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Private sector investments in climate change adaptation

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Amid escalating climate impacts, understanding private sector adaptation is critical. Here using data of actual adaptation expenditures from nearly 300,000 businesses in five coastal regions, we reveal variations in private sector adaptation across sectors and regions. The agriculture sector leads in adaptation efforts, while transport, construction and utilities—that is potential sources of system-wide cascading effects—lag. Small, medium and large businesses prioritize hard and soft measures, barely investing in ecosystem-based adaptations. Adding to the multifaceted discourse on adaptation effectiveness, our panel data reveal positive, although inelastic in the short run, relationships between private sector adaptations and aggregate regional economic performance. Business adaptations in the construction, transport and health sectors associate positively with regional economic performance, with the accommodation and food services sector yielding the highest return per euro invested in adaptation. Combining these findings with existing assessments of adaptation could support the development of societally effective adaptation strategies.

Climate-induced losses cause unprecedented disruptions to socio-economic systems globally[1–3]. As acute (for example, floods) and chronic (for example, sea level rise) physical climate risks intensify, the private sector bears mounting direct and indirect damages to the assets and operations of companies[4]. Such losses already constitute €52 billion in 2022 in the European Union (EU) alone[5], with developing countries projected to face US$500 billion annually[6], making inadequate climate change adaptation (CCA) a pivotal threat for the next decade[7]. Alongside well-studied public government-led adaptation[8,9] or private CCA by farmers and households[10,11], private CCA of businesses remains underexplored, constituting a key adaptation priority[12] (Supplementary Information, appendix A1). Several high-level assessments indicate that unmanaged climate risks are substantial and might trigger systemic effects[3,13,14]. Therefore, the ability of businesses to recognize climate risks and adapt in a timely way is crucial.

Grounded in early conceptual work[15–17] (Supplementary Information, appendix A), the empirical analysis of private sector CCA currently relies on either surveys or corporate disclosures (such as carbon disclosure project, CDP), both eliciting self-reported CCA. Surveys and interviews[18–27] provide valuable knowledge on mechanisms enabling intended or taken CCA, including awareness, perceived effectiveness, size of firm, owner characteristics, institutions (public adaptation and access to finance) and others (Supplementary Information, appendix A, layer 2). Understandably, such indepth data focus on specific geographies, usually small and medium enterprises (SMEs) or a single sector, at a snapshot in time, and remain limited to modest samples (usually 10s–100s respondents). Furthermore, the collected data are contingent on the theoretical foundations and survey item specifications, hindering generalization and comparison across places. Conversely, CDP[28,29] data rely on standardized questionnaires filled annually by businesses worldwide, albeit a small number of companies report climate physical risks (~2,000 globally). A recent analysis[30] reveals that businesses under-report climate risks by two orders of magnitude, warning about under-adaptation. While CDP provides generalizable global data, it covers primarily transnational corporations, and is prone to self-selection bias and under-reporting as a result of the CDP

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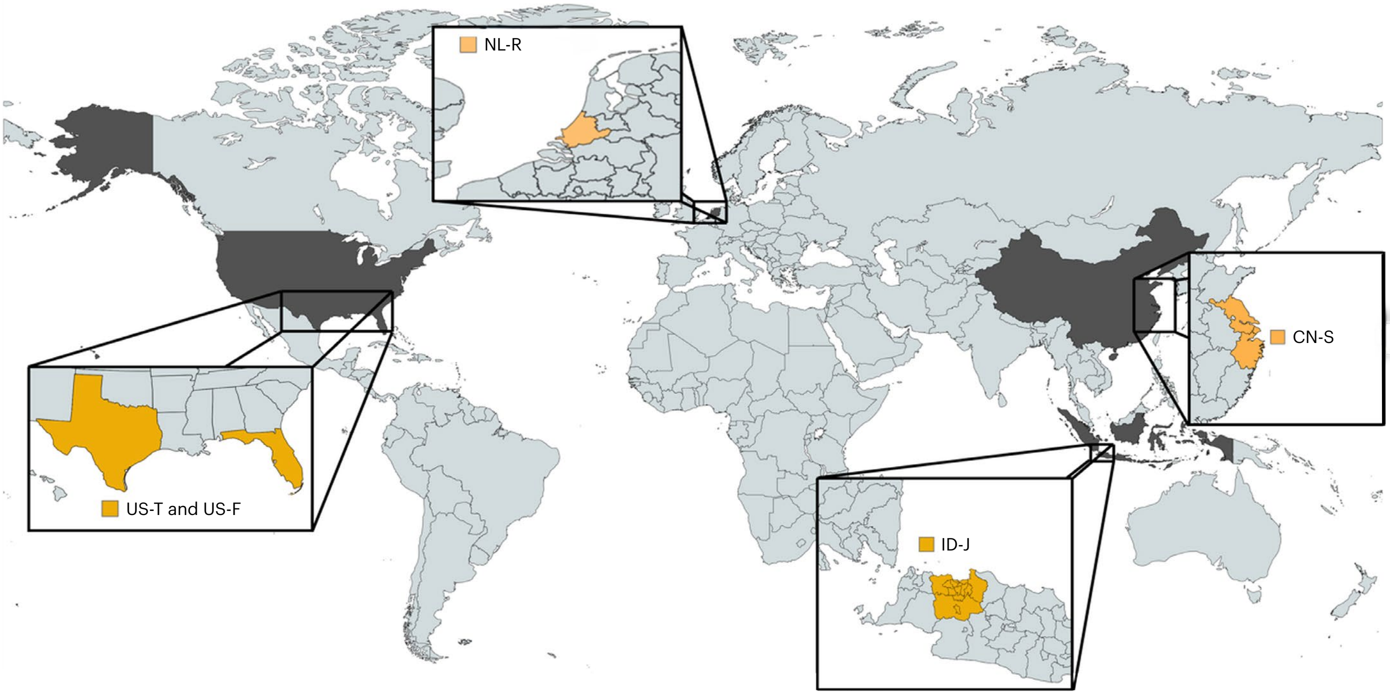

Fig. 1 | Coastal regions included in our adaptation investment dataset. The geographic coverage of our dataset reports business investments in climate adaptation in coastal regions: Texas and Florida, USA, with Houston and Miami as the biggest cities; South-Holland, the Netherlands, with the Rotterdam-The Hague metropolitan area; Jabodetabek, Indonesia, with the Jakarta metropolitan area; and Jaing Zhe Hu, China, with the Shanghai metropolitan area. We refer to these five regions in the paper as US-T, US-F, NL-R, ID-J and CN-S, respectively. Credit: Map adapted from MapChart under a Creative Commons license CC BY-SA 4.0.

investor-oriented purpose. Consequently, understanding of business CCA remains fragmented and incomplete, with little systematic evidence on actual adaptation costs, limiting consistent comparison of CCA investments across sectors and regions[5,12] (Supplementary Information, appendix A).

Our study addresses this empirical knowledge gap by analysing a unique dataset of actual CCA costs over time for businesses, differentiating across 18 economic sectors and 16 CCA types (Supplementary Table 1), spanning five coastal regions (Fig. 1; see Methods for selection criteria). Complementing traditional self-reported data, we rely on actual CCA costs retrieved from a market transactions database co-developed with kMatrix[31]. Therefore, we focus on CCA defined as a process of adjustment to current or expected climate impacts[32] via monetary investments that the private sector allocates to measures reducing harm or improving productivity. The transactions of businesses are classified as CCA investments through a multilayered filtering process and triangulation of data from at least seven sources (Methods). For a period of four fiscal years (2017/18–2020/21), our dataset contains 43,840 observations on private investments aggregated per sector and region, covering 299,367 businesses (the extended dataset contains 46,960 observations on 387,783 businesses across 19 economic sectors when our analysis includes the public services sector). Beside the main contribution of providing missing[5,12] empirical evidence on patterns in the actual CCA costs of businesses across regions and sectors, this Analysis also contributes to the multifaceted discussion on CCA effectiveness[15,33,34] by estimating the effects that private CCA has on the economy as measured by broader regional revenues. Although much is discussed about adaptation effectiveness (Supplementary Information, appendix A2), quantitative assessments of adaptation outcomes are still scarce, repeatedly calling for better evidence[5,12,35]. Notably, theoretical literature point to different mechanisms triggering either positive[36,37] or negative[38–40] outcomes of private sector adaptation for the broad economic system (conceptual framework in Supplementary Information, appendix A), calling for empirical theory testing[5]. Although explorative, our econometric analysis adds insights into the economic dimension of CCA effectiveness.

Preferred types of private sector adaptations

Our analysis covers five coastal regions: US-Texas (US-T), US-Florida (US-F), Netherlands-Rotterdam (NL-R), Indonesia-Jakarta (ID-J) and China-Shanghai (CN-S). We observe that businesses prioritize flood-related CCA, which nearly equals cumulative investments targeting all other hazards (€4.0 versus €4.7 billion, correspondingly). This is unsurprising, given that globally floods and coastal storms are the costliest hazards, accounting for 69% of all damages[41].

Following ref. 30, we group different forms of measures into hard, soft and ecosystem-based (EbA) adaptations (Supplementary Table 1). Our data reveal that between 2017/18 and 2020/21 the private sector invested 52% (€4.53 billion; Fig. 2) in hard structural adaptations compared with 47% (€4.12 billion) and about 1% (€0.07 billion) in soft and EbA measures, respectively. Among hard adaptations, investments were channelled into sustainable drainage and water management systems (water infrastructure, Fig. 2), energy efficiency installations (energy infrastructure, Fig. 2), retrofitting buildings and architectural engineering (infrastructure design or adjustments, Fig. 2). Among soft CCA, the private sector invests in consulting and early warning systems (knowledge generation, Fig. 2), project management and sandbags (planning, Fig. 2). Here hard CCA investments consistently dominate over soft across hazards (flooding versus non-flooding). Yet, previous CDP-based analysis found that large corporations self-report preferring soft (76%) over hard CCA (47%)[30]. These contrasting findings stem from the way adaptation effort is measured in the last study (count of the reported number of measures) versus ours (in monetary spending). While corporations implement more soft actions, hard measures are typically more expensive, constituting the bulk of investments despite being fewer in number. Moreover, large corporations in the CDP data

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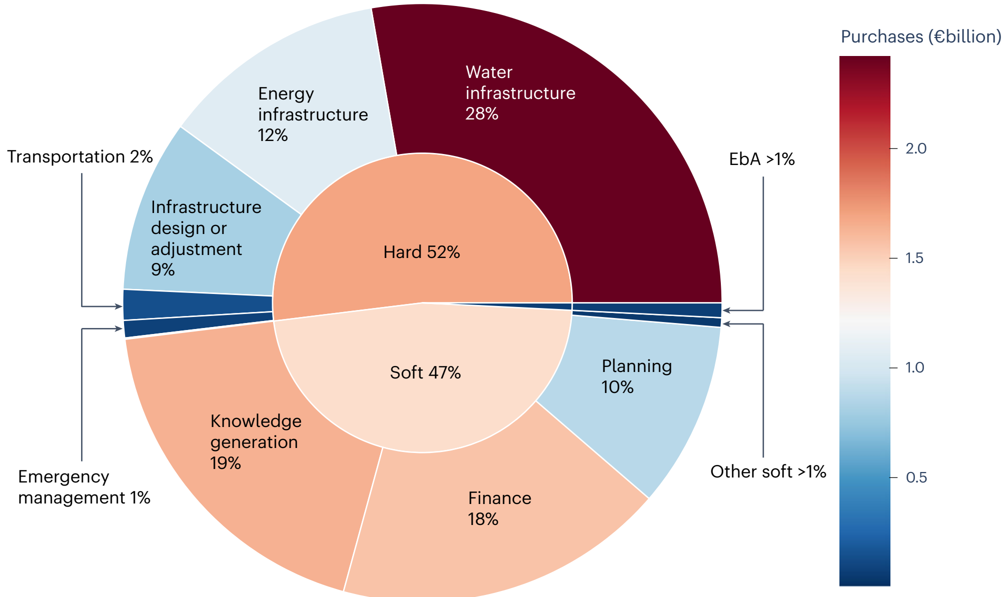

Fig. 2 | Types of private sector adaptations and their relative shares across five coastal regions. Distribution of adaptation investment across categories—hard, soft and ecosystem-based (EbA) adaptations—in our case study regions in 2017/18–2020/21 (n = 43,840 observations covering 299,367 firms across 18 economic sectors).

can afford financial services (insurance and comprehensive consultancy) before implementing hard measures. Our study aligns with previous literature reporting just 3% investment in EbA[24,30], despite its proven importance. Unsurprisingly, EbA typically offers positive public externalities, while implementation costs are private, making it an unlikely choice for businesses.

Location specifics of adaptation economies

Our data confirm that businesses adapt differently across locations. Private sector CCA investments exceed €3.4 billion in the ID-J region over a 4-year period, compared with €1.0 billion in the CN-S region. This contrast becomes more pronounced when considering the scale of the economies of these two global-south regions: in 2020/21, ID-J businesses CCA investments constituted 0.23% of total regional revenues, while in CN-S—only 0.009% (revenues, Table 1). When analysing the global-north cases, we observe a total business CCA investment of €3 billion over 4 years allocated across two American states (US-T and US-F) and €1.3 billion invested in the NL-R region. Despite the combined population of US-T and US-F being tenfold that of NL-R, their ratio of businesses CCA investments relative to regional revenues is four to ten times lower: 0.21% compared with 0.05% and 0.02% (revenues, Table 1). It is surprising that American businesses invest less in adaptation, given the emphasis on private action and limited government interventions. Furthermore, Georgeson et al.[42] found that global-north cities allocate 0.22% of GDP to CCA compared with about 0.15% by cities in the global south. Limited to five cases, our data reveal no clear differences in private sector CCA between global-south/north or in the presence/absence of strong public CCA: Indonesian businesses invest similarly to the Dutch and the Chinese similarly to the American. This signals physical (hazard nature), institutional (availability of insurance and governmental disaster relief funds), economic (sectoral mix and finance) and other contextual factors shaping the CCA decisions of businesses, as commonly revealed by indepth surveys[18,20,22,24–26,43].

In addition to assessing adaptation investments across geographies, we study the speed of CCA, finding that adaptation investments exhibit a similar growth pattern across regions (19–24%, Table 1). A comparison of shares of the CCA spendings of businesses in each regional economy over time (companies, Table 1) reveals that only a minority of businesses invest in CCA: 0.25–2.89% (CN-S versus NL-R in 2020/21). Additionally, we examine the proportion of employment in these CCA-investing businesses relative to the total employment in each region. We find that businesses investing in CCA, employ just 0.28–7.2% of the regional population (CN-S versus ID-J, employment, Table 1). Since we use aggregate rather than firm-level data, our employment figures rely on the average size of businesses, providing a broad, yet insightful, view of who adapts. Specifically, in NL-R, the share of adapting firms is greater than their average size, while ID-J features the opposite trend (compare companies and employment columns, Table 1). This signals that firms investing in CCA tend to be smaller

Table 1 | Trends in private sector adaptation investments in five regions in 2017/18–2020/21

Region	Fiscal period	Revenues (%)	Companies (%)	Employment (%)
CN-S	2017/18	0.007	0.210	0.210
	2020/21	0.009	0.251	0.281
	Change	20.000	19.050	33.330
ID-J	2017/18	0.190	1.750	5.710
	2020/21	0.234	2.160	7.213
	Change	21.050	23.430	26.380
NL-R	2017/18	0.173	2.432	0.730
	2020/21	0.211	2.890	0.962
	Change	23.530	18.930	31.510
US-F	2017/18	0.042	2.271	1.652
	2020/21	0.050	2.810	2.184
	Change	19.000	23.790	31.990
US-T	2017/18	0.016	1.750	1.623
	2020/21	0.020	2.084	2.070
	Change	20.000	18.860	27.780

The columns show: the first/last fiscal period and the percentage change between years 2017/18–2020/21 for each metric; the volume of adaptation investments as a percentage of annual regional sectoral revenues; the percentage of companies investing in adaptation in each region; and the percentage of regional employment that investing companies cover.

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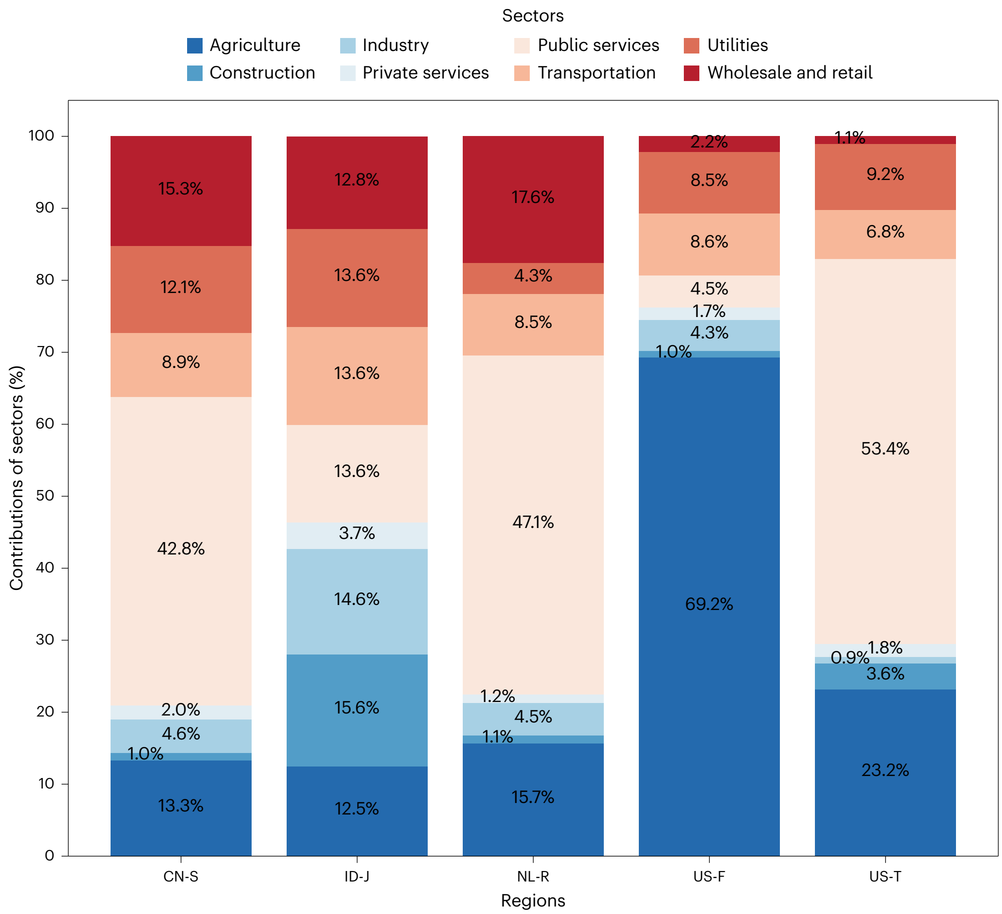

Fig. 3 | Differences in adaptation investment shares by economic sector across five coastal regions. Relative contributions of sectors investing in adaptation in each region over the period of 2017/18–2020/21 (n = 46,960 observations covering 387,783 firms, aggregated into eight economic sectors, that is seven private and one public), indicating which sectors 'buy' adaptation. The higher number of observations and firms is due to the addition of the public service sector. The share of the adaptation expenditure of each sector is estimated relative to the contribution to regional revenues of the sector.

(larger) in NL-R (ID-J) than are non-adapting firms. However, this pattern could also be partially driven by adaptation occurring through informal channels not captured in our transaction-based dataset, particularly among smaller firms in ID-J. These regional differences stress the importance of location-specific analyses when assessing the CCA dynamics of businesses.

Sectoral heterogeneity of business adaptation

Given the different sectoral structures of economies, we examine CCA investments normalized by the contributions of sectors to regional revenues. For comparison purposes, we introduce public CCA investment (public services sector, Fig. 3), which, in absolute terms, is the largest investor in adaptation. Yet, the CCA landscape becomes balanced when adjusting for sector size (Fig. 3). Everywhere, except ID-J, sectors such as private services, construction and industry lag behind in CCA investments (three light blue bars, Fig. 3). Despite being major contributors to economic activity and vulnerable to climate-induced hazards, these sectors exhibit low adaptation efforts. This is particularly concerning for construction and industry as a result of their exposure to operational disruptions and possible system-wide cascading effects. This is also the case for utilities and transportation (two orange bars, Fig. 3), signalling potential vulnerabilities of critical infrastructure networks. Notably, agriculture stands out for the high CCA investment of the sector relative to its size (dark-blue bars, Fig. 3). In ID-J—the climate hotspot with floods already occurring at least annually—businesses in all sectors, except private services, invest in CCA. Across regions, public services show substantial variability, even within the same country, with US-T showing the highest share and US-F the lowest. The wholesale and retail sector in the USA (US-F and US-T) performs poorly relative to its size, further underscoring uneven adaptation efforts across sectors and regions.

We further examine the types of CCA investments made by various private sectors across different regions. In absolute terms, private services invests the most in adaptation, which is expected since it is the largest sector in the economy (Fig. 4). Notably, all sectors except utilities follow the general trend of investing slightly more in hard adaptations than in soft (blue versus orange bars, Fig. 4). Unsurprisingly, agriculture is the only sector investing in EbA (green bars, Fig. 4). These investment choices reflect sector-specific vulnerabilities, operational needs and perceived feasibilities and advantages of various adaptations.

Economic implications of private sector adaptations

Despite many views on adaptation effectiveness[33,34] (Supplementary Information, appendix A2), quantifying adaptation outcomes remains understudied[5,12,35]. Particularly, private sector adaptation investments may either yield positive 'resilience dividends' for the wider system or divert scarce private capital from productive to protective use[36–40,44] (conceptual framework in Supplementary Information, appendix A). Complementing our descriptive analysis on the CCA investment patterns of businesses, we econometrically explore how changes in the

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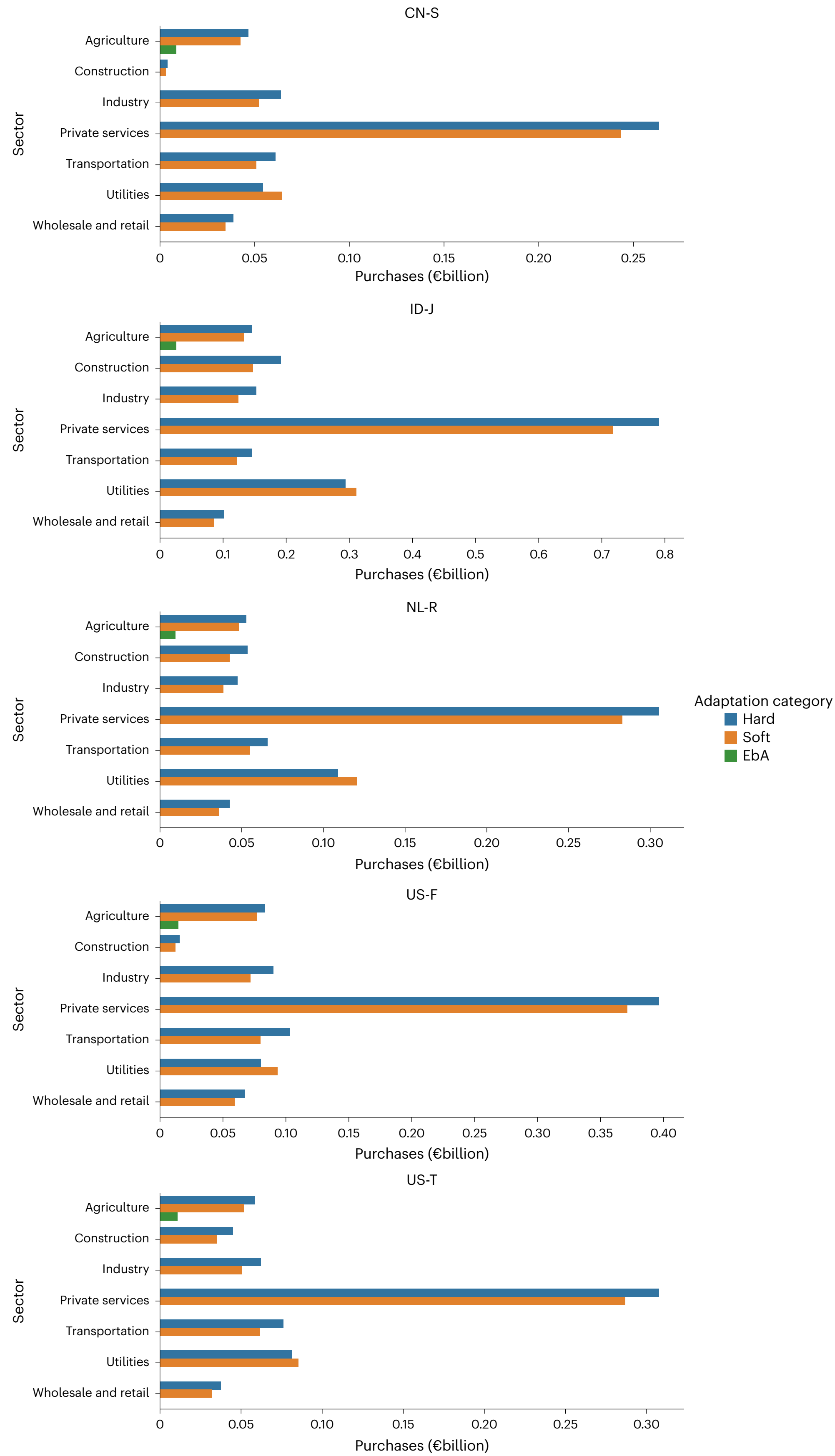

Fig. 4 | Patterns of private sector adaptations by measure type across five regions and seven economic sectors. Adaptation expenditures differentiated by measure type—hard, soft and ecosystem-based (EbA) adaptations—purchased by each sector per region (n = 43,840 observations covering 299,367 firms in 2017/18–2020/21).

broad economic outcomes relate to previous private investments in adaptation.

Specifically, we use a statistical method that accounts for potential two-way feedback between private CCA investments and regional business revenues (Methods; equation (1); Supplementary Information, appendix C). We find that when businesses spend more on adaptation, cumulative regional revenues tend to increase, although this effect is small (a 1% increase in CCA investments creates a 0.244% increase in revenues). This is unsurprising since private investment is one of many factors affecting regional economic performance. Importantly, our results are supportive of a positive causal relationship across our panel, and can be interpreted as an indication of business CCA increasing aggregate revenues, hence aligning with the resilience dividend conceptualization (Supplementary Information, appendix A). However, a longer period of available investment data is required for definite proof of causality (Methods) and, ideally, complementary microstudies accounting for potential confounding factors (Supplementary Information, appendix A1). The elicited positive effect could be explained by the replacement of older capital by new technologies, contributing to the productivity of the sectors. Indeed, hard measures, which constitute most in our database, imply structural changes to assets. For established economies with existing (old) infrastructure, new private CCA investments deliver local benefits, even over the short time span of our data. This indicates that private CCA investments are associated with modest indirect benefits for regional economic performance, even in the short run.

Furthermore, to account for differences in the effect of CCA investments across contexts, we complement this analysis with an exploration of sector- and region-specific effects. When disaggregating by sector and region, we use a simpler statistical model (Methods; equations (2) and (3); Supplementary Information, appendix C) that captures relationships but cannot test two-way feedbacks between investments and revenues because of fewer data points. Despite this, the results of this exploratory exercise match those of the more rigorous model above, revealing positive association between CCA investments and regional revenues across all sectors, increasing revenues by 0.08–0.49% for every 1% increase in CCA investments (Fig. 5a). Moreover, when splitting the analysis by region, the investment-on-revenue effect is positive in four regions (0.16–0.40%), while slightly negative in NL-R (−0.048%, Fig. 5b). While acknowledging that these region- and sector-specific results are exploratory because of data constraints, our analysis provides a valuable proxy assessment of regional differences in effectiveness.

Conclusions

Understanding private sector responses—including empirical evidence on costs, scope and speed of CCA—and assessing CCA effectiveness are key priorities in adaptation research[5,12,35] and practice[7] (Supplementary Information, appendix A). Using a unique dataset grounded in actual adaptation expenditures, our analysis elicits patterns of adaptation undertaken by businesses across economic sectors and quantifies private sector CCA effectiveness through its impact on regional revenues. By contributing empirical evidence on private sector CCA, we fill several research gaps. First, we report actual CCA expenditures of businesses across sectors and geographies. Our five selected regions cover different climatic, economic and institutional settings, representing both

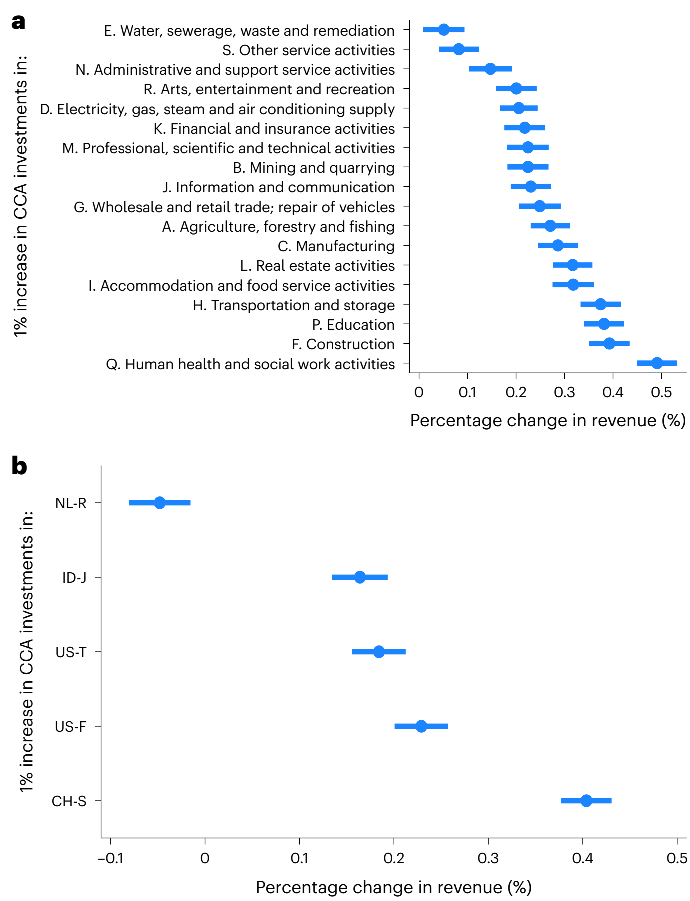

Fig. 5 | Effects of private sector adaptation investments on regional economic performance differentiated by sector and region. This figure shows how much total economy-wide regional revenues would change (in %) with an increase in private sector CCA investments of 1%. The circle symbolizes the estimated elasticity of regional revenues with respect to private sector CCA investments and the solid lines are the 95% confidence interval. The effects are estimated using a log–log regression based on data from 387,783 firms in 2017/18–2020/21 years (t), including country–sector–adaptation measure fixed effects. **a**, A plot of the regression coefficients (equation (2); Methods), showing the elasticity of total economy-wide revenues on sectoral CCA investment in all regions by sector. Here sectors correspond to the NACEv2 mapping: agriculture is A, industry is B and C, utilities are D and E, construction is F, wholesale and retail are G, transportation is H and private services are I, J, K, L, M, N, P, Q, R and S. Coefficients (Coef.), standard errors (s.e.), P values and significance stars are: A × ln(Investment(t − 1))−Coef.(0.271***), s.e.(0.021), P(0.00000); B × ln(Investment(t − 1))−Coef.(0.225***), s.e.(0.022), P(0.00000); C × ln(Investment(t − 1))−Coef.(0.286***), s.e.(0.021), P(0.00000); D × ln(Investment(t − 1))−Coef.(0.206***), s.e.(0.020), P(0.00000); E × ln(Investment(t − 1))−Coef.(0.051**), s.e.(0.022), P(0.01800); F × ln(Investment(t − 1))−Coef.(0.393***), s.e.(0.021), P(0.00000); G × ln(Investment(t − 1))−Coef.(0.249***), s.e.(0.022), P(0.00000); H × ln(Investment(t − 1))−Coef.(0.374***), s.e.(0.021), P(0.00000); I × ln(Investment(t − 1))−Coef.(0.318***), s.e.(0.022), P(0.00000); J × ln(Investment(t − 1))−Coef.(0.231***), s.e.(0.021), P(0.00000); K × ln(Investment(t − 1))−Coef.(0.218***), s.e.(0.022), P(0.00000); L × ln(Investment(t − 1))−Coef.(0.317***), s.e.(0.021), P(0.00000); M × ln(Investment(t − 1))−Coef.(0.225***), s.e.(0.022), P(0.00000); N × ln(Investment(t − 1))−Coef.(0.147***), s.e.(0.023), P(0.00000); P × ln(Investment(t − 1))−Coef.(0.382***), s.e.(0.021), P(0.00000); Q × ln(Investment(t − 1))−Coef.(0.491***), s.e.(0.021), P(0.00000); R × ln(Investment(t − 1))−Coef.(0.201***), s.e.(0.021), P(0.00000); S × ln(Investment(t − 1))−Coef.(0.082***), s.e.(0.021), P(0.00010). All tests are two-sided t-tests with d.f. = 5,459; no adjustment was made for multiple comparisons. **b**, Plots of the regression coefficients (equation (3); Methods), showing the regional CCA investment elasticity on total economy-wide revenues for all sectors by region. US-F×ln(Investment(t − 1))−Coef.(0.229***), s.e.(0.014), P(0.00000); ID-J×ln(Investment(t − 1))−Coef.(0.164***), s.e.(0.015), P(0.00000); CH-S×ln(Investment(t − 1))−Coef.(0.404***), s.e.(0.014), P(0.00000); NL-R×ln(Investment(t − 1))−Coef.(-0.048***), s.e.(0.017), P(0.00390); US-T×ln(Investment(t − 1))−Coef.(0.184***), s.e.(0.014), P(0.00000). All tests are two-sided t-tests with d.f. = 5,472. No adjustment was made for multiple comparisons.

global-north and global-south regions. Addressing previous calls[25,45], we dive into sectoral differences, revealing which sectors pioneer/lag in adaptation and where. Second, existing data typically cover either the CCA globally of large corporations[28,30] or fragmented snapshots of the CCA behaviour of SMEs in specific locations[11,13,19,23]. Our analysis includes small, medium and large companies in a single longitudinal dataset. Third, while existing self-reported data offer valuable qualitative insights, quantitative analyses of actual private sector adaptation costs and effectiveness remained elusive. Our analysis uniquely complements existing CDP and business surveys with systematic, comparable adaptation expenditure data, eliciting scope and speed of private CCA, and explores its effectiveness.

Regarding adaptation scope, our findings confirm that while businesses adapt, only a fraction of the private sector invests in CCA (0.25–2.89%). Those small, medium and large businesses that adapt, invest in hard, soft and EbA adaptations (52%, 47% and 1%, respectively). This aligns with previous findings[30]: EbA is the least popular among businesses. Adaptation policies could focus on designing incentives for the private sector to invest in EbA, which typically delivers societal co-benefits. Furthermore, this apparent preference for hard adaptations in our data probably reflects that it captures only monetary investments, omitting informal, behavioural and other soft CCA reported as prominent in other studies[30], especially in the global south[24].

Regarding the speed of CCA, we notice an increase in private sector adaptation, mainly by larger companies. Regional differences in the CCA uptake of businesses are evident since adaptation needs vary with hazard exposure and institutions (public CCA, norms and finances). Widening the geographic coverage across different climates, hazards and sectoral structures of economies is a valuable future research direction. It could provide the needed diversity of cases to indirectly quantify the societal effectiveness of private CCA, which is important in the absence of firm-level data on climate damages and adaptation benefits.

Our sectoral analysis reveals distinct regional differences, probably due to the variation in the sectoral structure of economies and contexts. Industry/manufacturing, construction, utilities and transportation lag in CCA, despite the economic importance and vulnerability to climate hazards of these sectors. This is concerning because of indirect cascading damages, which could escalate into systemic risks for society. However, it remains unclear whether critical sectors (utilities, transportation and industry) lack awareness, resources or incentives for adaptation, or they rely on past CCA measures or public funds for reconstruction. Our findings offer missing data for refining economic CCA assessments and pave the way for sector-specific research on policy interventions that incentivize targeted CCA strategies to facilitate climate-resilient regional development.

Last, our exploratory analysis quantifies the economic effectiveness of CCA. In general, business investments in CCA positively influence regional economies through increased revenues. Over the 4-year period, CCA benefits are small, since most benefits manifest over longer time spans. Notably, the construction, education, transport, accommodation and health sectors stand out with the highest benefits per euro invested in adaptation, while the rest of the economy benefits less. This sectoral heterogeneity of adaptation effectiveness indicates that CCA investment benefits are either unevenly distributed across the economy or manifest over different time scales for different sectors.

Our study has several limitations pointing to future research directions. First, by focusing on market transactions, we under-represent adaptation occurring through informal channels, particularly in global-south regions. Yet, non-monetary CCA could enhance overall socio-economic resilience[26], suggesting combining different data sources. Second, the short period of our analysis prohibits observing longer-term adaptation outcomes, which may manifest beyond our 4-year time frame. Longitudinal tracking of CCA investments is essential to capture adaptation as a dynamic iterative process evolving with the experiences of businesses, shifting climate risks and CCA effectiveness. Future work should also cover more geographies, although data acquisition costs remain prohibitive. Combining actual CCA costs, indepth surveys and existing supranational enterprise datasets[46–48] enables upscaling, for example, through statistical methods for synthetic populations. Last, regional economic outcomes are influenced by broader macroeconomic cycles, government investments and other confounding regional factors, in addition to private sector CCA investments we analysed. Future research could benefit from additional micro-level data or natural experiments to further disentangle causality, improving the quantification of CCA effectiveness.

Albeit in limited numbers, businesses invest in CCA. Their adaptation strategies and the resulting short-term economic impacts vary across sectors and regions. This calls for targeted policy formulations, acknowledging diverse sectoral priorities, regional vulnerabilities and gaps in adaptation finance. As climate change escalates, understanding and facilitating effective business adaptation is critical in curbing its economic adversities and adapting to this new evolving 'normal'.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-025-02423-w.

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Methods

Dataset

For this study, we use a unique dataset on the CCA investments of actual businesses in five coastal regions in four countries for the fiscal periods 2017/18–2020/21 (UK fiscal periods from 1 April 2017 to 31 March 2021). We focus on: Texas (US-T), Florida (US-F), Zuid-Holland including Rotterdam (NL-R), Jabodetabek including Jakarta (ID-J) and Jaing Zhe Hu including Shanghai (CH-S). These regions were selected because they host clusters of economic activities while being exposed to significant climate hazards and represent diverse institutional (for example, role of government-led adaptation) and economic (for example, sectoral structure) characteristics spanning global-north and global-south contexts. The selection also aligns with locations of an existing household adaptation survey[49], important for our broader research project. While we would have preferred wider global coverage, including for example African coastal regions, practical constraints limited our analysis to these five cases. Nonetheless, they provide valuable insights across different geographies, institutional and economic contexts.

For our analysis, the adaptation investments are categorized on the basis of the hazard, differentiating between flood-related and non-flood-related adaptation. This distinction is crucial as it highlights the varied nature of CCA strategies deployed in different geographical contexts. The flood-related category includes adaptation to fluvial, pluvial and coastal floods. Coastal storms and floods constitute 44% and 28% of all hazards worldwide and together account for 69% of all global damages[41]. Besides, the dataset provides insights into the nature of goods or services procured through these investments. Specifically, 61 different products encompass a wide range of CCA activities, ranging from coastal infrastructure and risk modelling to the implementation of early warning systems (Supplementary Information, appendix B7). Furthermore, in our dataset, the CCA investments are allocated across several economic sectors operating in five regions across four countries (Fig. 1). For most of our descriptive analysis, we aggregate the sectoral data into seven economic sectors. Only for our regression analysis do we dive deeper and differentiate among 18 economic sectors according to the NACEv2 mapping, with agriculture denoted as A, industry as B and C, utilities as D and E, construction as F, wholesale and retail as G, transportation as H and private services as I, J, K, L, M, N, P, Q, R and S. Note, that all investments that have been directly paid by the government (that is, excluding indirect subsidies) are classified as 'public services' and are included in the data in Fig. 3 for comparison purposes. For each sector, the data show how many firms are investing in a specific product and how many employees those firms have. Overall, our dataset contains a total of 43,840 observations for a total of 299,367 firms (or 46,960 observations on 387,783 firms across 19 economic sectors when our analysis includes public services).

The CCA investments dataset has been co-developed with kMatrix Data Services, which relies on a data consolidation approach[31] that combines various transactional and operational sources to estimate economic activity, mitigating biases from individual sources. Initially developed in collaboration with the Greater London Authority, Imperial College London, the UK Department for Environment, Food & Rural Affairs and the UK Climate Change Committee, this methodology has been previously used to reveal the 'adaptation economy', namely, the total investment in CCA activities worldwide[42]. In contrast to most estimations of economic activity pertaining to specific sectors, which are estimated from the top-down, our dataset is constructed from the bottom-up, by aggregating observed transactions that relate to a specific CCA measure or service. Consequently, our dataset includes neither monetary transactions that happen informally nor non-monetary CCA, probably underestimating adaptation efforts by SMEs in regions with higher informal economy rates, especially in the global-south. To determine what is considered a CCA-related investment, we follow the Intergovernmental Panel on Climate Change definition[32] of adaptation for human systems, seen as a process of adjustment to current or expected climate impacts. Here we refine the definition to conceptualize it as a process of adjustment to current or expected climate impacts via monetary investments that the private sector allocates to measures reducing harm or improving productivity. In our study, 61 different measures fitting this definition have been included in an adaptation taxonomy (Supplementary Information, appendices B2 and B7). We also tested this method in another application to European countries[50].

To estimate investments for a particular measure, the kMatrix approach uses a multilayered filtering process to isolate relevant transactions from 30,000 independent sources (both publicly available and confidential) that cover most global economic and financial transactions. Each database or source is coded to enable sector- and region-specific assessments. These empirical observations are filtered to only include executed monetary transactions between businesses (or businesses and the government) that relate to business CCA. Notably, this means that intended and planned adaptation measures are not included in these data; only CCA-related expenditures that have actually taken place are accounted for. For each final data point, at least seven different sources (that is, whose values cannot be traced back to a unique origin, such as a government report) are used to ensure accurate estimates that would not be achievable using only one source. The final data points represent the average value among these sources after removing outliers, with a confidence level defined as the difference between the mean value and the most extreme values in the range. The data used in this study have a confidence level ranging from 80% to 88%, which indicates that the difference between the mean and extreme values ranges from 20% to 12%. A more extensive explanation of the estimation methodology, as well as a worked example of a real data point, is provided by kMatrix Data Services and included in Supplementary Information, appendix B.

CCA categories

We adopted a categorization of adaptation investment into three distinct types, a framework that aligns with classifications used in previous literature analysing private sector CCA[30]. This approach not only facilitates systematic examination of adaptation investments across sectors and regions but also enhances transparency and enables comparison with other studies in the field. Specifically, we differentiate between the following categories of CCA (Supplementary Table 1):

(1) Hard adaptation measures: this category focuses on significant financial investments in technology or engineering infrastructure, which includes the construction of tangible structures and structural measures to buildings.
(2) Soft adaptation measures: these approaches encompass substantial yet non-structural responses to the impacts of climate change.
(3) EbA measures: these methods prioritize the sustainable management, conservation and restoration of ecosystems as an integral comprehensive strategy for adapting to climate change.

Some adaptation projects could feature characteristics of several categories, such as engineering infrastructure with inbuilt ecosystem-centred co-benefits. However, the data granularity required to capture this nuance demands project-level details for each of our 299,367 firms, which is outside the scope of this research and the data estimation methodology. Thus, we classify investments on the basis of the general description of the project and leave these particularities to future work.

Data analysis methods

Descriptive statistics. In our exploration of businesses CCA, we begin with an analysis of general investment patterns. This includes a comparison of total investments directed towards flood-related adaptations versus non-flood adaptations across the adaptation categories elicited in Supplementary Table 5.

Subsequently, we look at the private sector 'adaptation economy' and assess the total investment over time, aggregated at the regional scale, as a percentage of total regional revenues as well as the share of businesses investing in CCA compared with the total, which is also specified in the dataset. Additionally, we examine the employment demographics within businesses engaging in adaptation.

Next, we investigate adaptation trends across sectors by identifying the relative contribution of each economic sector to the total CCA investment of businesses in each region. Furthermore, we compare the absolute size of the investment across regions and adaptation categories of each sector for further insight.

Econometric analysis. Directly measuring adaptation effectiveness is challenging (Supplementary Information, appendix A2), particularly at the macro-level, because of the limited micro-level data linking private sector adaptation investments directly to adaptation outcomes or private benefits. Given these challenges, our analysis intentionally adopts an exploratory macro-level approach, using regional revenues as an indirect proxy to capture potential short-term aggregate economic effects of climate adaptation investments. We begin our analysis by exploring the effect of private sector CCA investments on regional economic outputs (revenues) for all periods and regions using the Blundell–Bond system generalized method of moments (GMM) (equation (1); Supplementary Information, appendix C). This elasticity of revenues to CCA investments is:

$$\ln R_{i,t} = a_0 + a_1 \ln R_{i,t-1} + a_2 \ln(\text{Investments}_{i,t-1}) + \text{FE}_i + \mathbf{M}_{it} + e_{i,t} \quad (1)$$

where $\ln R_{i,t}$ is the logarithm of revenues in each sector–region–adaptation measure combination (1) at year t (2017/18–2020/21), $\ln(\text{Investments}_{i,t-1})$ is the logarithm of total CCA investments; FE are the region and time fixed effects; $\mathbf{M}_{i,t}$ is a vector of firm and sector characteristics (the average number of employees per firm and the number of firms that adapt in a sector). In this specification, we find the CCA investment elasticity of revenues, in other words, how much the economic output of a region is affected by changes in CCA investments. The approach in equation (1) assumes that all CCA investments have the same effect on the productivity of firms.

To deepen our analysis, we study the effects of private sector CCA investments separately for each sector. Owing to the short panel ($T=4$), the system GMM estimator faces limitations for sector- and region-specific analyses due to limited data points. In particular, the necessary lagged instruments become weak, undermining the reliability of diagnostic tests and producing implausible coefficients. Although GMM is valuable in addressing endogeneity at the aggregate level, these diagnostics indicate that the instrument set may be insufficient at finer disaggregation. In contrast, the FE specification remains viable here because it does not rely on instrumental variables. Instead, it accounts for time-invariant unobserved heterogeneity within each unit by differencing out constant confounders. Although FE does not fully resolve endogeneity or reverse causality, it can yield consistent estimates under the assumption of strictly exogenous regressors. Hence, in the context of limited variation and failing diagnostic tests, the FE approach yields more robust and interpretable results for sector- and region-level analyses, even if certain endogeneity concerns remain. However, the alignment of coefficients between the GMM and FE in Supplementary Table 7 (Supplementary Information, appendix C) is an indication that, in practice, the considered sector/region endogeneity is not large enough to fundamentally change the estimated effect.

Therefore, we study the effects of private sector CCA investments separately for each sector (equation (2), corresponding to Fig. 5a) and region (equation (3), corresponding to Fig. 5b) using the FE estimator:

$$\ln R_{i,t} = a_0 + \sum_{j=1}^{19} \gamma_j \times \text{Sector}_i \times \ln(\text{Investments}_{i,t-1}) + \text{FE}_i + \mathbf{M}_{i,t} + e_{i,t} \quad (2)$$

$$\ln R_{i,t} = a_0 + \sum_{k=1}^{4} \beta_k \times \text{Region}_i \times \ln(\text{Investments}_{i,t-1}) + \text{FE}_i + \mathbf{M}_{i,t} + e_{i,t} \quad (3)$$

where $\text{Region}_i \times \ln(\text{Investments}_{i,t-1})$ is the interaction of each region in the dataset multiplied with the CCA investments. Similarly, for the sectoral effects, we have $\text{Sector}_i \times \ln(\text{Investments}_{i,-1t})$. The Analysis presents the results of these more nuanced regressions (equations (2) and (3)), omitting the discussion of the simplistic model (equation (1)).

In the context of our regression models, endogeneity concerns are mitigated by several means (Supplementary Information, appendix C). The inclusion of fixed effects controls for time-invariant characteristics of businesses that might correlate with both the dependent variable and the independent variable. This helps to account for unobserved heterogeneity across businesses that could otherwise bias the estimates. More importantly, the focus on climate adaptation investments specifically reduces concerns of reverse causality. Investments aimed at adapting to climate adversities are often driven by external environmental factors and long-term strategic considerations rather than immediate revenue outcomes. Therefore, the direction of causality is more likely to flow from these investments to revenues, rather than the reverse.

Data availability

The data on private sector adaptation investments that support the findings of this study are available from kMatrix Data Services. Restrictions apply to the availability of these data, which were used under license for the current study and are not publicly shareable. Any queries regarding the raw data should be directed to kMatrix Data Services (enquiries@kmatrix.org). Source data are provided with this paper.

Code availability

The Python code used to produce the display items and the STATA code used for the regression are available via Zenodo at https://doi.org/10.5281/zenodo.16602772 (ref. 51).

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Author contributions

T.F. designed the overall research project, conceived the research design and wrote the paper. A.T. conducted the descriptive analysis, produced the display items and wrote the paper. T.C. developed the regression model, conducted the sensitivity analysis, produced the display items and contributed to and commented on the paper. I.C.A. supported the data analysis, helped with the dataset description and contributed to and commented on the paper.

Competing interests

The authors declare no competing interests.

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Additional information

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