level in which applicant i has filed a patent in quarter q.
Sh. IPC A	Share of total IPC sub-classes in section A - Human Necessities - for patents filed by applicant i in quarter q.
Sh. IPC B	Share of total IPC sub-classes in section B - Performing Operations, Transporting - for patents filed by applicant i in quarter q.
Sh. IPC C	Share of total IPC sub-classes in section C - Chemistry, Metallurgy - for patents filed by applicant i in quarter q.
Sh. IPC D	Share of total IPC sub-classes in section D - Textiles, Paper - for patents filed by applicant i in quarter q.
Sh. IPC E	Share of total IPC sub-classes in section E - Fixed Constructions - for patents filed by applicant i in quarter q.
Sh. IPC F	Share of total IPC sub-classes in section F - Mechanical Engineering, Lighting, Heating, Weapons - for patents filed by applicant i in quarter q.
Sh. IPC G	Share of total IPC sub-classes in section G - Physics - for patents filed by applicant i in quarter q.
Sh. IPC H	Share of total IPC sub-classes in section H - Electricity - for patents filed by applicant i in quarter q.
No. Inventors	Average number of inventors listed in patents filed by applicant i in quarter q.
Sh. UK Inventors	Share of UK based inventors listed in patents filed by applicant i in quarter q.
Sh. EU Inventors	Share of EU based inventors listed in patents filed by applicant i in quarter q.
Sh. US Inventors	Share of US based inventors listed in patents filed by applicant i in quarter q.
Sh. ROW Inventors	Share of inventors based in the rest of the world listed in patents filed by applicant i in quarter q.
No. Coapplicants	Average number of co-applicants listed in patents filed by applicant i in quarter q.
Sh. UK Coapp.	Share of UK based co-applicants listed in patents filed by applicant i in quarter q.
Sh. EU Coapp.	Share of EU based co-applicants listed in patents filed by applicant i in quarter q.
Sh. US Coapp.	Share of US based co-applicants listed in patents filed by applicant i in quarter q.
Sh. ROW Coapp.	Share of co-applicants based in the restof the world listed in patents filed by applicant i in quarter q.

Table A2: Summary Statistics of Key Variables.

Variable	Obs	Mean	S.D.	Min.	Max.
No. Patent Families	987,589	2.15734	10.42464	1	1495
Patents Stock	987,589	21.81575	227.8396	1	39498
No. UK PTO Filings	987,589	0.103918	0.717604	0	103
No. EU PTOs Filings	987,589	1.900543	9.821715	0	1477
No. US PTO Filings	987,589	1.188229	5.533994	0	435
No. WIPO Filings	987,589	1.224721	6.013971	0	554
No. ROW PTOs Filings	987,589	0.677364	2.544976	0	161
No. Citations	987,589	2.307479	6.089659	0	377
Generality	527,436	0.294622	0.257412	0	0.911383
Originality	854,098	0.374392	0.226072	0	0.927937
Patent Quality	987,589	1.313048	3.197617	0	278.3541
No. IPC Classes	963,728	3.058492	1.884798	1	40
Sh. IPC A	963,728	0.23798	0.385643	0	1
Sh. IPC B	963,728	0.212257	0.358732	0	1
Sh. IPC C	963,728	0.111357	0.265037	0	1
Sh. IPC D	963,728	0.011829	0.093576	0	1
Sh. IPC E	963,728	0.0681	0.231062	0	1
Sh. IPC F	963,728	0.105256	0.270561	0	1
Sh. IPC G	963,728	0.149406	0.308532	0	1
Sh. IPC H	963,728	0.103815	0.266029	0	1
No. Inventors	947,101	2.511564	1.905159	1	130
Sh. UK Inventors	947,101	0.09577	0.27701	0	1
Sh. EU Inventors	947,101	0.77285	0.352191	0	1
Sh. ROW Inventors	947,101	0.103392	0.203381	0	1
Sh. US Inventors	947,101	0.027988	0.131129	0	1
No. Coapplicants	897,993	1.262816	0.735273	1	33
Sh. UK Coapp.	897,993	0.098914	0.2938	0	1
Sh. EU Coapp.	897,993	0.874601	0.318977	0	1
Sh. ROW Coapp.	897,993	0.010821	0.081398	0	1
Sh. US Coapp.	897,993	0.015664	0.105682	0	1

Table A3: Impact of policy uncertainty on innovation: log-linearised dependent variables.

	No. Coapp.	UK Coapp.	EU Coapp.	ROW Coapp.	US Coapp.
$BXT_t \times UK_i$	-0.0110***	0.000800	-0.000702	-0.000686	-0.000116
	(0.00339)	(0.00150)	(0.00131)	(0.00122)	(0.00143)
Observations	340,807	340,807	340,807	340,807	340,807
R-squared	0.824	0.994	0.987	0.862	0.857
	No. Invent.	UK Invent.	EU Invent.	ROW Invent.	US Invent.
$BXT_t \times UK_i$	0.0100	0.00915**	-0.00875***	0.000680	-0.00230
	(0.0103)	(0.00387)	(0.00317)	(0.00296)	(0.00298)
Observations	340,466	340,466	340,466	340,466	340,466
R-squared	0.718	0.945	0.897	0.754	0.758
	UK PTO	EU PTO	US PTO	WIPO	ROW PTO
$BXT_t \times UK_i$	-0.00441	-0.0640***	-0.0531***	-0.0453***	-0.0512***
	(0.0118)	(0.0129)	(0.0133)	(0.0124)	(0.0124)
Observations	351,795	351,795	351,795	351,795	351,795
R-squared	0.843	0.842	0.847	0.851	0.813
	No. Patents	Citations	Generality	Originality	Quality
$BXT_t \times UK_i$	-0.0598***	-0.0865***	-0.00757	0.00604	-0.0826***
	(0.0119)	(0.0215)	(0.00636)	(0.00431)	(0.0191)
Observations	351,795	351,795	196,463	317,109	351,795
R-squared	0.842	0.762	0.559	0.605	0.688

Notes: Estimates from a panel two-way fixed effects (TWFE) difference-in-differences (DID) model using PATSTAT data at the applicant-quarter level for the period 2013-2019. Quarter and applicant-year fixed-effects included in all estimations. Robust standard errors clustered at the applicant-quarter level reported in parenthesis. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A4: Impact of policy uncertainty on innovation: Poisson count model.

	(1) No. Patents	(2) UK PTO	(3) EU PTO	(4) US PTO	(5) WIPO	(6) ROW PTO
$BXT_t \times UK_i$	-0.105***	-0.0920	-0.120***	-0.128***	-0.0981***	-0.176***
	(0.0251)	(0.0642)	(0.0255)	(0.0274)	(0.0255)	(0.0368)
Observations	351,795	31,572	335,651	269,972	265,366	212,555
R-squared	0.957	0.826	0.958	0.929	0.935	0.880

Notes: Estimates from a panel two-way fixed effects (TWFE) difference-in-differences (DID) poisson count model using PATSTAT data at the applicant-quarter level for the period 2013-2019. Quarter and applicant-year fixed-effects included in all estimations. Robust standard errors clustered at the applicant-quarter level reported in parenthesis. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A5: Impact of policy uncertainty on innovation: Brexit Uncertainty Index.

	No. Coapp.	UK Coapp.	EU Coapp.	ROW Coapp.	US Coapp.
$BUI_t \times UK_i$	-0.000824***	2.23e-05	-4.61e-05	3.45e-07	2.34e-05
	(0.000301)	(8.55e-05)	(5.31e-05)	(4.70e-05)	(5.91e-05)
Observations	340,807	340,807	340,807	340,807	340,807
R-squared	0.810	0.993	0.983	0.885	0.882
	No. Invent.	UK Invent.	EU Invent.	ROW Invent.	US Invent.
$BUI_t \times UK_i$	-0.00250*	0.000328*	-0.000250*	-0.000152	7.43e-05
	(0.00151)	(0.000184)	(0.000138)	(0.000121)	(0.000127)
Observations	340,466	340,466	340,466	340,466	340,466
R-squared	0.692	0.945	0.889	0.760	0.758
	UK PTO	EU PTO	US PTO	WIPO	ROW PTO
$BUI_t \times UK_i$	-0.000699	-0.0115***	-0.00884***	-0.00793***	-0.00718***
	(0.00176)	(0.00290)	(0.00282)	(0.00255)	(0.00179)
Observations	351,795	351,795	351,795	351,795	351,795
R-squared	0.826	0.958	0.929	0.935	0.880
	No. Patents	Citations	Generality	Originality	Quality
$BUI_t \times UK_i$	-0.00909**	-0.0326***	-0.000187	0.000181	-0.0253***
	(0.00359)	(0.00471)	(0.000277)	(0.000185)	(0.00345)
Observations	351,795	351,795	196,463	317,109	351,795
R-squared	0.957	0.706	0.560	0.605	0.679

Notes: Estimates from a panel two-way fixed effects (TWFE) difference-in-differences (DID) model using PATSTAT data at the applicant-quarter level for the period 2013-2019. Quarter and applicant-year fixed-effects included in all estimations. Robust standard errors clustered at the applicant-quarter level reported in parenthesis. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.