# Climate Risk, Innovation, and the Diffusion of Green Technologies *

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**Abstract**

Climate technologies are central to addressing rising climate risks, yet existing research has largely emphasized policy as the primary driver of innovation. We examine whether climate vulnerability itself shapes innovation incentives as an additional channel alongside policy. Using patent data for mitigation and adaptation technologies in 77 countries from 1995–2021, we exploit within-country variation in vulnerability while controlling for policy and distinguishing key margins of heterogeneity, including between domestic invention and international technology diffusion. Climate vulnerability does not generate a uniform innovation response. High-income economies capable of influencing global emissions shift innovation towards mitigation. Middle-income countries face constraints that limit access to foreign adaptation technologies precisely when adaptation needs are greatest, and the increase in domestic innovation – often reflecting the context-specific nature of adaptation technologies – is not sufficient to offset this decline. Falsification tests rule out competing mechanisms and provide evidence of an independent association between climate vulnerability and innovation, pointing to a previously underexplored channel shaping technological change.

**JEL codes**: O44, O31, O33, Q55, Q37

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# 1 Introduction

Climate change imposes both an environmental externality and a persistent, uneven shock to economic activity. Technological innovation plays a central role in both mitigating climate change and adapting to its impacts, but the forces that shape climate-related innovation remain imperfectly understood. Existing research has largely emphasized government regulation as the primary driver of clean technological change. Yet climate risks themselves may shape innovation incentives by altering the expected returns to technologies that reduce emissions or increase resilience. This paper examines whether climate vulnerability independently affects climate innovation beyond the effects of policy, and how these risk-driven incentives alter patterns of technological change across countries.

Whether climate vulnerability ultimately stimulates or constrains innovation is not immediately clear. On the one hand, more vulnerable countries may face stronger demand for technologies that reduce climate damage or improve resilience. On the other hand, vulnerability can increase uncertainty, tighten investment constraints, and weaken capacity to absorb or diffuse knowledge. Empirical evidence on these effects remains limited and inconclusive. Two studies document declines in green innovation as climate risks rise (Xiao and Fei 2024; Wen et al. 2023), while another reports positive responses (Tran et al. 2025). A key limitation of this literature is that it does not cleanly separate the effects of climate risk from those of regulatory policy. By jointly observing climate vulnerability and climate policy across countries, our analysis isolates innovation responses to climate risk from those associated with regulatory incentives.

We exploit cross-country heterogeneity to provide a more nuanced view of these dynamics, examining differences across income groups, technology types, industries, and the origin of innovation. This perspective reveals patterns that aggregate analyses can obscure as countries vary in their exposure and contributions to climate risks as well as in their institutional and innovative capacity. These structural differences shape whether countries build domestic capabilities or rely on external sources of technology – an adjustment margin largely overlooked in the literature. In this context, climate vulnerability may reinforce divergent development pathways (Fagerberg and Srholec 2007) and influence the position of countries in the global technology race, with climate-related industries emerging as key domains of future growth and strategic leadership.

To study these questions, we assemble a panel dataset of climate-related patent filings, climate policy measures, and vulnerability indicators for 77 countries between 1995 and 2021. The patent data allows us to distinguish between mitigation and adaptation technologies [1], as well as between

[1]Mitigation refers to technologies that reduce greenhouse gas emissions, such as renewable energy or energy-

new domestic inventions and cross-border technology transfers. We further link patents to broad sectors of economic activity. This structure enables us to move beyond aggregate measures of innovation and examine how climate vulnerability affects not only the level of inventive activity, but also the sources and composition of technological change.

Our empirical strategy exploits within-country changes in climate vulnerability over time, while accounting for differences in climate policies across countries. We measure climate risk using the ND-GAIN vulnerability index. Unlike temperature or weather-based measures, this index captures the economic relevance of climate risk by combining physical exposure with structural sensitivity. To reduce concerns about endogeneity, we exclude the adaptive capacity components of the index that can reflect technological adoption or institutional readiness. We further implement a range of tests to ensure that the estimated effects reflect climate-specific innovation responses rather than anticipatory or general changes in innovative capacity. While our approach does not rely on a quasi-experimental source of variation, it leverages this within-country variation, extensive controls, and falsification tests to isolate a robust relationship between climate risk and innovation outcomes. We therefore interpret these results as evidence of an independent association between climate vulnerability and innovation that is distinct from policy-driven effects, highlighting an important and largely unexplored channel of technological change.

The results reveal that climate vulnerability reshapes innovation incentives in ways that differ sharply across countries. In high-income economies, vulnerability strengthens incentives to develop mitigation technologies, reinforcing policy-driven incentives. At the same time, adaptation patenting declines, reflecting a drop in cross-border technology transfers and a shift toward more locally tailored solutions. This pattern implies a strategic reallocation of innovative effort toward mitigation among major emitters that can meaningfully influence future climate risks.

Middle-income countries follow a markedly different trajectory. Rather than stimulating climate innovation, rising vulnerability appears to constrain it. Mitigation activity weakens primarily through reductions in access to foreign technologies, while adaptation responses remain limited and concentrated in lower-value domestic inventions. These patterns suggest that financial constraints, institutional capacity, and investment risk may limit both the development and diffusion of climate technologies in more vulnerable economies. China stands apart as a hybrid case. It resembles high-income emitters in expanding mitigation activity, but this response relies almost entirely on foreign technology inflows.

The paper makes three contributions. First, we identify the independent role of climate vulner-

efficient production, while adaptation refers to technologies that reduce vulnerability to climate damages, such as drought-resistant crops or flood protection systems.

ability in shaping innovation, separating its effects from those of environmental regulation. While existing work emphasizes policy-induced innovation, which operates through deliberate institutional design, we show that vulnerability to climate risk constitutes a distinct and economically meaningful determinant of technological change.

Second, we extend the analysis beyond OECD economies, treating high- and middle-income countries as analytically distinct. These country groups differ not only in their innovation capacity and institutional strength, but also in their contributions to global emissions and in the forms of climate risk they face. This distinction allows us to show that climate vulnerability does not operate uniformly across countries, but instead generates different innovation responses under different development conditions.

Finally, we provide a rich account of how climate vulnerability affects technological change across multiple margins. By distinguishing between new domestic inventions and international technology transfers, we separate countries' ability to generate innovation from their ability to access and absorb foreign technologies. We further differentiate between mitigation and adaptation technologies, which differ in their objectives and in their scope for diffusion, with adaptation being more context-specific (Moscona and Sastry 2025). Examining sectoral variation allows us to examine whether these responses are broad-based or concentrated in specific parts of the economy.

The rest of the paper proceeds as follows. Section 2 lays out the mechanisms through which we might expect climate vulnerability to affect innovation and technology adoption. In section 3, we present the sources of the data, explain the construction of the variables and the method to address endogeneity, and detail the estimation strategy. Sections 4 and 5 explain results for high- and middle-income countries respectively. Section 6 provides several robustness tests of our results and section 7 concludes.

# 2 Channels linking climate vulnerability, regulation, and innovation

## 2.1 Inter-playing effects of regulation & climate risk on innovation

Environmental regulation plays a central role in shaping incentives for climate-related innovation. Because firms do not internalize the social costs of emissions, private investment in cleaner technologies may be inefficiently low. A large empirical literature shows that regulations can stimulate domestic innovation in clean technologies and influence patterns of international diffusion (Jaffe and Palmer 1997; Johnstone et al. 2010; Brunel 2019; Peters et al. 2012; Popp 2006; Dechezleprêtre et al. 2013). By increasing the relative cost of emission-intensive production and strengthening demand for low-carbon alternatives, policy interventions redirect research and development toward cleaner processes and products, consistent with theories of induced innovation (Hicks 1932; Acemoglu et al. 2012; Aghion et al. 2016). The strength of these responses depends on the credibility and persistence of regulatory signals, which shape expectations and support long-term innovative investment (North 1993; Nemet et al. 2017). Consequently, regulatory environments influence not only the level of climate-related innovation but also its technological direction.

Yet, while regulation plays a central role, climate vulnerability may shape innovation incentives by conditioning how firms respond to policy signals. Unlike regulation, which reflects deliberate institutional design, vulnerability captures exposure to physical and economic risks arising from climate change. These forces can generate implicit price signals that alter expected returns to innovation under a given regulatory environment. Holding regulation fixed, firms may respond by developing new technologies to hedge against climate-related risks, improve resilience, or adapt production processes to changing conditions. Vulnerability may also shape innovation indirectly by affecting expectations of future policy tightening, prompting firms to invest preemptively in cleaner or more resilient technologies (Acemoglu et al. 2012; Goulder and Mathai 2015).

At the same time, climate vulnerability may constrain innovation by weakening the resources required for research and development, thereby shaping how firms respond to regulatory incentives. Physical shocks can destroy capital, raise operating costs, and redirect financial and managerial resources toward short-term recovery rather than long-term investment. Heightened risk may also reduce access to finance or increase the cost of capital, limiting firms' ability to sustain innovative activity even in the presence of policy support. These constraints are particularly salient for international technology diffusion: foreign firms may be less willing to seek patent protection or transfer technologies into highly vulnerable environments when expected returns are uncertain or enforcement capacity is weak. As a result, vulnerability can simultaneously increase demand for new technologies and reduce the capacity to develop or adopt them, making its net effect on innovation – and its interaction with regulation – theoretically ambiguous.

Whether vulnerability ultimately accelerates or inhibits patenting therefore depends on the broader regulatory environment. Strong and predictable policy frameworks can amplify vulnerability-driven incentives by lowering investment uncertainty and supporting long-term innovative effort. Conversely, weak, inconsistent, or poorly enforced regulation may magnify the constraining effects of vulnerability by discouraging investment and slowing technology adoption.

## 2.2 Climate vulnerability and innovation beyond regulation

Climate vulnerability may also influence innovation independently of policy through demand, financial, and expectation-based channels. Greater exposure to climate risks can shift consumer preferences toward more environmentally sustainable products and alter firms' market opportunities (Delmas and Burbano 2011; Testa et al. 2018). At the same time, climate vulnerability can erode household incomes, dampening demand for sustainable products. Vulnerability may also affect firms' access to finance by increasing perceived investment risk or changing capital allocation in response to climate exposure, regardless of regulatory incentives (Whelan et al. 2021; Krueger et al. 2020; Kempa 2026).

A small but growing body of research has begun to examine the relationship between climate vulnerability and innovation directly. Wen et al. (2023) and Xiao and Fei (2024) find that climate vulnerability reduces green investment. By contrast, Tran et al. (2025) reports a positive association between vulnerability and green patenting, underscoring an ambiguity within the literature. While these studies provide valuable early insights, they rely on patent and innovation data that are less comprehensive and less finely classified than PATSTAT, making it difficult to distinguish systematically between mitigation and adaptation technologies or between new inventions and technology transfers. Moreover, their empirical approaches rely on linear models, which are not well suited to outcomes characterized by many zero observations and heteroskedasticity. Finally, because some studies omit climate policies altogether and others control for them only imperfectly, it remains unclear whether their results capture an independent mechanism beyond established policy-driven innovation effects.

## 2.3 Heterogeneity in climate innovation responses

The mechanisms at play are likely to differ across countries, technologies, and industries. Across income groups, differences in regulatory stringency, enforcement capacity, and domestic innovation systems shape how climate risks translate into technological change. In many non-OECD settings, climate-related technological progress often relies heavily on the adoption of foreign technologies rather than on domestic invention (Dechezlepretre et al. 2011; Popp 2006). In such contexts, climate vulnerability may simultaneously increase demand for external technologies while deterring technology transfer due to concerns about market size, enforcement, or political and economic instability.

Heterogeneity also arises between mitigation and adaptation technologies. Mitigation technologies tend to exhibit stronger scale economies and greater potential for global diffusion, while adaptation technologies are often location-specific and complementary to local knowledge (Moscona and Sastry 2025; Ma 2025). As a result, climate vulnerability may affect innovation in mitigation and adaptation through distinct channels, and policy instruments effective for one domain may be less effective for the other.

Distinguishing between new inventions and transferred technologies further clarifies these responses. New patents reflect domestic research capacity and institutional support for innovation, while transfer patents capture the international diffusion of existing technologies and a country's absorptive capacity. Climate vulnerability may therefore stimulate local invention where foreign solutions are ill-suited to local conditions while constraining technology inflows by increasing uncertainty for foreign innovators.

Finally, responses may differ across industries, since climate risks and regulatory pressures affect sectors through distinct channels. Some sectors, such as agriculture and construction, are more directly exposed to physical climate hazards and heat-related labor disruptions, while others, such as manufacturing, may be affected more strongly through productivity losses through supply-chain linkages (Zhang et al. 2018; Pankratz and Schiller 2023; Pörtner et al. 2022). Accounting for sectoral variation therefore helps distinguish economy-wide innovation responses from adjustments concentrated in particularly exposed sectors.

# 3 Data and method

We combine various pieces of data including a measure of innovation and technology adoption, a measure of climate exposure and vulnerability, and data on policy stringency for the 77 countries in our dataset between 1995 and 2021.[2] The next subsections describe how those variables are created and provide a description of the estimation procedure.

## 3.1 Innovation and technology adoption

We measure innovation and technology adoption using patent data from the EPO Worldwide Patent Statistical Database (PATSTAT), which covers patent applications filed at national patent offices as well as at the European Patent Office (EPO). Patents grant legal protection in the country

[2]The countries are listed in Appendix Table A1

where they are filed, giving the inventor the exclusive right to make, use, sell, or license the technology for a limited period. Inventors may file in multiple countries to secure protection in markets where they intend to commercialize or prevent unauthorized use. Patents are widely used as indicators of inventive activity because they provide standardized information on technological novelty and economic value across countries. We construct country–year counts of patent filings based on application dates to align patenting with the timing of underlying inventive activity. [3]

To capture differences in economic value across inventions, we weight patents by family size, defined as the number of jurisdictions in which protection is sought.[4] More valuable inventions tend to seek broader geographic protection and therefore receive greater weight. As an additional measure of value, we identify triadic patents, defined as patent families with filings in the United States, Japan, and Germany, as the highest-value subset of inventions (Dernis and Khan 2004).

Table 1: Countries With Most Patent Filings

| | Total Patent | | Total Patent (Weighted) | |
|---|---|---|---|---|
| Ranking | 1995 | 2021 | 1995 | 2021 |
| 1 | JPN (16,931) | CHN (450,740) | DEU (54,384) | CHN (599,348) |
| 2 | DEU (8,093) | USA (41,184) | USA (43,248) | USA (245,158) |
| 3 | USA (7,269) | JPN (35,858) | AUT (40,248) | JPN (144,466) |
| 4 | ESP (4,563) | KOR (30,489) | ESP (40,066) | DEU (128,347) |
| 5 | AUT (4,530) | DEU (25,224) | JPN (36,221) | GBR (124,518) |
| 6 | GBR (4,085) | GBR (23,269) | DNK (35,219) | ESP (122,867) |
| 7 | DNK (3,966) | ESP (23,092) | FIN (32,941) | DNK (121,929) |
| 8 | FRA (3,952) | LUX (22,812) | PRT (31,537) | PRT (121,903) |
| 9 | FIN (3,862) | NLD (22,777) | GRC (30,537) | LUX (121,756) |
| 10 | GRC (3,701) | DNK (22,723) | GBR (30,297) | NLD (121,641) |

*Notes:* This table reports the countries with the highest number of patent filings in 1995 and 2021 using PATSTAT data. Rankings are shown separately for total raw patent counts and for patent counts weighted by family size, which account for the number of jurisdictions in which an invention is protected.

Climate-related patents are identified using the Cooperative Patent Classification (CPC) Y02 code, which distinguishes mitigation technologies from adaptation technologies (Y02A). Adaptation technologies cover flood prevention, water conservation, infrastructure and health protection, and agricultural or forestry adaptations. Mitigation technologies address energy generation and distribution, transportation, waste management, carbon capture and storage, and building efficiency. This

[3]Grant dates are heavily dependent on administrative processing time, which can vary extensively across jurisdictions.

[4]Citations provide another measure of value, as highly cited patents typically reflect influential technologies. Both family size and citations correlate with patent value (Harhoff et al. 2003), but since citation practices vary across countries, family size is preferred for international comparisons (de Rassenfosse et al. 2016).

classification allows us to examine how climate vulnerability affects not only the level of innovation but also its technological direction.

We further distinguish between new domestic inventions and international technology transfers. This distinction is particularly relevant because climate innovation is highly concentrated in a small number of countries (Dechezlepretre et al. 2011; Touboul et al. 2023), making international technology diffusion an important channel of access. We classify the earliest filing of an invention as a new domestic invention, and any later filing of that same invention in another country as a technology transfer.

Table 2: Patent Summary Statistics for Select Countries

| | | **Value-weighted count** | | | | **Simple count** |
|---|---|---|---|---|---|---|
| | | Mean | Std. Dev. | Min. | Max. | Mean |
| High-income | **Germany** | 126,113 | 35,317 | 54,384 | 186,850 | 18,879 |
| | New | 20,215 | 7,887 | 7,812 | 30,617 | 5,945 |
| | Transfer | 105,898 | 28,787 | 46,572 | 160,630 | 12,935 |
| | **United States** | 173,864 | 94,022 | 37,669 | 351,939 | 25,254 |
| | New | 30,473 | 8,042 | 17,087 | 42,762 | 7,080 |
| | Transfer | 143,391 | 87,095 | 19,056 | 313,327 | 18,174 |
| Upper-middle | **China** | 172,967 | 158,500 | 12,575 | 599,348 | 86,984 |
| | New | 84,403 | 118,007 | 990 | 453,941 | 75,783 |
| | Transfer | 88,563 | 52,273 | 11,585 | 163,988 | 11,201 |
| | **Mexico** | 17,125 | 9,015 | 3,190 | 31,001 | 1,085 |
| | New | 548 | 449 | 26 | 1,563 | 95 |
| | Transfer | 16,577 | 8,644 | 3,004 | 29,438 | 990 |
| Lower-middle | **India** | 1,597 | 4,291 | 2 | 21,295 | 138 |
| | New | 105 | 275 | 0 | 1,335 | 24 |
| | Transfer | 1,493 | 4,027 | 0 | 19,960 | 113 |
| | **Egypt** | 378 | 353 | 0 | 1,134 | 23 |
| | New | 15 | 27 | 0 | 92 | 3 |
| | Transfer | 363 | 336 | 0 | 1,124 | 21 |

*Notes:* This table summarizes patenting activity over the full sample period for selected countries within each income group. For each country, we report statistics for total patents as well as the breakdown between new domestic patents and transferred patents. Patent counts are shown both as simple counts and as counts weighted by family size.

To assign patents to industries, we use the probabilistic CPC–ISIC concordance proposed by Goldschlag et al. (2016), which estimates the likelihood that a given CPC code is associated with each ISIC industry. All CPC codes listed on a patent are matched to the concordance, and the resulting industry probabilities are combined with patent family weights to construct weighted patent counts. Patents are therefore counted across industries according to both the predicted industry relevance of their CPC codes and their family size.

Finally, patents filed through the European Patent Office are assigned to member countries in the relevant year. Assigning EPO patents to all member states works well for the EU-15 but may overestimate technology adoption in the more recent EU members. We thus provide some robustness checks excluding EPO filings.

Table 1 highlights the strong concentration and evolving geography of climate patenting over our sample period. A notable development is the rapid rise of Chinese filings: while China does not appear among the top filers in 1995, it becomes the largest source of patent filings by 2021. When patents are weighted by family size, China remains the leading filer, though the gap with other major economies narrows.

Summary statistics in Table 2 further illustrate differences in the value and origin of patenting activity across income groups. High-income countries such as Germany and the United States exhibit larger patent family sizes – around six on average –and a higher share of filings corresponding to new domestic inventions. By contrast, China's average family size for new inventions is much smaller, suggesting that many filings remain domestically oriented even as the country receives substantial inflows of foreign technologies. In other middle-income countries, patenting activity is considerably lower and more heavily concentrated in transferred technologies rather than new inventions.

## 3.2 Climate vulnerability

Climate vulnerability can be measured in various ways. Our preferred measure is the Notre-Dame Global Adaptation Initiative (ND-GAIN) index,[5] which captures country-level climate-related risks by averaging climate exposure, sensitivity, and adaptive capacity components across key sectors such as food, water, health, ecosystem services, human habitat, and infrastructure – and ranges from 0 to 100, with higher values indicating greater vulnerability (see Figure 1 for category details). To limit endogeneity concerns, we recalculate the index excluding adaptive capacity indicators that may reflect prior technological adoption. Focusing on exposure and sensitivity allows us to capture climate-related challenges without mechanically overlapping with innovation outcomes.

As a robustness check, we use global temperature change from FAO data. Since global temperature trends are determined by cumulative emissions and large-scale climatic dynamics, they offer a plausibly exogenous source of variation in climate conditions. However, temperature captures only

[5] Notre Dame Global Adaptation Initiative (ND-GAIN), Country Index. Extracted from: https://gain.nd.edu/our-work/country-index/. Accessed on 2026-02-18.

Figure 1: ND-GAIN Vulnerability Indicators

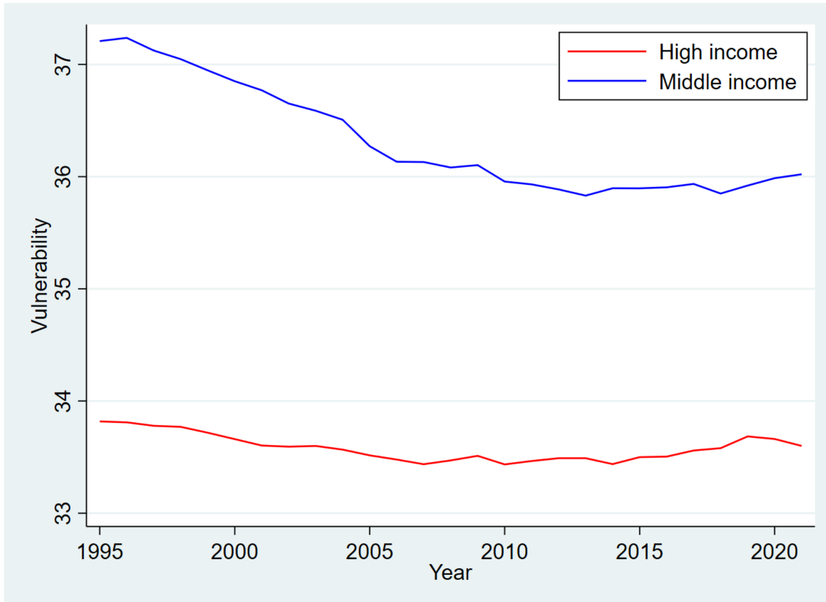
| Sector | Exposure component | Sensitivity component | Adaptive Capacity component |
|---|---|---|---|
| **Food** | Projected change of cereal yields | Food import dependency | Agriculture capacity (Fertilizer, Irrigation, Pesticide, Tractor use) |
| | Projected population change | Rural Population | Child malnutrition |
| **Water** | Projected change of annual runoff | Fresh water withdrawal rate | Access to reliable drinking water |
| | Projected change of annual groundwater recharge | Water dependency ratio | Dam capacity |
| **Health** | Projected change of deaths from climate change induced diseases | Slum population | Medical staffs (physicians, nurses and midwives) |
| | Projected change of length of transmission season of vector-borne diseases | Dependency on external resource for health services | Access to improved sanitation facilities |
| **Ecosystem services** | Projected change of biome distribution | Dependency on natural capital | Protected biomes |
| | Projected change of marine biodiversity | Ecological footprint | Engagement in International environmental conventions |
| **Human Habitat** | Projected change of warm period | Urban concentration | Quality of trade and transport-related infrastructure |
| | Projected change of flood hazard | Age dependency ratio | Paved roads |
| **Infrastructure** | Projected change of hydropower generation capacity | Dependency on imported energy | Electricity access |
| | Projection of Sea Level Rise impacts | Population living under 5m above sea level | Disaster preparedness |

*Notes:* The table reports the ND-GAIN indicators used to construct sector-level climate vulnerability measures. In our analysis, we exclude the adaptive capacity component and use only exposure and sensitivity indicators to reduce potential endogeneity.

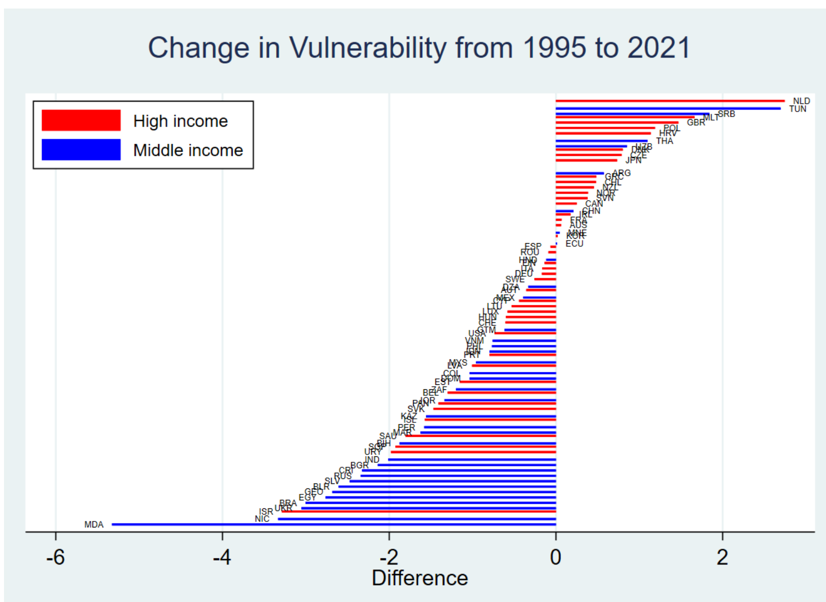
exposure and does not account for cross-country differences in economic sensitivity that are central to how climate risks translate into innovation incentives. Consequently, although it provides a clean identification benchmark, it is not our preferred measure for assessing innovation responses to climate risk.

Patterns in the ND-GAIN index highlight substantial heterogeneity across countries and income groups. Vulnerability levels are generally higher in middle-income economies, and evolve unevenly over time (Figure 2.i and Figure 2.ii). This variation provides the basis for our empirical analysis of how changes in climate vulnerability relate to innovation outcomes.

Figure 2: Climate vulnerability over time and across income groups



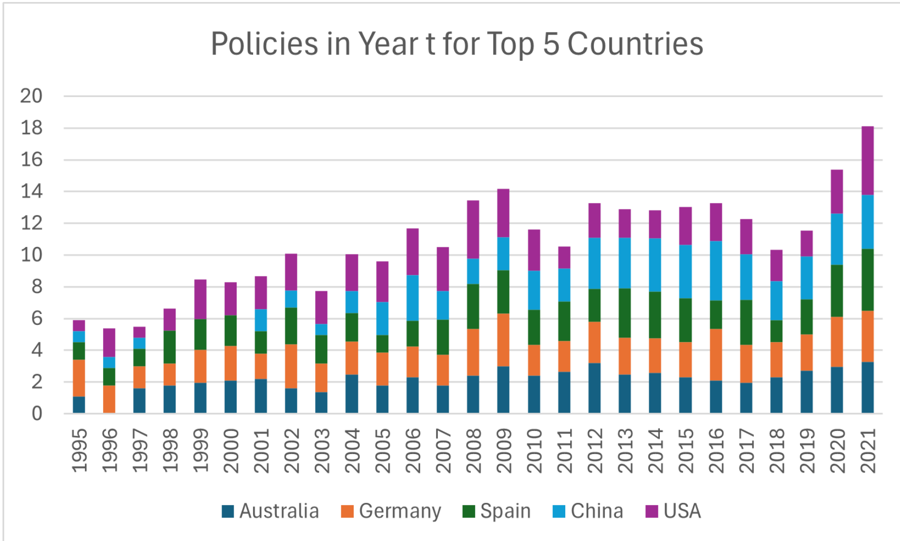

(i) Climate vulnerability over time, by income group



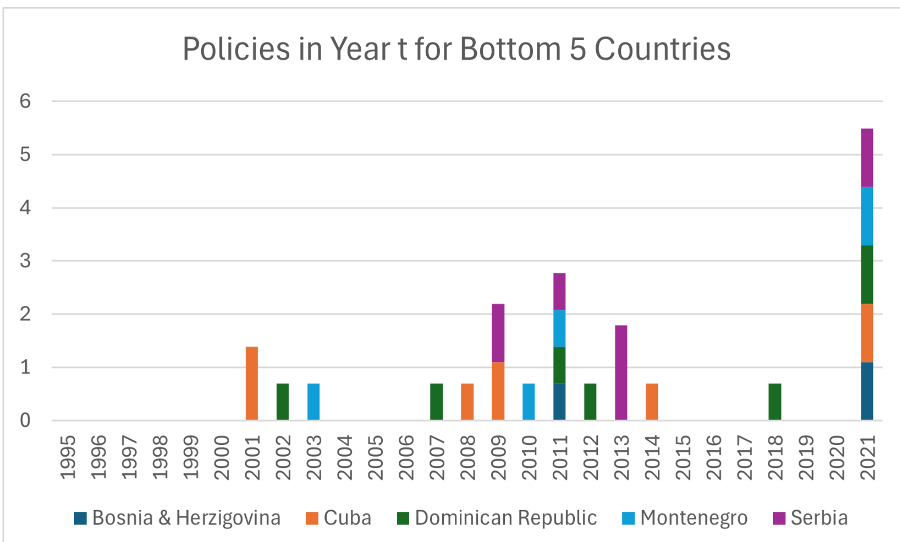

(ii) Change in climate vulnerability, 1995–2021

*Notes:* Panel (i) shows the evolution of average climate vulnerability for high-income and middle-income countries from 1995 to 2021. While vulnerability declines gradually for both groups, middle-income countries remain consistently more vulnerable throughout the period. Panel (ii) reports the country-level change in vulnerability over the same period, illustrating substantial heterogeneity across countries. Together, the figures show that although global vulnerability has generally improved over time, large cross-country differences in exposure to climate risks remain.

Figure 3: Policy Count - Select Countries




(a) Top 5 countries




(b) Bottom 5 countries

*Notes:* Panel (i) shows the number of climate policies adopted each year in the five countries with the largest number of policies, while Panel (ii) reports the same for the five countries with the fewest. Policy data are drawn from the IEA Policies Database.

## 3.3 Policy measure

To capture the effect of policies on innovation, we draw on the IEA/IRENA Global Policies Database, which records national and supranational policies aimed at reducing greenhouse gas emissions, improving energy efficiency, and supporting renewable and clean energy technologies. We construct a country–year count of newly enacted climate policies[6] following Johnstone et al. (2010) and Brunel (2019).[7]

Our baseline specification employs a flow measure of policy activity, reflecting evidence that firms often respond quickly to new regulatory incentives (Guo 2023). Using flows is also consistent with much of the literature and avoids overstating policy presence, since the dataset records enactment dates but not policy expirations. As a robustness check, we additionally construct a stock measure capturing the cumulative policy environment faced by innovators.

Figure 3 presents a graphical representation of the count of climate policies in select countries. We see that the number of policies in force has increased over time and was most active in the late 2000s and early 2010s. The most active countries can implement dozens of climate-related policies in a given year. China sees a sharp rise in policies starting in 2012 and now has surpassed the US in terms of the number of existing policies. Some of the countries that implemented the fewest number of policies include Gabon, Cuba, and Montenegro.

## 3.4 Estimation Procedure

To examine the link between climate and innovation, we estimate the following equation:

$$PATENTS_{it} = \exp(\beta_1 CC_{it} + \beta_2 POL_{it} + \beta_3 \boldsymbol{X}_{it} + \gamma_i + \delta_t) + \varepsilon_{it}$$

Here, $PATENTS_{it}$ is the value-weighted count of patents, either total or separated into mitigation, adaptation, new, transfer, and sector specific patents. $CC_{it}$ represents climate measures, either the ND-GAIN vulnerability index focusing on the exposure and sensitivity components (0–100) or logged global temperature anomaly. $POL_{it}$ is the count of climate policies in country $i$ at time $t$. $\boldsymbol{X_{it}}$ contains control variables described below, while $\gamma_i$ and $\delta_t$ capture country and year fixed effects, respectively.

The regression is estimated using Poisson Pseudo Maximum Likelihood (PPML), which accommodates roughly 15% of observations with zero patent filings, a share that can be even higher in some subsamples. PPML also provides consistent estimates in the presence of heteroskedasticity (Silva and Tenreyro 2006). Because our analysis separates high- and middle-income groups and fur-

[6]For more information on the difficulty of capturing environmental policy stringency, see Brunel and Levinson (2016).

[7]European Union countries receive an additional count for each policy implemented at the European Commission level.

ther distinguishes by innovation type, the number of clusters ranges from 10 to 42 depending on the specification. The econometric literature cautions that conventional cluster-robust variance estimators may be biased downward with a limited number of clusters, potentially leading to over-rejection of the null (Cameron and Miller 2015; Correia and Constantine 2025). To address this concern, we present heteroskedasticity robust standard errors as our main inference approach. As a robustness check, we pool income groups to increase the number of clusters above conventional thresholds and show that our main conclusions hold under a more conservative choice of variance estimator.

The control vector includes trade openness (UNCOMTRADE),[8] GDP per capita (IMF World Economic Outlook), [9] and measures of overall innovative activity (PATSTAT). Trade openness captures access to foreign technologies and exposure to external shocks, while GDP per capita proxies for innovation capacity. We also include value-weighted counts of non-climate patents and the stock of past technologies to proxy for broader innovation trends, changes in intellectual property rights regime, [10] and the cumulative knowledge base. Including both the flow of new patents and the stock of existing technologies allows us to capture short-term innovation responses as well as long-term capacity and technology spillovers.

Time fixed effects absorb global developments such as changes in international climate policy, trade conditions, and the global stock of renewable energy patents. These trends matter because inventors may respond to technologies developed abroad, by building upon them or seeking to compete against them. Inventors may also develop technologies in response to foreign climate policies (Popp 2006), especially those in neighboring countries with strong trade and investment ties. Country fixed effects account for persistent differences in geography, natural resources, climate, population, colonial history, human capital, institutional quality, and legal and political systems.

By focusing on exposure and sensitivity components of climate vulnerability and incorporating extensive controls and fixed effects, our approach mitigates concerns about reverse causality and omitted variable bias. Results using global temperature anomalies provide an additional identification benchmark based on a plausibly exogenous common climate shock.

[8] United Nations Statistics Division (UNSD), UN Comtrade Database. Extracted from: https://comtradeplus.un.org/. Accessed on 2026-02-18.

[9] International Monetary Fund (IMF), World Economic Outlook Database, October 2024 edition, GDP per capita. Extracted from: https://www.imf.org/en/Publications/WEO/weo-database. Accessed on 2026-02-18.

[10] See Maskus (2010) for a review of mixed evidence on IP protection and innovation.

# 4 High-income countries results

## 4.1 Policy and mitigation: establishing the benchmark

We begin by examining mitigation technologies in high-income countries to establish consistency with the existing literature on policy-driven green innovation, and to provide a benchmark for interpreting the role of climate vulnerability. Table 3 reports the baseline results for mitigation patent filings. Column (1) estimates the effect of policy counts on total mitigation patent filings, excluding climate vulnerability or global climate change variables. The policy coefficient is positive and statistically significant, consistent with the established finding that environmental regulation in high-income countries stimulates technological development for climate mitigation as measured by patent filings.

Table 3: High-income Mitigation and Adaptation

| | Mitigation | | | Adaptation | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| VARIABLES | Policy Alone | Baseline Vulnerability | Share of Green Patents | Policy Alone | Baseline Vulnerability | Share of Green Patents |
| Vulnerability | | 0.021*** | 0.025*** | | -0.031** | -0.029*** |
| | | (0.006) | (0.009) | | (0.015) | (0.009) |
| Policies | 0.030*** | 0.029*** | 0.010 | -0.134** | -0.132** | -0.013 |
| | (0.009) | (0.009) | (0.009) | (0.060) | (0.060) | (0.009) |
| GDP Per Capita | -0.052 | -0.036 | -0.033 | 0.287*** | 0.257*** | 0.064 |
| | (0.033) | (0.032) | (0.045) | (0.102) | (0.095) | (0.046) |
| Trade Openness | 0.001*** | 0.001*** | 0.001 | -0.002*** | -0.002*** | -0.000 |
| | (0.000) | (0.000) | (0.000) | (0.001) | (0.001) | (0.000) |
| Patent Trend | 0.964*** | 0.968*** | -0.051*** | 1.115*** | 1.109*** | 0.042*** |
| | (0.034) | (0.034) | (0.010) | (0.074) | (0.073) | (0.010) |
| Lagged Patent Stock | -0.031 | -0.021 | -0.017 | 0.117 | 0.112 | 0.033** |
| | (0.078) | (0.076) | (0.015) | (0.098) | (0.098) | (0.017) |
| Constant | -0.847 | -1.949** | 1.006 | -9.692*** | -8.151*** | -0.263 |
| | (1.095) | (0.984) | (0.633) | (1.526) | (1.386) | (0.652) |
| Observations | 1,081 | 1,081 | 1,043 | 1,063 | 1,063 | 1,043 |
| Robust SE | Yes | Yes | Yes | Yes | Yes | Yes |
| Country FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes | Yes | Yes |

Robust standard errors in parentheses
*** p<0.01, ** p<0.05

Trade openness and broader innovation trends are also positively associated with mitigation patenting, indicating that countries with greater exposure to international knowledge flows and stronger innovative capacity tend to exhibit higher levels of climate-related technological activity. These patterns suggest that not only do targeted environmental policies matter, but so too do the broader institutional and economic environments that facilitate innovation and technology diffusion.

### 4.2 Climate vulnerability and the direction of innovation

Having established this policy-driven benchmark, we now turn to the central question of the paper: whether climate vulnerability itself reshapes innovation incentives beyond the effects of policies, trade openness, and general innovative capacity. Column (2) introduces our measure of national climate vulnerability, capturing country-specific exposure and sensitivity. The policy coefficient is virtually unchanged in both magnitude and significance relative to Column (1). This stability indicates that vulnerability is not proxying for environmental policy intensity; rather, it captures an independent channel of influence. Vulnerability itself is positively associated with mitigation patent filings. A one-point increase in the vulnerability index corresponds to a 2.1% rise in value-weighted patent counts. Evaluated at the sample mean, with an average value-weight of 6.7, this translates into roughly 102 patents per country per year. Although this magnitude may appear large, it corresponds to a substantial shift in vulnerability: a one-point change in the index is greater than the average absolute change observed across countries over the entire 1995–2021 period (Figure 2.ii).

Turning to adaptation technologies in columns (4) and (5), the pattern shifts markedly. First, the policy coefficient is negative and statistically significant, consistent with policies primarily targeting mitigation and thereby reallocating innovative effort away from adaptation. Introducing vulnerability leaves the policy coefficient largely unchanged while vulnerability enters with a negative and significant effect, suggesting an additional shift of innovative resources away from adaptation technologies. Columns (3) and (6) using the shares of mitigation and adaptation patents reinforce this interpretation: vulnerability increases the share of mitigation within total green patenting and reduces the share of adaptation. The evidence points to a systematic reorientation of climate innovation toward emissions-reducing technologies and away from adaptation in high-income countries.

Although vulnerability is often viewed primarily through the lens of adaptation, many high-income economies are also major emitters capable of influencing global temperature trajectories. In this context, rising vulnerability may strengthen incentives to prioritize mitigation-oriented technological development by increasing the strategic value of innovations aimed at reducing the underlying drivers of climate risk. Vulnerability therefore shapes not only the level of climate-related innovation but also its direction.[11]

In the next subsection, we examine the mechanisms underlying this divergence. Later, in Section 6 we assess the robustness of these findings to alternative patent assignments and climate measures. Additionally, we present placebo tests to further support the interpretation of the effect of vulnerability on green patenting.

## 4.3 Mechanisms

We unpack these patterns along three dimensions: the value of innovation, the distinction between domestic invention and foreign technology transfer, and sectoral heterogeneity.

### 4.3.1 Value

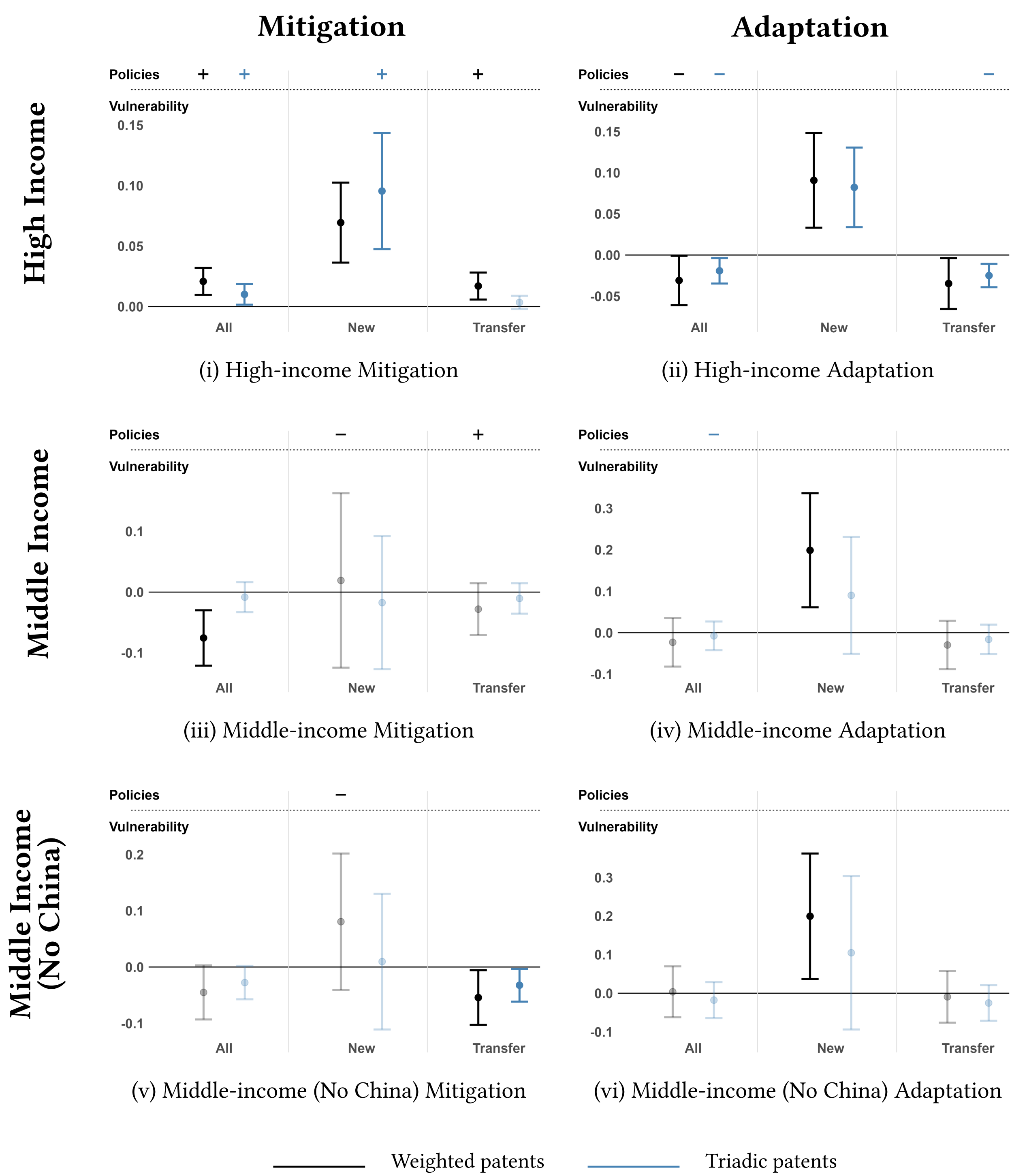
Focusing on the "All" category of Figures 4.i and 4.ii, we show that a significant part of the increase in mitigation patent filings – and the decrease in adaptation filings – is driven by high-value patents, measured using triadic patents jointly filed in the United States, Japan, and the EPO. Because triadic filings capture commercially significant technologies with broader market relevance, their responsiveness to climate vulnerability indicates that the observed reallocation between mitigation and adaptation technologies is not confined to marginal or low-quality patenting activity. Instead, vulnerability appears to influence the direction of the most economically meaningful technological investments, shaping not only the quantity of innovation but also its expected market value and strategic importance. This strengthens the interpretation that vulnerability contributes to a substantive shift in innovation priorities rather than a mechanical increase in patent counts.

### 4.3.2 Domestic innovation versus international diffusion

Distinguishing between patents arising from new domestic inventions and those reflecting the adoption of foreign technologies, Figure 4.i reveals that the positive response of mitigation innovation to vulnerability is driven primarily by new patenting activity. Coefficients are sizable and precisely estimated for all new patents but especially for high-value (triadic) filings, indicating a strong

[11] Results using high- and low-emitter groupings rather than income classifications confirm these findings and are available upon request.

Figure 4: Estimated Effects of Climate Vulnerability Across Patent Types and Sectors




(i) High-income Mitigation

(ii) High-income Adaptation

(iii) Middle-income Mitigation

(iv) Middle-income Adaptation

(v) Middle-income (No China) Mitigation

(vi) Middle-income (No China) Adaptation

*Notes:* Panels (i)–(vi) report coefficient estimates across income groups and technology categories. Rows correspond to high-income, middle-income, and middle-income countries excluding China, while columns distinguish mitigation and adaptation patents. Within each panel, the symbols at the top indicate the sign and significance of the climate policy coefficient, while the plotted points and confidence intervals report the estimated effect of climate vulnerability. Estimates are shown separately for all, new, and transfer patents. Black markers represent patent counts weighted by family size, and blue markers represent triadic patent counts. Bold markers indicate estimates that are statistically significant at the 5 percent level.

domestic innovation response notably in commercially relevant technologies. Effects on transfer patents are smaller and concentrated in lower-value filings. In short, while vulnerability supports mitigation partly through increased uptake of existing technologies, the dominant channel is the generation of new, economically meaningful innovations.

For adaptation technologies, the negative overall effect of vulnerability is primarily driven by reductions in transfer patents – both total and triadic – while new adaptation patenting increases. However, because new patents constitute a substantially smaller fraction of adaptation filings, the domestic inventive response is not sufficient to offset the decline in international diffusion. This asymmetry is consistent with the location-specific nature of many adaptation technologies, which may require local customization and therefore diffuse less easily across borders. In addition, because most adaptation innovation originates in high-income economies (Touboul et al. 2023), a shift within this group toward innovative effort aimed at mitigation may reduce the global availability of adaptation technologies for transfer.

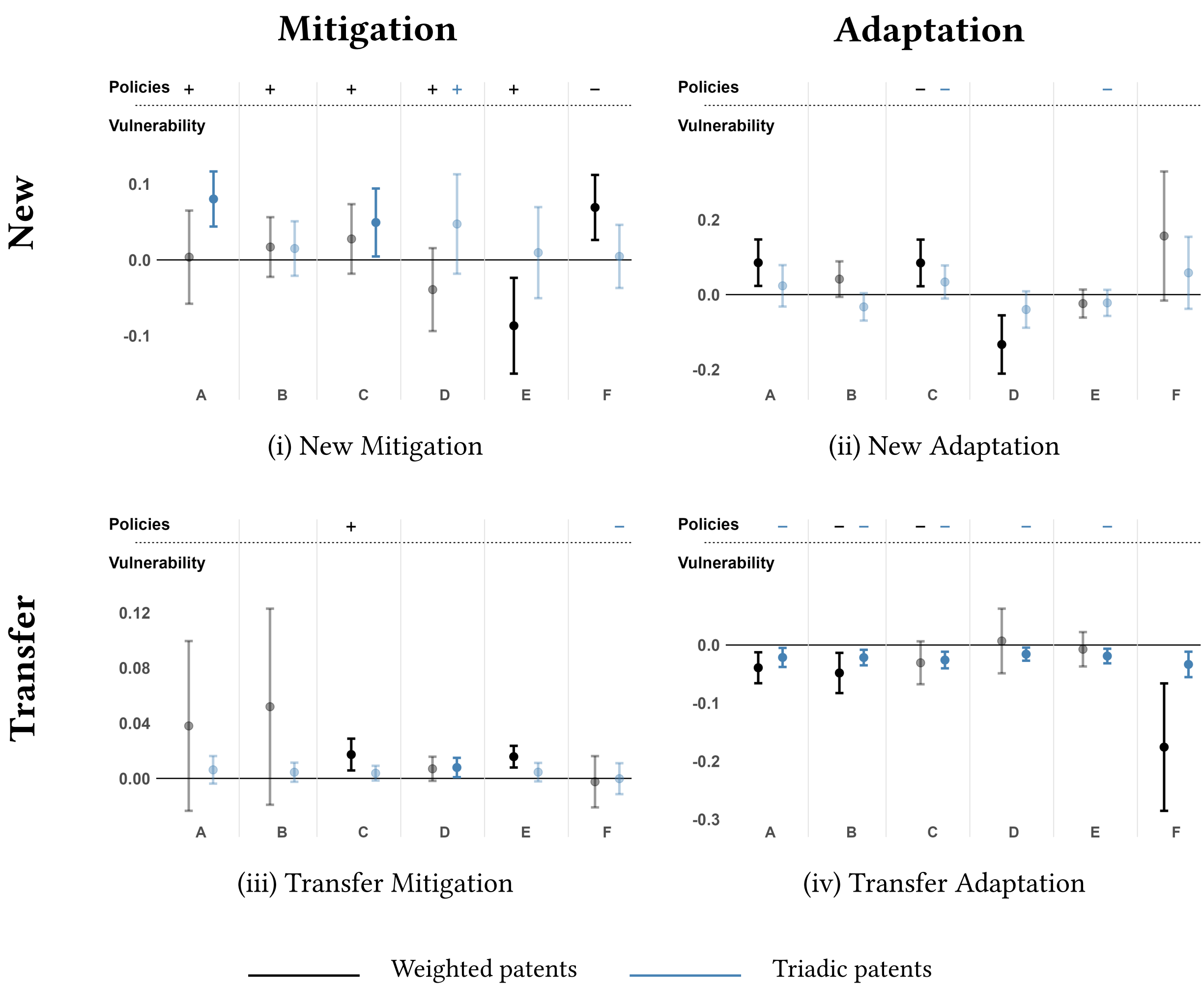
#### 4.3.3 Industry heterogeneity

Sectoral estimates reported in Figure 5 reveal substantial heterogeneity in how policy and climate exposure shape mitigation innovation and diffusion. For policy, the positive association with domestic innovation is present across most sectors, while its effects on technology transfer are concentrated in manufacturing. This suggests that cross-border diffusion of technologies is more prevalent in sectors deeply embedded in global value chains, where production processes and technological standards are more internationally integrated.

The relationship between climate vulnerability and mitigation patenting is more sector-specific. New patenting increases most strongly in climate-exposed sectors such as agriculture, manufacturing, and construction, with effects concentrated among higher-value inventions for the first two. In manufacturing, domestic invention and technology transfers tend to move together, consistent with complementarities between local innovative capacity and the adoption of foreign technologies (Keller 2004). By contrast, evidence from the water and waste sector points to substitution, with increases in domestic patenting coinciding with weaker transfer activity, implying that domestic invention may be displacing reliance on foreign technologies in this sector.

A few sectors merit particular attention. In the electricity sector, mitigation policies are strongly associated with new high-value patenting, while vulnerability primarily affects diffusion of high-value patents. As one of the largest sources of greenhouse gas emissions, the sector has been a

Figure 5: High-income – By Sector




*Industry codes:*

A: Agriculture B: Mining C: Manufacturing D: Electricity E: Water & Waste F: Construction

*Notes:* Panels (i)–(iv) report coefficient estimates for high-income countries by sector. Rows correspond to new and transfer patents, while columns distinguish mitigation and adaptation technologies. Within each panel, the symbols at the top indicate the sign and significance of the climate policy coefficient, while the plotted points and confidence intervals report the estimated effect of climate vulnerability. Black markers represent patent counts weighted by family size, and blue markers represent triadic patent counts. Bold markers indicate estimates that are statistically significant at the 5 percent level.

primary target of climate policy, leaving limited scope for vulnerability to generate additional innovation incentives beyond those created by regulation. Moreover, the sector's long planning horizons and capital-intensive infrastructure may explain why innovation responds more to stable policy frameworks rather than short-term changes in climate vulnerability. In this context, firms may adjust by adopting mature, internationally validated technologies rather than developing new ones domestically. Construction shows the opposite tendency, with weak or negative policy responses but positive associations between vulnerability and innovation, suggesting a more vulnerability-driven innovation process in a sector characterized by lower formal R&D intensity (Xue et al. 2014; Ghaffar et al. 2022).

Sectoral estimates for adaptation technologies point to a shift in the margins through which countries respond to rising climate risks. In highly exposed sectors such as agriculture and manufacturing, vulnerability is associated with increases in new domestic patenting but declines in transfer activity, especially for high-value technologies. These findings align with evidence that effective adaptation often requires locally tailored solutions in sectors where technologies must be adapted to local climatic and ecological conditions or specific production environments (Moscona and Sastry 2025; Ma 2025). More broadly, the reduced reliance on standardized technologies developed abroad is confirmed across other sectors. However, in those sectors the decline in technology transfer is not offset by increased domestic innovation so rising vulnerability potentially weakens overall adaptive capacity.

# 5 Middle-income countries results

## 5.1 Policy and climate vulnerability in middle-income countries

We now turn to middle-income countries to assess whether the patterns observed in high-income economies hold under different institutional, financial, and technological conditions (Table 4). The first result of note is that the policy count has no significant effect on mitigation patent filings (Column 1). This suggests that regulatory incentives may be too limited in scope, credibility, or enforcement to generate measurable technological responses. While policy-driven innovation is well documented in more advanced economies, these results indicate that similar mechanisms may operate more weakly in middle-income contexts.

A second notable difference concerns the role of climate vulnerability. In middle-income countries vulnerability is associated with a decline in mitigation patenting (Table 4, Column 2), while its

Table 4: Middle-income Mitigation and Adaptation

| | Mitigation | | | Adaptation | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| VARIABLES | Policy Alone | Baseline Vulnerability | Share of Green Patents | Policy Alone | Baseline Vulnerability | Share of Green Patents |
| Vulnerability | | -0.076*** | 0.008 | | -0.023 | -0.011 |
| | | (0.023) | (0.014) | | (0.030) | (0.014) |
| Policies | 0.002 | 0.007 | 0.020 | -0.043 | -0.042 | -0.014 |
| | (0.017) | (0.016) | (0.012) | (0.023) | (0.023) | (0.012) |
| GDP Per Capita | -0.173 | -0.100 | 0.127*** | -0.729*** | -0.704*** | -0.139*** |
| | (0.091) | (0.091) | (0.045) | (0.094) | (0.099) | (0.045) |
| Trade Openness | 0.001 | 0.001 | 0.001 | -0.002 | -0.002 | -0.001 |
| | (0.001) | (0.001) | (0.001) | (0.002) | (0.002) | (0.001) |
| Patent Trend | 1.058*** | 1.066*** | -0.019 | 1.099*** | 1.101*** | 0.024** |
| | (0.033) | (0.033) | (0.011) | (0.041) | (0.041) | (0.011) |
| Lagged Patent Stock | -0.161** | -0.130 | -0.022 | -0.016 | -0.012 | 0.018 |
| | (0.070) | (0.067) | (0.024) | (0.050) | (0.051) | (0.024) |
| Constant | 0.952 | 2.297*** | -0.364 | 2.578*** | 3.042*** | 1.619** |
| | (0.681) | (0.792) | (0.658) | (0.847) | (0.941) | (0.670) |
| Observations | 883 | 883 | 677 | 782 | 782 | 677 |
| Robust SE | Yes | Yes | Yes | Yes | Yes | Yes |
| Country FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes | Yes | Yes |

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$

relationship with adaptation patents remains statistically insignificant (Column 5). Rising exposure to climate risks therefore appears to reduce mitigation-oriented innovative effort without triggering a compensating expansion in adaptation technologies. Estimates using mitigation and adaptation shares (Columns 3 and 6) reinforce this interpretation. The internal composition of climate innovation remains broadly unchanged, indicating that vulnerability affects the scale of climate patenting more than its direction in middle-income economies.

These results are consistent with rising vulnerability tightening fiscal space, raising investment uncertainty, and weakening incentives for long-term innovative investment. These constraints can reduce mitigation patenting while also limiting the expansion of adaptation innovation, even as climate risks intensify. At the same time, adaptation patenting does not decline, suggesting a degree of relative resilience. Because adaptation technologies often address more immediate and localized needs, innovation in this domain may be less compressible under climate stress.

## 5.2 Mechanisms

We examine how vulnerability affects domestic invention and international technology transfer, distinguishing between mitigation and adaptation technologies. Middle-income countries are highly heterogeneous, most notably due to the inclusion of China, which follows a distinct innovation trajectory (Table 2). In unweighted terms, China's volume of climate patent filings is substantially higher than that of any other middle-income country and exceeds that of the United States, reflecting both the scale of patenting activity and smaller average patent family sizes. Using value-weighted patent counts – the measure employed in the regression analysis – reduces this gap: China's average level of climate patenting becomes comparable to that of the United States. Value-weighting therefore moderates, but does not eliminate, China's quantitative dominance within the middle-income sample.

To assess how this heterogeneity shapes the results, we compare estimates for the full middle-income sample (MI) with those excluding China (MINC), shown in the middle and bottom rows of Figure 4, respectively. This approach isolates China's contribution to aggregate patterns while preserving the panel structure required to include country fixed effects.

### 5.2.1 Domestic innovation versus international diffusion

The role of climate policy in mitigation differs markedly depending on whether China is included in the sample. In the full middle-income sample, climate policies are positively associated with transfer patents, an association that disappears once China is excluded. In this sense, China resembles high-income economies in responding to policy signals, but through a different adjustment margin: rather than stimulating domestic mitigation innovation, policies are linked primarily to increased inflows of lower value foreign technologies.[12] Across both specifications, policies are also associated with a decline in new domestic mitigation patents, potentially reflecting limited innovation capacity.

Climate vulnerability, by contrast, operates mainly as a constraint on mitigation technology transfers from abroad. In the full middle-income sample, vulnerability is negatively associated with total mitigation patenting, although disaggregated effects are imprecisely estimated (Figure 4.iii). Excluding China weakens the aggregate relationship, leaving a significant negative effect only for transfer patents (Figure 4.v). This suggests that outside China, rising vulnerability primarily reduces access to foreign mitigation technologies rather than domestic inventive activity. Because most

[12]This finding is consistent with the descriptive analysis in Dechezlepretre et al. (2011) which documents a surge in mitigation patent transfers to China coinciding with major environmental policy reforms.

middle-income countries are not major emitters, mitigation technologies may receive lower strategic priority, and investment in or adoption of such technologies may contract as fiscal and institutional pressures intensify.

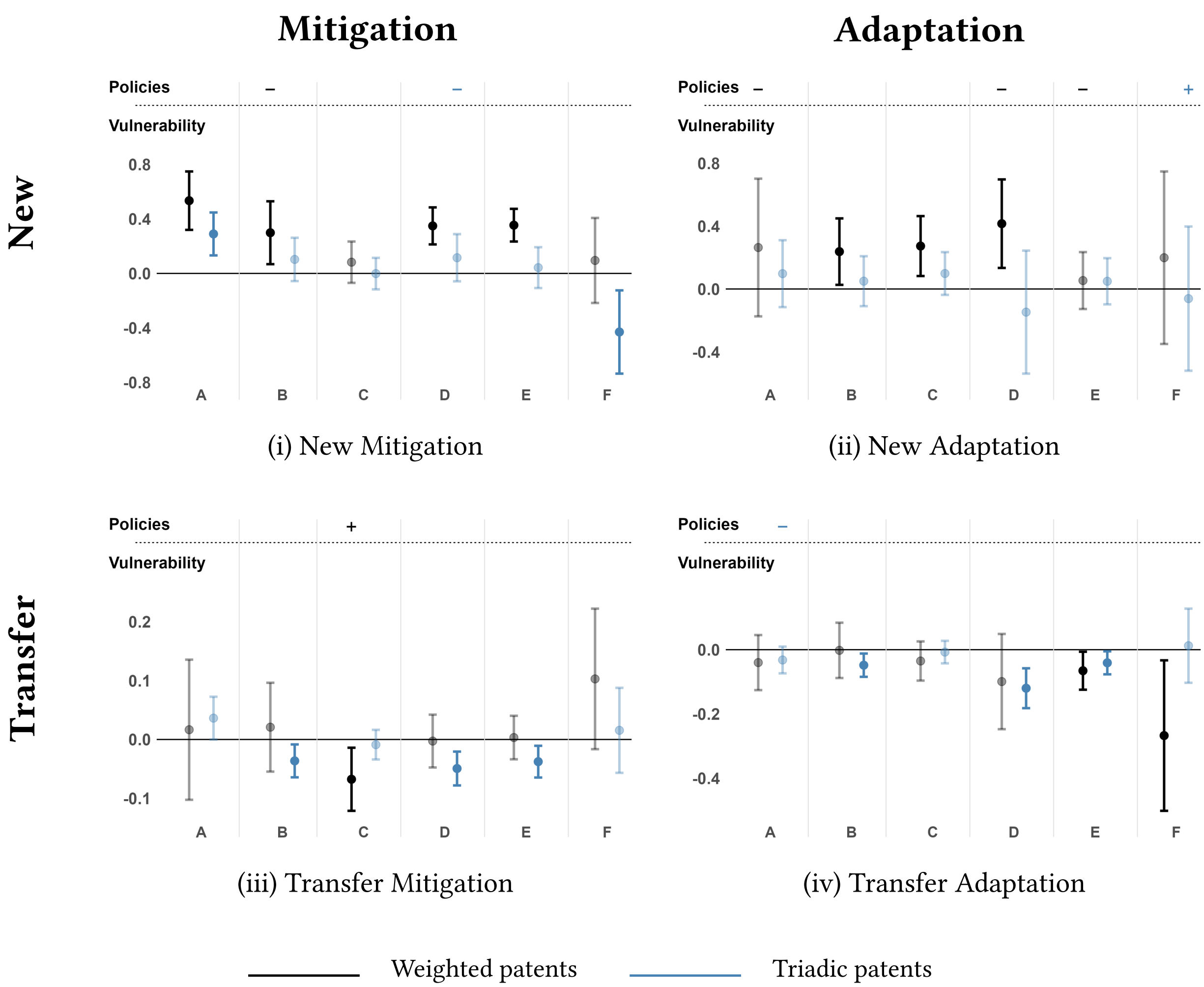
For adaptation technologies, the aggregate null result for both the MI group and MINC group conceals a very important adjustment margin. Vulnerability is associated with an increase in new domestic adaptation patents, while transfer activity does not rise (Figure 4.vi). Because middle-income economies often rely on international diffusion to access green technologies, the lack of growth in adaptation transfers represents a binding constraint. The rise in new patents therefore points to a within-category substitution as countries develop local solutions when foreign technologies fail to materialize. However, these inventions are concentrated in lower-value patents, with no corresponding increase in triadic filings. As a result, the expansion in domestic innovation is insufficient to raise overall value-weighted adaptation patenting, and access to adaptation technologies does not increase when they are most needed.

### 5.2.2 Industry heterogeneity

Sectoral estimates for middle-income countries (Figures 6 and 7) reveal that policy responses are concentrated in a limited number of industries. The aggregate decline in new mitigation patents induced by climate policy is driven primarily by upstream sectors such as mining and, in the case of China, by high-value electricity technologies. Meanwhile, manufacturing – a downstream sector – experiences increased technology inflows across middle-income countries and rising domestic patenting outside China. These patterns suggest that policy responses in middle-income economies occur at specific points along the production chain rather than generating broad-based innovation.

Climate vulnerability produces a wider but uneven sectoral adjustment in mitigation technologies. Vulnerability increases new patenting in agriculture, mining, electricity, and water/waste management, while high-value technology transfers decline in several of these sectors. Across these sectors, weaker access to foreign technologies is concurrent with modest increases in local patenting. However, these largely positive sectoral responses are masked in the aggregate results by the dominant role of the manufacturing sector, which accounts for more than half of mitigation patents in the MI sample. In this sector, vulnerability reduces technology inflows without stimulating additional domestic innovation, driving the overall decline in mitigation patenting. Comparing MI and MINC results shows that China appears uniquely capable of continuing to attract commercially significant mitigation technologies in manufacturing.

Figure 6: Middle-income – By Sector




(i) New Mitigation (ii) New Adaptation

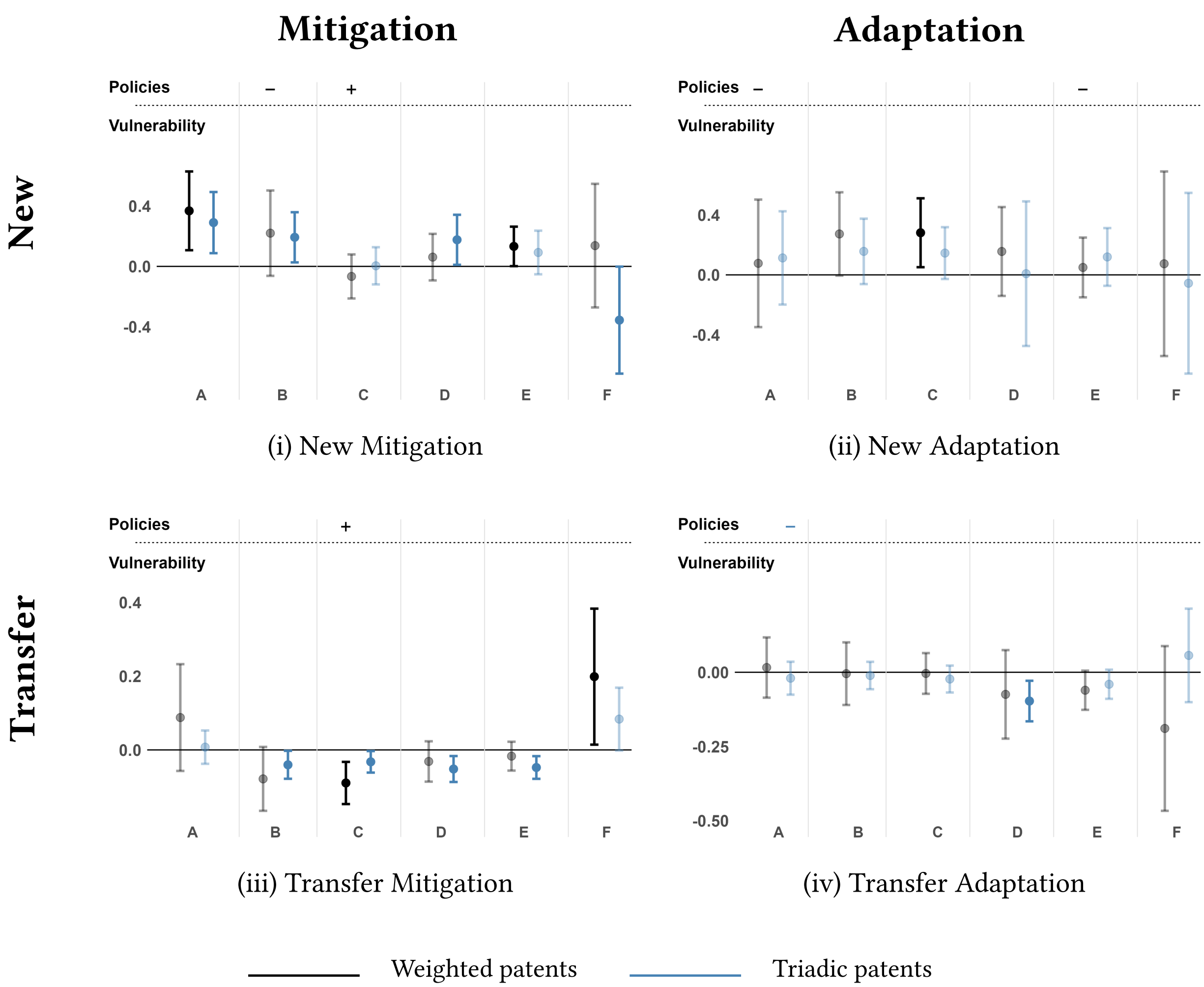
(iii) Transfer Mitigation (iv) Transfer Adaptation

*Industry codes:*

A: Agriculture B: Mining C: Manufacturing D: Electricity E: Water & Waste F: Construction

*Notes:* Panels (i)–(iv) report coefficient estimates for middle-income countries by sector. Rows correspond to new and transfer patents, while columns distinguish mitigation and adaptation technologies. Within each panel, the symbols at the top indicate the sign and significance of the climate policy coefficient, while the plotted points and confidence intervals report the estimated effect of climate vulnerability. Black markers represent patent counts weighted by family size, and blue markers represent triadic patent counts. Bold markers indicate estimates that are statistically significant at the 5 percent level.

Figure 7: Middle-income excluding China – By Sector




*Industry codes:*

A: Agriculture B: Mining C: Manufacturing D: Electricity E: Water & Waste F: Construction

*Notes:* Panels (i)–(iv) report coefficient estimates for middle-income countries excluding China by sector. Rows correspond to new and transfer patents, while columns distinguish mitigation and adaptation technologies. Within each panel, the symbols at the top indicate the sign and significance of the climate policy coefficient, while the plotted points and confidence intervals report the estimated effect of climate vulnerability. Black markers represent patent counts weighted by family size, and blue markers represent triadic patent counts. Bold markers indicate estimates that are statistically significant at the 5 percent level.

Agriculture stands out as the only sector where vulnerability increases both total and high-value new mitigation patents across specifications. Given the sector's central economic role in many middle-income countries, climate exposure appears to spur economically meaningful innovation where adaptation and mitigation pressures are most immediate. Construction exhibits the opposite adjustment margin, with weaker domestic inventive activity and, outside China, greater reliance on imported mitigation technologies.

Sectoral responses in adaptation technologies are considerably weaker. Outside China, vulnerability generates little measurable adjustment, with the only consistent effect being an increase in lower-value domestic adaptation patents in manufacturing. When China is included, vulnerability is associated with broader increases in local patenting across several industries, but these responses remain concentrated in low-value inventions and do not coincide with sectors experiencing declining technology transfers. Manufacturing therefore emerges as the primary locus of adaptation innovation across country groups, suggesting that protecting industrial production becomes a common technological priority as climate risks intensify.

Unlike the high-income results, vulnerability does not stimulate adaptation innovation in agriculture. One possible explanation is that in middle-income countries agricultural adaptation responses take the form of local production practices or process innovations that are difficult to codify as patentable technologies (Douthwaite et al. 2001). In addition, adaptation technologies in agriculture are often highly location-specific and serve limited markets, weakening incentives for formal innovation relative to more widely applicable mitigation technologies.

# 6 Robustness tests

## 6.1 Identification and sample robustness

We conduct additional robustness checks to assess the sensitivity of the results to sample structure, timing, and outcome definition. First, we re-estimate the baseline specifications on the full sample, pooling high- and middle-income countries to increase the number of clusters and reduce finite-sample bias in clustered standard errors (Table 5 Column 3 & Column 6). The results confirm that climate vulnerability is linked to more mitigation patents and fewer adaptation patents. The full sample effects thus appear to be driven primarily by high-income countries, a predictable outcome for mitigation given that most major emitters fall into this group, and for adaptation since most patent filings also originate in high-income countries.

Table 5: General Robustness Checks: Full Sample Clustering and Placebo Outcomes

| | Full Sample | | Mitigation | | | Adaptation | | |
|---|---|---|---|---|---|---|---|---|
| | High Income | Middle Income | | High Income | Middle Income | | High Income | Middle Income |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| VARIABLES | All Patents | All Patents | Clustered Standard Errors | Lead Vuln | Lead Vuln | Clustered Standard Errors | Lead Vuln | Lead Vuln |
| Vulnerability | -0.006 | 0.051 | 0.023** | 0.016 | -0.053 | -0.050** | 0.005 | -0.043 |
| | (0.007) | (0.033) | (0.009) | (0.009) | (0.048) | (0.023) | (0.040) | (0.075) |
| Lead Vulnerability | | | | 0.003 | -0.027 | | -0.041 | 0.028 |
| | | | | (0.009) | (0.047) | | (0.035) | (0.079) |
| Policies | -0.022** | -0.003 | 0.010 | 0.031*** | 0.016 | -0.119** | -0.129** | -0.027 |
| | (0.009) | (0.026) | (0.015) | (0.009) | (0.015) | (0.055) | (0.059) | (0.023) |
| GDP Per Capita | -0.078 | 1.031*** | -0.177** | -0.033 | -0.070 | -0.031 | 0.270** | -0.710*** |
| | (0.045) | (0.144) | (0.078) | (0.035) | (0.090) | (0.146) | (0.108) | (0.100) |
| Trade Openness | -0.000 | -0.004 | 0.001*** | 0.001*** | 0.001 | -0.002*** | -0.002*** | -0.002 |
| | (0.000) | (0.002) | (0.000) | (0.000) | (0.001) | (0.001) | (0.001) | (0.002) |
| Patent Trend | | | 0.975*** | 0.984*** | 1.028*** | 1.023*** | 1.089*** | 1.040*** |
| | | | (0.037) | (0.036) | (0.032) | (0.047) | (0.075) | (0.041) |
| Lagged Patent Stock | 1.352*** | 0.915*** | -0.090 | -0.022 | -0.134** | 0.145 | 0.151 | -0.022 |
| | (0.082) | (0.129) | (0.077) | (0.079) | (0.066) | (0.118) | (0.106) | (0.050) |
| Constant | -6.850*** | -12.259*** | 0.513 | -2.144** | 2.668*** | -3.758*** | -8.494*** | 3.733*** |
| | (1.321) | (1.295) | (0.612) | (0.987) | (0.778) | (1.390) | (1.517) | (0.900) |
| Observations | 1,090 | 900 | 1,964 | 1,023 | 851 | 1,845 | 1,023 | 753 |
| Robust SE | Yes | Yes | No | Yes | Yes | No | Yes | Yes |
| Country FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Clusters | - | - | 77 | | | 72 | | |

Robust standard errors in parentheses

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

Second, we implement a placebo test adding lead vulnerability as a regressor. This addresses the concern that our baseline relationship may reflect a spurious association, since current innovation should not respond to future realized vulnerability. The estimated coefficients are statistically insignificant across technologies and income groups (Columns 4–5 and 7–8), providing no evidence that patenting activity systematically precedes changes in vulnerability. This supports the interpretation that the baseline estimates capture contemporaneous innovation responses rather than pre-existing trends or anticipatory effects.

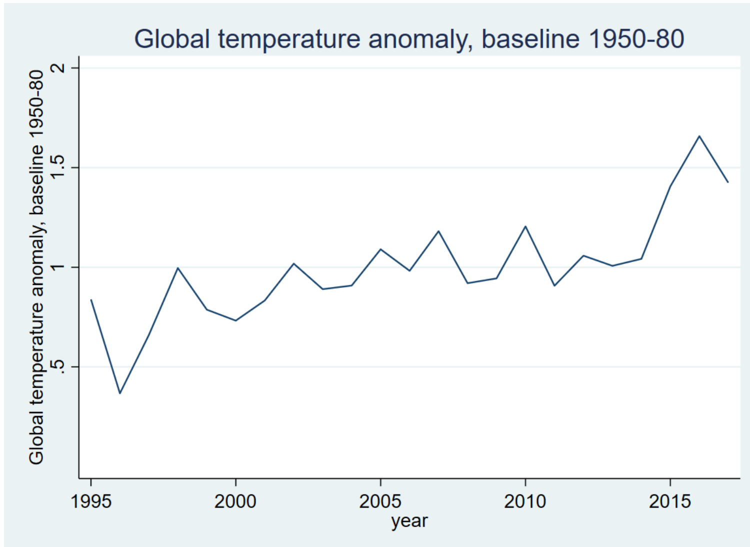
Finally, we replace climate-related patent filings with non-climate patents as the outcome variable to test if the estimated relationship is specific to green innovation or applies to patenting more generally. Vulnerability is not significantly associated with overall patenting in either country group, indicating that the baseline results reflect climate-specific shifts in technological effort rather than broader changes in innovative capacity.

## 6.2 Robustness specific to high-income results

We conduct a series of robustness checks to assess whether the main finding for high-income countries – that higher vulnerability is associated with an increase in mitigation patents – is sensitive to different measures of climate risk, alternative patent assignments, or policy counts. These tests address potential concerns about measurement and specification that could otherwise confound the interpretation of vulnerability-driven innovation responses. First, we replace the national vulnerability with global climate change (6 Column 1). Because this measure does not vary across countries, we replace the year fixed effects with a time trend. The estimated relationship becomes negative, a result driven by two dynamics. First, Figure 9 shows that vulnerability and exposure are imperfectly aligned, as vulnerability also incorporates economic and institutional sensitivity. Second, while global temperatures have risen over time (Figure 8), many countries in our sample have experienced declines in their vulnerability scores (Figure 2.ii), reflecting improvements in resilience through reductions in sensitivity. As a consequence, vulnerability and global temperature change are negatively correlated, explaining the reversal in sign relative to the baseline specification. Despite this difference in sign, climate conditions remain significantly associated with mitigation patenting, confirming that the main results do not hinge on a specific measure of climate exposure. More broadly, the comparison underscores that vulnerability is a more informative indicator of innovation incentives than temperature alone.

Second, we exclude EPO-wide patent assignments (Column 2). The positive association between vulnerability and mitigation patents remains qualitatively unchanged. This check is particularly

Figure 8: Global Temperature Anomaly - Basline 1951-1980

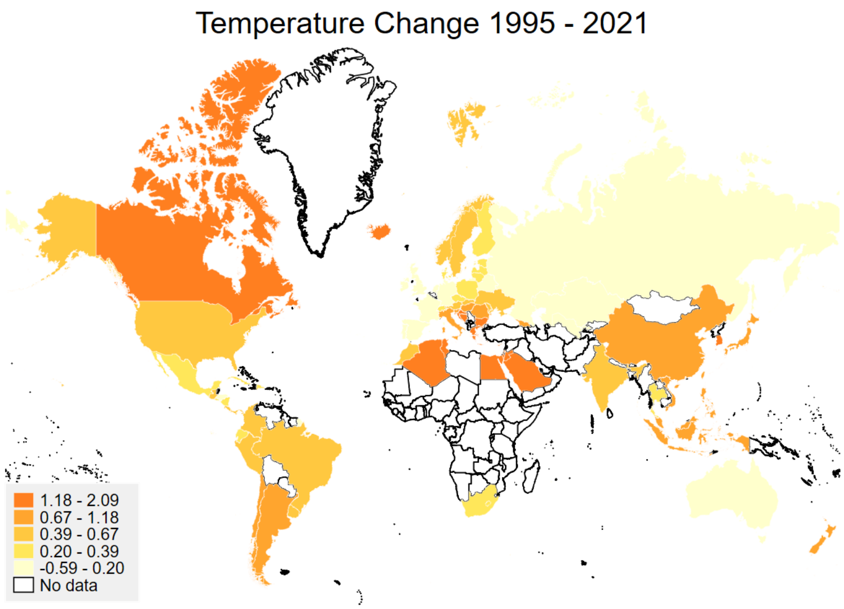



*Notes:* Annual global land temperature anomalies (°C) relative to the 1951–1980 baseline, using FAOSTAT climate indicators. The figure illustrates the steady rise in global temperatures over the sample period (1995–2021), with warming exceeding 0.5°C.

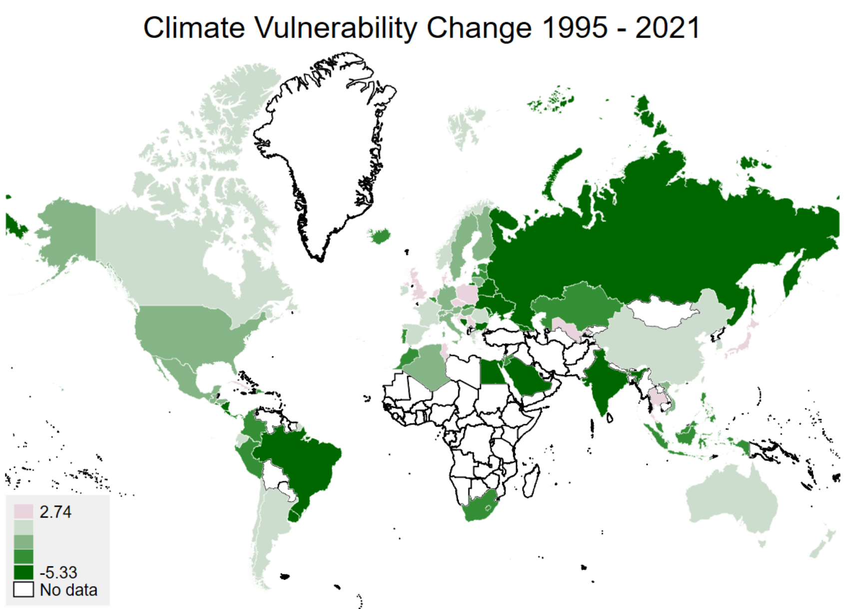
important for the high-income sample because, with the exception of Bulgaria, EU members are all classified as high-income economies. For adaptation technologies, however, the vulnerability coefficient becomes statistically insignificant once EPO filings are excluded (Column 5), suggesting that the positive response observed in the baseline specification is largely driven by patents filed through the EPO. One possible explanation is that, although adaptation technologies are often highly context-specific, climatic and regulatory conditions are relatively similar across many European countries. This may allow adaptation innovations appropriate for one location to be deployed across multiple EU markets, making EPO filing a more attractive strategy than national patent protection.

Finally, we replace the policy flow variable with a stock measure capturing the accumulated climate policy environment. This distinction is particularly important for high-income countries, where the most impactful and economically significant climate policies are concentrated. The estimated relationship between vulnerability and both mitigation and adaptation patenting in high-income countries remains stable under this alternative policy measure (Column 3 & Column 6), indicating that the main findings are not sensitive to the representation of policy incentives.

Figure 9: Change in Temperature and Vulnerability, 1995-2017




(a) Temperature




(b) Vulnerability

*Notes:* Panel (i) shows country-level temperature change between 1995 and 2021, while Panel (ii) reports the change in ND-GAIN climate vulnerability over the same period. The patterns do not fully overlap across countries, highlighting that temperature change captures only one dimension of climate change, whereas vulnerability reflects a broader set of environmental impacts and exposure channels.

Table 6: High-income Robustness Tests

| | Mitigation | | | Adaptation | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| VARIABLES | Global Temp Change | No EPO | Policy Stock | Global Temp Change | No EPO | Policy Stock |
| Vulnerability | | 0.057*** | 0.023*** | | 0.035 | -0.043*** |
| | | (0.018) | (0.006) | | (0.038) | (0.014) |
| Global Temp Change | -0.422*** | | | -0.499*** | | |
| | (0.031) | | | (0.130) | | |
| Policies (Flow) | 0.035*** | -0.000 | | 0.000 | -0.189** | |
| | (0.011) | (0.012) | | (0.053) | (0.074) | |
| Policies (Stock) | | | 0.046*** | | | -0.159** |
| | | | (0.014) | | | (0.062) |
| GDP Per Capita | -0.282*** | 0.287** | -0.035 | 0.347** | -0.310 | 0.266*** |
| | (0.068) | (0.115) | (0.032) | (0.173) | (0.178) | (0.080) |
| Trade Openness | 0.002*** | 0.002*** | 0.001*** | -0.002** | -0.000 | -0.002*** |
| | (0.000) | (0.001) | (0.000) | (0.001) | (0.001) | (0.000) |
| Patent Trend | 0.910*** | 0.946*** | 0.970*** | 0.979*** | 1.127*** | 1.113*** |
| | (0.037) | (0.021) | (0.034) | (0.102) | (0.054) | (0.065) |
| Lagged Patent Stock | 0.216*** | -0.042 | -0.038 | 0.660*** | 0.108 | 0.162 |
| | (0.025) | (0.055) | (0.079) | (0.094) | (0.094) | (0.095) |
| Constant | -61.956*** | -6.547*** | -1.951 | 54.378*** | -3.499 | -8.261*** |
| | (5.270) | (1.525) | (1.000) | (10.453) | (2.099) | (1.284) |
| Observations | 1,081 | 1,081 | 1,081 | 1,063 | 1,063 | 1,063 |
| Robust SE | Yes | Yes | Yes | Yes | Yes | Yes |
| Country FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Year FE | No | Yes | Yes | No | Yes | Yes |

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$

# 7 Conclusion

Climate vulnerability reshapes innovation incentives in ways that differ sharply across countries and technologies. In high-income economies, rising vulnerability strengthens incentives to develop mitigation technologies, reinforcing policy-driven innovation and shifting the overall composition of climate innovation toward emissions reduction. At the same time, reliance on internationally diffused adaptation technologies declines, while domestic adaptation invention expands in selected sectors, consistent with the context-specific nature of many resilience technologies.

Middle-income countries follow a markedly different trajectory. Rather than stimulating climate innovation, vulnerability appears to constrain it. Mitigation activity weakens primarily through reduced access to foreign technologies, while adaptation responses remain limited and concentrated in lower-value domestic inventions that do not compensate for declining technology inflows. China stands out as a hybrid case: vulnerability is associated with increased mitigation patenting, but the response operates through foreign technology adoption rather than domestic invention.

These patterns carry important policy implications. Expanding access to finance, reducing investment risk, and strengthening mechanisms that support international technology diffusion will be critical for enabling adaptation in vulnerable middle-income economies. At the same time, mitigation-oriented policy frameworks in high-income countries can amplify vulnerability-driven incentives for technological development, but should be complemented by targeted efforts to sustain adaptation innovation.

More broadly, the results highlight climate vulnerability and regulatory policy as distinct yet interacting forces shaping the scale, direction, and geography of climate innovation. As climate risks intensify, understanding how these forces jointly influence technological change will be central to designing policies that support both emissions reduction and economic resilience in an unevenly warming world.

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# A Appendix

Table A1: Country classification by income group

| High income | | Upper middle income | Lower middle income |
|---|---|---|---|
| Australia | Lithuania | Argentina | Algeria |
| Austria | Luxembourg | Belarus, Rep. of | Egypt, Arab Rep. of |
| Belgium | Malta | Bosnia and Herzegovina | El Salvador |
| Canada | Netherlands, The | Brazil | Honduras |
| Chile | New Zealand | Bulgaria | India |
| Croatia, Rep. of | Norway | China, P.R.: Mainland | Indonesia |
| Cyprus | Panama | Colombia | Morocco |
| Czech Rep. | Poland, Rep. of | Costa Rica | Nicaragua |
| Denmark | Portugal | Dominican Rep. | Philippines |
| Estonia, Rep. of | Romania | Ecuador | Tunisia |
| Finland | Saudi Arabia | Georgia | Ukraine |
| France | Singapore | Guatemala | Uzbekistan |
| Germany | Slovak Rep. | Jordan | Vietnam |
| Greece | Slovenia, Rep. of | Kazakhstan, Rep. of | |
| Hungary | Spain | Malaysia | |
| Iceland | Sweden | Mexico | |
| Ireland | Switzerland | Moldova, Rep. of | |
| Israel | United Kingdom | Peru | |
| Italy | United States | Russian Federation | |
| Japan | Uruguay | Serbia, Rep. of | |
| Korea, Rep. of | | South Africa | |
| Latvia | | Thailand | |

*Notes:* This table lists all countries included in the sample by World Bank income classification. In the empirical analysis, upper-middle-income and lower-middle-income countries are combined into a single middle-income group.