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Carbon taxes and the geography of fossil lending☆

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ABSTRACT

Using data on syndicated loans, we find that the introduction of a carbon tax is associated with a decline (increase) in bank lending to coal, oil, and gas companies in domestic (foreign) markets. This manifestation of tax arbitrage is particularly pronounced for banks with large fossil-lending exposures, suggesting a role for bank specialization. Lending to private companies in foreign markets increases relatively more, implying bank incentives to avoid public scrutiny. We also find that banks reallocate a relatively larger share of their fossil loan portfolio to countries with less strict environmental regulation and bank supervision.

1. Introduction

There is a near-universal consensus among economists that carbon taxes are the most cost-effective tool to reduce carbon emissions at the scale and speed that is necessary to address the climate crisis.[1] Moreover, pricing carbon induces firms

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[1] See, for example, the "Economists' Statement on Carbon Dividends", which was originally published in the Wall Street Journal on 16 January 2019 and has since been signed by >4000 economists from around the world.

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to develop and adopt low-carbon technologies, speeding up the green transition (Acemoglu et al., 2012; Acemoglu et al., 2016). Yet, at present few countries in the world tax carbon-intensive activities at the required levels.[2] The implementation of carbon taxes is further plagued by practical difficulties, such as how to measure emissions precisely and how to rebate the proceeds in an efficient and fair manner. The most daunting challenge, however, stems from imperfect global coordination: national authorities may be loathe to impose carbon taxes unilaterally, for fear that the affected economic activities will simply move across borders. This would reduce growth at home while making little difference in terms of aggregate emissions.

We study the cross-border reallocation of fossil lending by internationally active banks in response to changes in the domestic cost of carbon due to the introduction of a carbon tax. Between 1990 and 2020, 25 countries imposed some form of carbon tax. A further 22 countries joined an Emissions Trading Scheme (ETS) which charges certain sectors of the economy for the greenhouse gases they emit. We study the evolution of lending to coal, gas, or oil companies by syndicated creditors, both at home and abroad, around these events. To that end, we employ a comprehensive global dataset of >2 million bank-firm loan tranches made between 1988 and 2021.

We focus on lending to fossil fuel companies—that is, coal mines and oil and gas extraction companies—because they stand at the source of the carbon dioxide emissions chain. Carbon dioxide is a byproduct of burning fossil fuel in industry, transportation, or energy generation. Because of its sunlight-capturing properties, and in combination with its large quantity already in the atmosphere, carbon dioxide is the main anthropogenic contributor to global warming. Accordingly, global plans to slow down climate change rest heavily on foregoing the extraction of existing coal, oil, and gas reserves (UNFCCC, 2015).[3] At the same time, to the indignation of the international community, financing for companies which extract fossil reserves and produce fossil fuel does not appear to be slowing down. For example, a recent report by a group of NGOs pointed out that the world's biggest 60 banks have provided $3.8 trillion of financing for fossil fuel companies since the Paris climate deal in 2015, and that overall funding for said companies remains on an upward trend.[4] An important unanswered question, therefore, is whether carbon taxes are an effective tool in reducing bank lending to fossil companies.

Existing work on the impact of climate policies on bank lending takes a purely domestic perspective, assessing how climate policies affect bank lending at home (e.g., Delis et al., 2021; Reghezza et al., 2021; and Degryse et al., 2021). Our contribution is to take an international perspective on the impact of climate policies on bank lending, focusing on the introduction of carbon taxes. This allows us to assess not only the impact of such policies on bank lending at home but also to measure the spillovers of such policies on lending abroad. In so doing, we can evaluate the relevance of international carbon tax arbitrage in bank lending and assess the effectiveness of carbon taxes in reducing fossil lending globally.

Our primary finding is that following an exogenous increase in the price of carbon in the domestic market as a result of the introduction of a carbon tax, banks reduce their fossil lending at home and increase their fossil lending abroad. This reallocation of fossil lending across national borders is immediate, economically meaningful, and statistically significant. In particular, after a country adopts a carbon tax, foreign fossil lending by banks domiciled in this country is on average higher by 6.8%, relative to non-fossil lending. The same effect is in place regardless of whether we look at the imposition of carbon taxes or at the introduction of Emissions Trading Schemes, which represent an alternative way of pricing carbon emissions. The main result still obtains when we look at a shorter window around the introduction of a carbon tax, as well as when we exclude countries that dominate the sample in terms of lending. Moreover, the increase in lending to fossil companies is also accompanied by a significant increase in the size of such fossil loans, as well as by a significant decline in their interest rate. These results are obtained after controlling for a rich set of fixed effects: bank fixed effects, company fixed effects, as well as interactions of home and host country dummies with time dummies. In all, they point towards a mechanism whereby credit demand by domestic fossil companies goes down following the introduction of a carbon tax, leading banks to increase the supply of credit to fossil companies abroad.

The main result of the paper is visualized in Figs. 1 and 2. In these figures, we plot point estimates and 95% confidence bands of a regression where the dependent variable is a dummy equal to one if the loan is to a fossil company, and to zero if not. The main explanatory variables are dummies equal to 1 in years −3, −2, …, 2, and 3 around the introduction of a carbon tax in the home country, and to 0 otherwise, with the year of the carbon tax introduction used as a reference point. Because we include bank fixed effects, the point estimates should be understood as growth rates in lending to particular categories of firms. The regressions also control for home-country GDP growth, population growth, return to capital, and exchange rates (data come from the Penn Tables). The evidence suggests that the growth rate of lending to fossil companies was not statistically different from zero in the years prior to the introduction of the tax, relative to the year in which the tax was introduced. At the same time, the evidence also points to a significant reduction in domestic fossil lending (Fig. 1), and a significant increase in foreign fossil lending (Fig. 2), in the two years after the tax comes into force in the bank's domestic market.[5]

We confirm that the relationship between changes in carbon taxes and lending obtains not only for lending to fossil companies, but also for lending to carbon-intensive industrial activities, such as metallurgy and cement production. We also show that the results only obtain for carbon-intensive sectors that are covered by the EU ETS, and not for ineligible carbon intensive sectors

[2] Estimates of the optimal carbon tax vary depending on model assumptions, ranging from $25 USD to $1500 USD per ton (see, e.g., Golosov et al., 2014; Van der Ploeg and Rezai, 2021).

[3] According to Meinshausen et al. (2009)'s calculations, more than half of all economically recoverable fossil reserves should be left in the ground if humanity is to have at least a 50% chance of not exceeding temperatures higher by at most 2 degrees Celsius, compared with pre-industrial levels.

[4] See https://www.bankingonclimatechaos.org/wp-content/uploads/2021/10/Banking-on-Climate-Chaos-2021.pdf.

[5] While the upward trend in lending to domestic fossil companies prior to the introduction of a carbon tax (Fig. 1) may point to anticipatory effects, the differences with the reference year are not statistically significant.

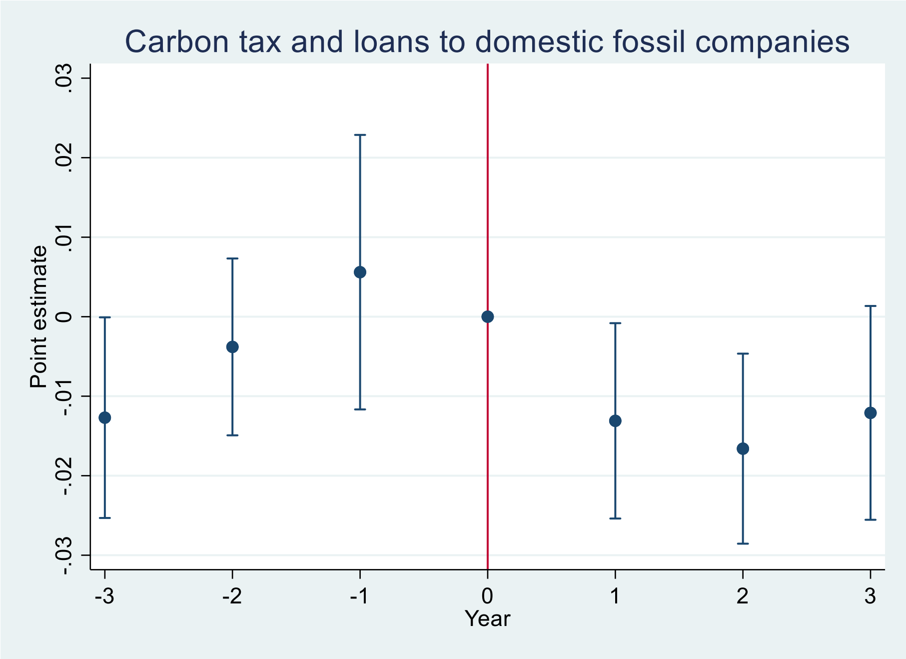

Fig. 1. Carbon taxes and the evolution of syndicated lending to domestic fossil companies.
Note: The Chart presents regression coefficients and confidence bands for domestic loans to fossil companies (i.e., companies in SIC sectors 12xx and 13xx.) after the introduction of a carbon tax. The regression controls for bank fixed effects, home-country GDP growth, population growth, return on capital, and exchange rates. Annual data from Dealscan, the Penn Tables, and authors' calculations.

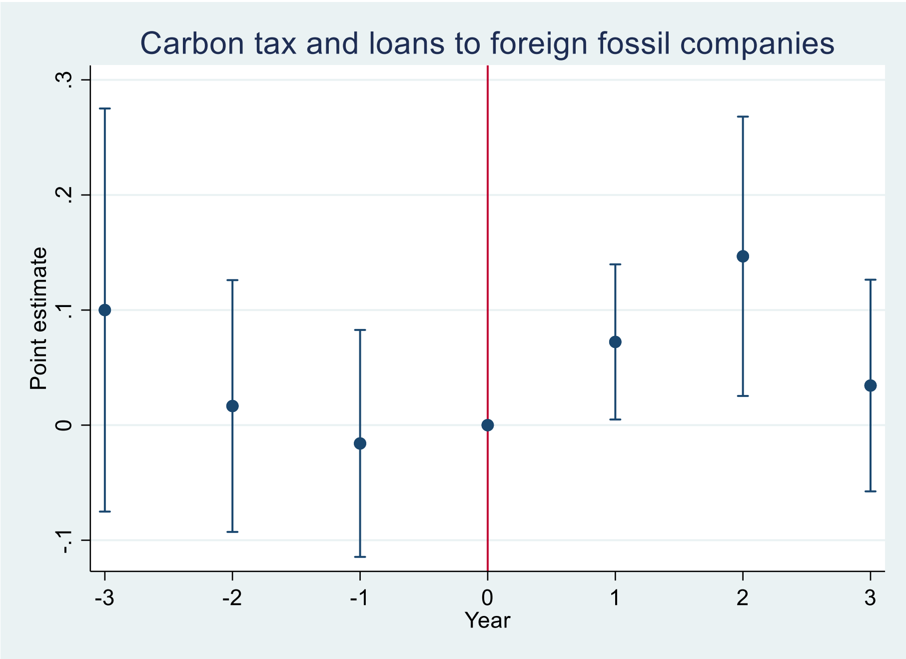

Fig. 2. Carbon taxes and the evolution of syndicated lending to foreign fossil companies.
Note: The Chart presents regression coefficients and confidence bands for foreign loans to fossil companies (i.e., companies in SIC sectors 12xx and 13xx.) after the introduction of a carbon tax. The regression controls for bank fixed effects, home-country GDP growth, population growth, return on capital, and exchange rates. Annual data from Dealscan, the Penn Tables, and authors' calculations.

of the economy. This suggests that our results are not driven by the introduction of carbon pricing being endogenous to the overall performance of the carbon-intensive sector.

In addition, we confirm the validity of our results by subjecting our data to two falsification tests. First, we demonstrate that the reallocation of fossil lending does not pre-date the introduction of carbon taxes. On the contrary, domestic fossil lending appears to increase on average in the years leading to the carbon tax, after which the trend reverses. Second, we show that lending to economic activities that are associated with a negligible carbon footprint—namely retail trade, wholesale trade, and clean manufacturing—does not respond, one way or another, to the introduction of carbon taxes. We conclude that the statistical relation between changes in carbon taxes and fossil lending appears to be causal.

In the second part of our paper, we investigate the potential mechanisms responsible for the regularities we observe. We find that certain bank-specific, firm-specific, and host country-specific factors are associated with higher elasticity of fossil lending reallocation to a carbon tax.

On the bank side, we find that banks with relatively high fossil exposures are more likely to reallocate fossil lending across national borders. This result is consistent with sector-specific bank specialization, with some banks having a comparative advantage in making fossil loans (Paravisini et al., 2015). The carbon tax makes lending to fossil companies domestically less attractive, prompting banks that specialize in fossil loans to increase their lending internationally. At the same time, bank capitalization or profitability does not seem to play a role. Our results thus lend support to the notion that bank specialization counteracts the negative balance-sheet effect of a carbon tax on overall bank lending, but do not offer support for the role of low bank capital in increased risk taking.

On the firm side, we find that in response to carbon taxes at home, banks are more likely to increase lending abroad to privately held fossil companies. This is consistent with the notion that in a policy environment which is increasingly hostile to the funding of fossil operations, banks may prefer to avoid the inevitable public scrutiny which comes with lending to listed firms (Doidge et al., 2017; Stulz, 2020). We also find that banks are more likely to reallocate lending abroad to firms with which they have an existing lending relationship. This is consistent with evidence that prior information matters for bank decisions (e.g., Berger and Udell, 1995; Giannetti and Laeven, 2012; De Haas and Van Horen, 2013), inducing them to increase lending on the intensive, rather than on the extensive, margin. It is also consistent with the notion that banks often choose to preserve the value of preexisting relationships when these relationship firms are hit by adverse shocks (e.g., Petersen and Rajan, 1994; Berger and Udell, 1995; Bolton et al., 2016) even though the type of shocks in that literature is different.

On the host-country side, we find that banks are more likely to increase lending to fossil companies in countries with less strict environmental regulation, as well as to countries with less stringent bank supervision. This is consistent with the notion that tighter regulation at home increases bank risk taking abroad (Ongena et al., 2013). These results imply that exogenous increases in domestic prices of carbon are subject to foreign leakage and that this leakage abroad is a function of the regulatory environment in which international banks operate. This finding has two important implications. First, to be effective from a global perspective, environmental rules in general, and carbon pricing in particular, need to be sufficiently strict throughout the world. Else, the effect of pricing carbon will be arbitraged away by international banks, which will dampen the desired effect on global fossil lending. Second, even in the absence of strict environmental regulation in a foreign market, fossil lending to that market may increase less if bank supervision in general is sufficiently strict.

Finally, we study the response of fossil firms' investment and sales over time, depending on their market of operation. We find that after the introduction of a carbon tax in one market, fossil companies in that market (in foreign markets) experience a relative decline (increase) in investment and in sales. This effect is consistent with the idea that increased lending to foreign fossil companies in response to a tightening in domestic carbon pricing leads these foreign fossil companies to invest relatively more and to grow relatively faster. Our evidence thus suggests that in addition to bank lending effects, there are also real effects associated with the reallocation of fossil lending across geographic borders.

Our work contributes to several strands of the literature. First, the analysis we present speaks to the growing literature about the effect of climate change on the decisions taken by firms and households (Matos, 2020; Giglio et al., 2021). Much of this literature studies how investors and asset prices respond to climate policies and the prospect of climate disasters (e.g., Alok et al., 2020; Krueger et al., 2020; Engle et al., 2020; Choi et al., 2020; and Giglio et al., 2021). Due to firms' and households' exposure to climate risks, investors in general, and banks in particular, can ask for higher returns on their loans (Bolton and Kacperczyk, 2021; Delis et al., 2021). This can incentivize the firms to reallocate their operations to jurisdictions with less strict climate policies (Bartram et al., 2022). We contribute to this literature by providing evidence that in response to a higher cost of carbon, banks take actions to reduce the effect of higher carbon prices on their loan portfolios. In particular, we demonstrate that large international banks reduce domestic fossil lending and increase foreign fossil lending, after their home country imposes a carbon tax or joins an ETS. Our paper differs from the analysis in Bartram et al. (2022) by identifying international tax differences as a driver of cross-border spillovers from climate policies while they focus on differences in financial constraints.

Second, our paper adds to the literature that examines banks' propensity to engage in cross-border lending. Researchers have documented extensively that cross-border lending is one important mechanism whereby shocks to banks' balance sheets are transmitted across national borders (Cetorelli and Goldberg, 2011; Giannetti and Laeven, 2012; Popov and Udell, 2012; De Haas and Van Horen, 2013; Hale et al., 2020; Doerr and Schaz, 2021). This literature has also shown that regulatory arbitrage opportunities can be an important driver of cross-border lending (Houston et al., 2012; Ongena et al., 2013; Karolyi and Taboada, 2015), as well as of real decisions by multinational firms (Barrios et al., 2012). Closest to our work, Ben-David et al. (2021) show that firms headquartered in countries with strict environmental policies perform their polluting activities abroad in countries with relatively weaker policies. Building on their work, Benincasa et al. (2021) study a sample of 12,500 cross-border loans, and find that banks' share of overall foreign lending is higher in countries with stricter environmental regulation. Our paper differs from this work in that we use a very granular sample of over 2 million bank-firm-loan tranches and exploit an exogenous shift in carbon prices to show that carbon taxes induce a reallocation of *fossil* lending across national borders. Our analysis confirms the notion that a lack of tax homogeneity can reduce the effectiveness of such regulations through the channel of cross-border bank lending. Our paper also differs from the analysis in Ivanov et al. (2020) who show that a California cap-and-trade bill affected credit conditions for high-emissions firms by increasing interest rates and shortening loan maturities. In contrast, we study the cross-border reallocation dimension of the interaction between carbon taxes and lending decisions.

Finally, our paper contributes to the emerging literature which examines the interaction between environmental policies and bank lending. De Haas and Popov (2023) document that economies that rely relatively more on equity than debt financing experience faster reductions in carbon emissions, suggesting that banks are at a comparative disadvantage in funding the development and adoption of low-carbon technologies. Goetz (2019) and Levine et al. (2019) show that more favorable funding conditions lead firms to reduce their toxic emissions. Degryse et al. (2020) argue that banking can cause barriers to the "green" economy as the entry of innovative and "green" firms in polluting industries risks devaluing banks' legacy positions with incumbent clients. Examining the effect of the Paris Agreement on the pricing of carbon-intensive technologies, Delis et al. (2021) find evidence of a significantly higher cost of bank credit for fossil fuel firms, but only after 2015. Reghezza et al. (2021) show that following the ratification of the Paris Agreement, banks reallocated credit away from polluting firms. They further show that in the aftermath of the US withdrawal from the Paris Agreement European banks decreased lending to polluting firms in the United States. Degryse et al. (2021) provide evidence that environmentally conscious banks could play a positive role in the green transition by granting cheaper loans to environmentally conscious firms. We contribute to this emerging literature by examining the propensity of banks to extend loans to fossil companies, and by documenting important changes in this propensity in response to changes in carbon prices.

2. Theoretical mechanisms

Our aim is to investigate the relation between carbon taxes and the domestic-foreign mix of bank lending to fossil companies. Our prior is informed by theoretical and empirical work which has implications for the supply and the demand of bank credit to firms whose operations are affected by the introduction of a price of carbon. Theory offers conflicting predictions about the effect of a carbon tax on bank lending at home and abroad.

On the credit demand side, the reallocation of resources induced by (environmental) regulation takes time and is very costly because it requires large upfront expenditures (Walker, 2013). As a result, at least in the short-to-medium run, the tax will force such firms to shift resources which is costly. This will depress these firms' investment (Kanzig, 2021), which by extension will reduce their demand for loans. In addition, tight carbon budgets implied by climate stabilisation greatly reduce the long-term value of fossil fuels (Krause et al., 1989). As a consequence, a carbon tax, while socially optimal in that it minimizes the discounted social cost of the transition to clean capital, may prompt the premature retirement of existing polluting capacities (Rozenberg et al., 2020). This can be associated with significant private costs in the form of stranded assets, depressing their returns. This in turn lowers the demand for loans for legacy projects. Consequently, as the demand for fossil lending at home declines, banks can be expected to increase their credit supply to fossil companies abroad.[6] Based on these existing theories, we can formulate the following hypothesis.

H1A. The introduction of carbon taxes in one country is associated with a decline in fossil lending in that country and an increase in fossil lending in other countries.

At the same time, opposing forces can act to increase lending after the introduction of a carbon tax. On the credit demand side, carbon taxes may push firms to invest in green technologies (Aghion et al., 2016) which would increase their demand for loans. Consequently, lending to domestic firms in countries with a carbon tax may increase. On the credit supply side, the profitability of fossil companies in countries with a carbon tax may decline, increasing their probability of default. This may prompt their lenders to support them further by maintaining the flow of credit. This situation is akin to banks increasing lending to zombie firms to forestall credit losses, especially by banks with low levels of regulatory capital (Acharya et al., 2021). Such support in domestic fossil lending would in turn reduce the bank's lending capacity abroad. This discussion points to the following hypothesis:

H1B. The introduction of carbon taxes in one country is associated with an increase in fossil lending in that country and a decline in fossil lending in other countries, especially by low-capital banks.

At the same time, the proliferation of stranded assets as a result of carbon pricing also has implications for the overall credit supply. Kiyotaki and Moore (1997) argue that when the value of collateral declines for exogenous reasons, banks' willingness to extend credit to the affected firms declines as a result of a tightening of collateral constraints. It follows that by reducing the value of fossil assets, a carbon tax should generate an analogous reduction in the value of collateral at fossil firms, resulting in a reduction in credit to those firms by their creditors. Moreover, to the extent that a carbon tax also reduces the value of fossil-linked assets that serve as collateral on banks' balance sheets, the introduction of a carbon tax will further reduce the supply of credit by tightening banks' capital constraints (Holmström and Tirole, 1997). The implication of these credit supply shocks would be

[6] At the same time, evidence to this effect is not unambiguous. For example, Martin et al. (2014) find that a carbon tax has a strong negative impact on energy intensity and electricity use, but no effect on employment, profits, or exit.

that both domestic and foreign lending to fossil companies would decline. However, there may be important compositional effects between domestic and foreign lending in the presence of bank specialization (Paravisini et al., 2015). To the extent that banks specialize and some banks have a comparative advantage in making fossil loans, these same creditors now have an incentive to increase lending to similar fossil companies in foreign jurisdictions that have not been affected by changes in carbon taxes. These theoretical mechanisms point to the following hypothesis:

H1C. The introduction of carbon taxes in one country is associated with a decrease in overall fossil lending, but with an increase in such lending abroad by banks specializing in fossil lending.

Testing these opposing hypotheses allows us to assess the relative importance of alternative theoretical mechanisms at the bank level. An increase in fossil lending abroad would be consistent with sector-specific bank specialization, while a decline in fossil lending abroad would be consistent with a dominant role for banks' balance sheet effects.

On the firm side, the introduction of a carbon taxes will create an environment that is more hostile to the funding of fossil operations. Publicly listed firms that are subject to more intense public scrutiny from investors, rating agencies and the public at large will be especially affected by this (Doidge et al., 2017; Stulz, 2020). This may prompt banks to increase their lending abroad especially to privately held fossil companies as opposed to publicly held fossil companies. These theories point to the following additional hypothesis:

H2. The increase in fossil lending abroad following the introduction of carbon taxes is more pronounced for privately held companies.

Evidence in support of this hypothesis would point to the relevance of private costs associated with the public scrutiny of publicly listed firms.

Moreover, banks may prefer to lend to firms with which they have an existing lending relationship, either because prior information helps overcome informational asymmetries in lending decisions (Berger and Udell, 1995; Giannetti and Laeven, 2012; De Haas and Van Horen, 2013) or because banks have an incentive to preserve the value of preexisting relationships when these relationships are hit by adverse shocks (Petersen and Rajan, 1994; Berger and Udell, 1995; Bolton et al., 2016). This discussion leads to the following hypothesis:

H3. The increase in fossil lending abroad following the introduction of carbon taxes is more pronounced for firms with prior lending relationships.

Testing this hypothesis will show the relevance of theories of relationship lending based on asymmetric information between banks and borrowers in our context.

Finally, at the country level, a less profitable business environment at home resulting from the introduction of carbon taxes may prompt banks to increase bank risk taking abroad (Ongena et al., 2013). This could be done by lending to fossil companies in countries with less strict environmental regulation, as well as to countries with less stringent bank supervision. This argument supports the development of the following hypothesis:

H4. The increase in fossil lending abroad following the introduction of carbon taxes is more pronounced in countries with less strict environmental regulation and less stringent bank supervision.

Evidence in support of this hypothesis will lend support to theories of the private costs associated with environmental regulation and banking supervision.

3. Data

3.1. Data sources

Our data come from a number of sources. First, we collect information on the date of implementation of carbon taxes from the Carbon Tax Center (https://www.carbontax.org/). While information is also available on the size of the tax, we only classify countries based on a binary criterion (has carbon tax, yes or no). From the same data source, we obtain information on which country joined an Emissions Trading Scheme (ETS) and when. We cross-checked the data from the Carbon Tax Center with data on carbon taxes and ETS from the International Carbon Action Partnership (ICAP) and the World Bank Group Carbon Pricing Dashboard to verify the accuracy of the data and found no differences across these alternative data sources. The resulting global data are summarized in Appendix Table 1. Between 1990 and 2020, 25 countries imposed some form of carbon tax. During the same period, a further 22 countries joined an ETS which charges some (but typically not all) sectors of the economy for the greenhouse gases they emit.[7] Consequently, 47 countries in the world apply some form of carbon pricing to at least part of their economy. Of these, 11 countries (all EU member states) both have a carbon tax and are members of an ETS. Fig. 3 visualizes our data.[8]

[7] For example, the EU's ETS covers carbon dioxide, nitrous oxide, and perfluorocarbon emissions from about 11,000 heavy energy-using installations, including power stations and industrial plants, such as oil refineries, steelworks and production of iron, aluminum, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals. At the same time, it excludes a number of greenhouse gas emitting sectors, such as agriculture, transportation, and residential buildings. As a result, only 45% of the sources of the EU's greenhouse gas emissions are covered by the ETS.

[8] We only incorporate information on country-wide carbon taxes. Therefore, by necessity we do not make use of carbon taxes that cover a single region (e.g., British Columbia since 2008, Tokyo since 2010, California since 2012, Quebec since 2013, or Alberta since 2017).

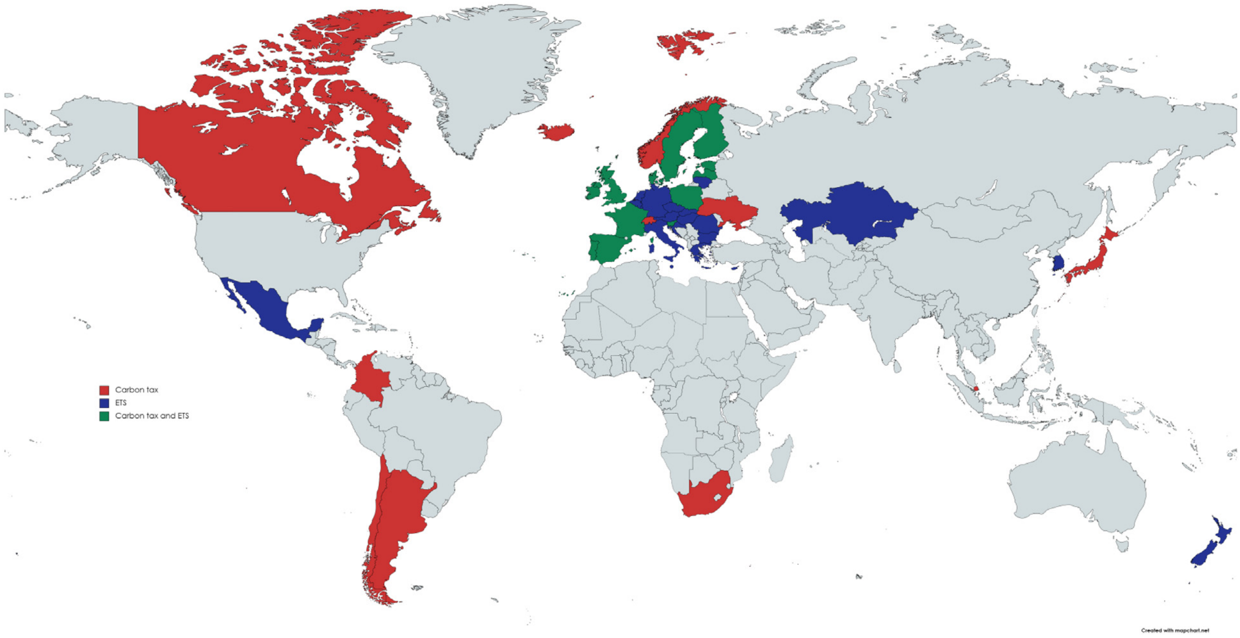

Fig. 3. Countries with a carbon tax, an ETS, or both: 1988–2020.
(Source: Carbon Tax Center, International Carbon Action Partnership (ICAP), and World Bank Group Carbon Pricing Dashboard.)

Next, we obtain loan-level data from the DealScan database. DealScan contains comprehensive information on virtually all syndicated loans since the 1980s. We download all syndicated loans extended to non-financial corporates worldwide, focusing on the period 1988–2020. This allows us to observe bank lending behavior before and after each carbon tax event in our dataset. We treat all Dealscan observations as new loan originations, even if in fact some of them may be renegotiated versions of previous loans. Following the literature, we exclude loans to financial companies (SIC between 6000 and 6999) from the sample. Our unit of observation is a syndicated loan tranche issued by an individual bank to an individual borrower during a particular year. To this end, we split each loan into the portions provided by the different syndicate members.

To do so, we make a series of empirical choices. For a start, Dealscan provides exact loan breakdown among the syndicate members for about 26% of all loans. For the rest of the loans, in each case we calculate an average bank share based on each bank's history of loans for which the exact breakdown among syndicated members is known. We then assign this average and calculate the resulting loan size.[9] In addition to establishing the bank's and firm's identity and constructing loan amounts, we also gather data on loan maturity and loan origination date. Regardless of the original currency, all loans are converted into US dollars. The time unit of observation is the year of loan origination. From Dealscan we also obtain information on the borrowing firm's primary industrial sector. We classify as "fossil loans" loans that have been made to firms in SIC 12 (Bituminous coal and lignite mining) and firms in SIC 13 (Oil and gas wells, exploration, and services). Finally, Dealscan also contains information on both the lender's and the borrower's country, allowing us to match the data in Dealscan to data on carbon taxes and ETS membership.

Next, we obtain bank-specific information on the lenders in our dataset from BankFocus (formerly Bankscope). To that end, we obtain data on bank balance sheets by merging Dealscan with BankFocus at the level of the individual bank (as opposed to the bank holding company). From BankFocus, we obtain information on a range of bank-specific variables, including equity, regulatory capital, and profitability.

We also obtain firm-specific information on all borrowers in our dataset from Compustat. From there, we obtain information on a range of firm-specific variables, including sales, employment, output, and assets.

3.2. Datasets matching

The primary data sources for this paper are Loan Pricing Corporation's (LPC) Dealscan, Standard and Poor's Compustat, and Bureau van Dijk's Orbis BankFocus. To conduct the empirical analysis, we need to first merge information on (non-financial) corporate loan tranches available in Dealscan with financial information on the borrower and lender (available in Compustat and BankFocus, respectively) in the quarter of loan tranche origination. We then aggregate this information across years, for a dataset

[9] For example, if a bank participated in a syndicate in 2005 and the exact share is not known, we look at the historical shares for this bank whenever known, we average over time, and we assign that average to the loan in 2005. The main results of the paper are robust to alternative methods for imputing missing loans shares.

containing annual bank-company-tranche observations from 1988 to 2020. To achieve both matches of DealScan with Compustat and BankFocus, we rely on two matching files created by Chava and Roberts (2008) and Schwert (2018), respectively.

Dealscan contains quarterly information on corporate loans and loan tranches. Lenders usually report several loans per quarter and borrowing companies often either receive several loans per quarter or one combined loan from several lenders. As a first step, we merged this loan and tranche level data with financial information on the borrowing company from Compustat Global Quarterly Fundamentals based on the matching table by Chava and Roberts (2008). The matching table focuses on USD-denominated loan tranches to non-financial, U.S. corporations. It links loan tranches (called facilities in Dealscan) based on their tranche identifier (facility ID[10]) in DealScan to a borrower's unique company identifier in Compustat (called GVKEY).

Our matching is carried out using the Chava and Roberts' (2008) matching table and the quarter of loan tranche origination.[11] In order to maximise the number of matches between DealScan and Compustat, we used the matching table in two ways. First, we utilise the link between the tranche identifier in DealScan and the borrower's company identifier in Compustat to match tranches to their borrower's financial information in the quarter of tranche origination. In order to increase the number of matched observations, we then additionally match observations by taking advantage of the link available in the matching table between the borrower company's identifier in Dealscan (Borrower Company ID,[12] called bcoid in the linking file) and its counterpart in Compustat (GVKEY). This allows us to match loan tranches beyond the ones specifically matched by Chava and Roberts (2008).

As a second step, we merged these company-tranche observations with financial information on the lender available in Orbis BankFocus based on the matching table by Schwert (2018). The matching table links the identifier variables for lenders in Dealscan (lender name and lender company ID) of the most active lenders, based in the United States, with the identifier of the respective bank holding company in Orbis BankFocus (bvd id number) starting in 1987. Specifically, Schwert (2018) focuses on USD-denominated loans to non-financial corporations with an origination date on or before December 31, 2019. The matching focuses on lenders that served as lead arranger on a minimum of 50 loans or for a minimum of 10 billion USD in loan volume in this set of loans and the affiliated subsidiaries.

Once again, our matching is carried out using the link between lender identifiers of both databases established in Schwert's (2018) matching table and the quarter of loan tranche origination. In order to increase the number of matched observations, we carry out additional rounds of matching using iteratively up to three lags and leads for the quarter of loan tranche origination. The reasoning behind this lead- and lag-approach is that lender characteristics are sticky in the short-run and lender characteristics serve as control variables rather than the variable of interest in this study.

The final sample is based on 2,142,170 company-bank-loan tranches made between 1988 and 2020. The sample includes 263,879 distinct loans, 21,284 unique creditors, and 98,126 unique borrowers. We obtain an 10.5% match between Dealscan and BankFocus, and a 12.4% match between Dealscan and Compustat.

Appendix Table 2 reports summary statistics for the full Dealscan sample, for the matched Dealscan-BankFocus sample, and for the matched Dealscan-Compustat sample. There are fewer fossil loans and fewer foreign loans in the full sample than in either of the matched samples. Also, the average loan amount and loan maturity is lower in the full sample than in the matched Dealscan-BankFocus sample, and they are higher in the full sample than in the matched Dealscan-Compustat sample.

3.3. Summary statistics

In Table 1, we present summary statistics of the main variables used in the analysis. The first panel reports the characteristics of the loan tranches in the sample. Recall that we have calculated the portion that each bank participates in a syndicated loan with. The summary statistics refer to the individual portions rather than to the syndicated loans themselves.

About 4.2% of all loan tranches in the sample are to fossil companies, meaning companies engaged in the extraction and processing of coal, gas, and oil. There is, however, substantial heterogeneity, with a large number of banks making no loans to, and a number lending exclusively to, fossil companies. 95.5% of all loans are to domestic companies, and 4.5% are to foreign ones. Loans to the wholesale and retail sector constitute 9.5% of all lending. Manufacturing loans, excluding metallurgy and cement, constitute 26.1% of all loans. Finally, the average loan per bank is 4.3 million US dollars, and the average maturity is 56.7 months.

The second panel of Table 1 reports summary information on a number of bank characteristics. A bank's average fossil loan exposure is 0.052, meaning that 5.2% of the lending of the average bank is to fossil companies. This variable is calculated using each bank's lending history in Dealscan. In addition, from BankFocus we calculate summary statistics on the banks' capitalization and profitability. On average, the banks in the sample have an equity ratio of 18.9%, and a return on assets of 1.5%.[13]

Next, in the third panel we report summary statistics for the main country-specific variables of interest. 9.6% of the loans in the dataset are by banks in countries that have a carbon tax. Alternatively, 19.3% of said loans are by banks in countries that either have a carbon tax or are members of an ETS.

We also summarize host-country markets in terms of environmental policy and the population's climate awareness. First, we use data from the EBRD on the number of green laws and policies enacted up to a particular year. On average, the countries in the

[10] The Facility ID is a unique Reuters system-generated identifier for a loan facility/tranche.

[11] The quarter of loan origination is based on the quarter of the variable 'Facility Start Date' in DealScan.

[12] The Borrower Company ID is a unique Reuters system-generated identifier for a company (borrower).

[13] Appendix Table 3 demonstrates that there is a very weak correlation between these bank factors, averaged at the country-year level, and the presence of a carbon tax in the country. This alleviates concerns that carbon taxes are imposed in response to weaknesses in the banking sector.

Table 1
Summary statistics.

	Observations	Mean	Median	St. dev.	Min	Max
Loan characteristics						
Fossil loan	2,142,170	0.042	0	0.201	0	1
Foreign loan	2,142,170	0.045	0	0.207	0	1
Wholesale or retail	2,142,170	0.095	0	0.293	0	1
Clean manufacturing	2,142,170	0.261	0	0.439	0	1
Including all mining	2,142,170	0.053	0	0.224	0	1
Including metallurgy and cement	2,142,170	0.071	0	0.256	0	1
ETS-eligible sector	427,382	0.791	1	0.406	0	1
Log (Loan amount)	2,113,216	13.733	14.262	2.347	1	22.548
Log (Loan maturity)	2,062,739	3.795	4.094	0.752	1	7.100
Interest rate spread	2,035,104	207.371	206.494	6.246	181.267	267.523
Bank characteristics						
Fossil lending share	2,137,477	0.052	0.040	0.056	0	1
Capital	235,058	18.898	10.110	25.603	0.776	159.494
ROA	223,216	1.513	0.083	2.335	−11.840	20.98
Country characteristics						
Home country carbon tax	3104	0.096	0	0.295	0	1
Home country carbon tax or ETS	3104	0.193	0	0.395	0	1
Host country green policy	5910	8.260	2	17.313	0	197
Host country bank supervision	2700	1.289	1.188	0.711	0.188	2.938
GDP per capita ('000 USD)	5675	12.486	3.969	20.035	0.164	196.061
CO2 per capita (aggregate)	5704	4.318	2.377	5.514	0	50.954
Firm characteristics						
Private firm	667,087	0.639	1	0.480	0	1
Growth	94,193	0.028	0.019	0.197	−0.97	0.974
Debt	185,748	0.101	0.078	0.099	0	2.357
Profit	162,363	0.158	0.129	0.123	−0.281	1.939
Repeat borrower	870,985	0.523	1	0.499	0	1
Investment growth	86,825	0.031	0.045	1.038	−7.983	8.646
Sales growth	75,213	0.033	0.038	0.440	−6.503	5.196
Sector characteristics						
CO2 per capita (extraction)	17,123	0.450	0.075	1.184	<0.001	15.479

Note: 'Fossil loan' is a dummy variable equal to 1 if the loan is to a company in SIC sectors 12xx and 13xx. 'Foreign loan' is a dummy variable equal to one if the loan is to a company domiciled in a foreign country. 'Wholesale or retail' is a dummy variable equal to 1 if the loan is to a company in SIC sectors 50xx—59xx. 'Clean manufacturing loan' is a dummy variable equal to 1 if the loan is to a company in SIC sectors 20xx—39xx, excluding metallurgy and cement production. 'Including all mining' is a dummy variable equal to 1 if the loan is to a company in SIC sectors 10xx to and including 14xx. 'Including metallurgy and cement' is a dummy variable equal to 1 if the loan is to a company in SIC sectors 12xx, 13xx, 32xx, and 33xx. 'ETS-eligible sector' is a dummy variable equal to 1 if the loan is to a company in the fossil sector, cement production, metallurgy, or energy generation, and to 0 if the loan is to a company in transportation or agriculture. 'Log (Loan amount)' is the natural logarithm of the loan amount, in USD. 'Log (Loan maturity)' is the natural logarithm of the maturity of the loan, in months. 'Interest rate spread' is the default base rate on the loan. 'Fossil lending share' is the bank's share of fossil loans before the introduction of the carbon tax. 'Capital' is the bank's total equity divided by total assets. 'ROA' is the bank's return on assets. 'Home country carbon tax' is a dummy variable equal to one after the introduction of a carbon tax in the home country. 'Home country carbon tax or ETS' is a dummy variable equal to one after the introduction of a carbon tax in the home country or after the home country joined an Emissions Trading Scheme (ETS). 'Host country green policy' is a variable equal to the number of green laws and policies enacted up to the current year. 'Host country bank supervision' is a variable equal to the stringency of bank supervision in the host country. 'GDP per capita ('000 USD)' denotes per capita GDP, in thousands USD. 'CO2 per capita (aggregate)' is aggregate carbon emissions. 'Private firm' is a dummy variable equal to one if the firm is privately owned, and to 0 if it is public. 'Growth' denotes the firm's average sales growth. 'Debt' denotes the firm's average debt, divided by assets. 'Profit' denotes the firm's average profit, divided by assets. 'Repeat borrower' is a dummy variable equal to 1 if the loan is not the first loan the borrower is taking from the same credit. 'Investment growth' is the percentage change in the firm's investment over the year after receiving a loan. 'Sales growth' is the percentage change in the firm's sales over the year after receiving a loan. 'CO2 per capita (extraction)' is sector-level CO2 emissions from combustion, for the extraction sector. The sample period is 1988—2020. Data come from Dealscan, BankFocus, Carbon Tax Center, International Carbon Action Partnership (ICAP), World Bank Group Carbon Pricing Dashboard, EBRD, Abiad et al. (2008), and the World Bank.

dataset have 8.3 such laws and policies, but this metric has a wide variation in the sample, ranging from 0 to 197. Second, we use a proxy for the average strictness of bank supervision, from Abiad et al. (2008), which is evaluated on a range of 0 (weakest) to 3 (strongest). Finally, we include information on GDP per capita, to control for the stage of economic development and the general quality of institutions (LaPorta et al., 1998).

In the last panel we report summary statistics on firm-specific variables of interest. 36% of the loans in our dataset are to listed firms, and 64% to privately owned firms. On average, the borrowers in the dataset exhibit annual growth of 2.8%, a debt-to-asset ratio of 0.1, and a profit-to-asset ratio of 0.16. Finally, 47.7% of the companies in the dataset are first-time borrowers, with the rest being companies receiving repeat loans.

4. Empirical model and identification

Our main econometric model focuses on the relationship between the propensity of a bank to extend fossil loans, both at home and abroad, and the extent of carbon pricing in the bank's domestic market. We estimate the following linear probability model:

$$FossilLoan_{b,f,t} = \beta_1 ForeignLoan_{b,f,t} + \beta_2 CarbonTax_{i,t} \times ForeignLoan_{b,f,t} + \gamma_b + \mu_{i,t} + \phi_{j,t} + \varepsilon_{b,f,t}, \quad (1)$$

$FossilLoan_{b,f,t}$ is a dummy variable equal to one if during year t, bank b has issued a loan to firm f whose primary SIC code is 12 (Bituminous coal and lignite mining) or 13 (Oil and gas wells, exploration, and services). The same variable equals zero if firm f's primary SIC code is neither 12 nor 13.

We next turn to the main explanatory variables. First, $ForeignLoan_{b,f,t}$ is a dummy variable equal to one if bank b and firm f are domiciled in different countries, and zero if they are domiciled in the same country. Next, $CarbonTax_{i,t}$ is a dummy variable equal to one if country i, in which bank b is domiciled, has some level of carbon tax during year t, and zero otherwise. We abstract from the level of the tax itself and classify countries in a binary fashion. We treat the introduction of the carbon tax as an exogenous increase in the price of carbon in the home country of the lender.

We include a number of dummy interactions to make sure that we hold constant a range of unobservable background forces. First, we include γ_b, a vector of interactions of bank foxed effects. This absorbs any unobservable bank-specific factors that do not change over time, such as business models, managerial quality, or appetite for risk.[14] Second, we include $\mu_{i,t}$, a matrix of interactions of home-country and year dummies. This absorbs any time-varying factors that are common to all creditors domiciled in a particular country, such as home-country regulation or the business cycle. Finally, we include $\phi_{j,t}$, a matrix of interactions of host-country and year dummies. This absorbs any time-varying factors that are common to all borrowers domiciled in a particular country, such as host-country regulation or changes in local demand. Identification thus rests on exploiting differences between fossil and non-fossil borrowers and their interaction with various lenders, based on whether there is a carbon tax in the lenders' country or not. Finally, $\varepsilon_{b,f,t}$ is the idiosyncratic error term. In all regressions, we cluster the standard errors at the lender level, to account for potential correlation among borrowers within the unit where the lending adjustment takes place.

We do not include the variable $CarbonTax_{i,t}$ on its own because its direct effect on fossil lending is absorbed by the host-country-year dummy interactions. At the same time, we also estimate specifications that are less saturated with fixed effects, and which therefore allow us to gauge the independent effects of being treated and the economic cycle.

The main coefficient of interest β_2 therefore measures whether a bank in a country that has some form of carbon pricing is more or less likely to extend a loan to a fossil company abroad, relative to its propensity to extend a loan to a non-fossil company abroad. A positive coefficient implies that a carbon tax increases the propensity of banks to engage in foreign fossil lending, at the expense of domestic fossil lending. The point estimate of β_2 thus measures the numerical change in the propensity to extend a fossil loan abroad, as opposed to at home, from switching the bank from the control group (banks in countries with no carbon tax) to the treatment group (banks in countries with a carbon tax).[15]

5. Carbon taxes and bank lending: empirical evidence

5.1. Headline result

We begin by estimating more parsimonious versions of Eq. (1), gradually building towards the most saturated specification. In Table 2, column (1), we estimate a specification which includes only one set of dummy interactions, namely interactions of host country and year dummies. This allows us to control for shocks to host-country factors, such as local demand. At the same time, it also allows us to include the dummy variable capturing the introduction of a carbon tax in the home country on its own. We then advance the model to include interactions of home country and year dummies (column (2)), which allows to control for all domestic trends that are common to banks from different countries lending to the same borrower. Finally, we extend the model to include bank fixed effects (column (3)), which control for unobservable time-invariant bank-specific heterogeneity, including those arising from bank supply.

The estimates reported in column (1) point to three separate facts. First, banks are significantly more likely to lend to coal, oil, and gas companies in their domestic market than they are to do the same abroad. Second, carbon taxes are associated with lower domestic fossil lending. The coefficient of −0.0097 suggests that after a carbon tax is introduced in a country, domestic lending to fossil companies declines by about 1%. Third, after a carbon tax is introduced in a country, the share of foreign lending to fossil companies increases by about 9 percentage points. The effect is significant at the 1% statistical level and represents a sizeable reallocation of lending across national borders.

In column (2), we include interactions of home country and year dummies. These allow us to net out the independent effect of any home country-specific trends, related to the business cycle, regulation, or changes in voters' preferences. As a result, we can no longer identify the independent effect of home country carbon taxes which is now subsumed in the dummy interactions. Armed with this specification, we no longer find any difference in banks' average propensity to extend fossil loans abroad, relative

[14] In robustness tests, we also control for bank-year fixed effects, to account for the possibility that such unobservables at the bank level may be time-varying.

[15] The empirical setup implicitly assumes that carbon taxes work, in that they reduce carbon emissions domestically, setting in motion a credit demand/supply mechanism whereby fossil lending is reallocated across markets. To show that this is the case, we collected data from the International Energy Agency (IEA) on country-level carbon emissions and on carbon emissions at the sector level. Because of data aggregation, we collected information on the extraction sector as opposed to the fossil sector only. In Appendix Table 4, we show that both aggregate carbon emissions and sector-level carbon emissions decline significantly in countries in which carbon taxes are imposed or Emissions Trading Systems come into force. In both cases, the effect is significant at the 1% statistical level. The evidence thus suggests that carbon taxes are indeed associated with a reduction in overall emissions, and emissions in the extraction sector in particular.

Table 2
Domestic carbon taxes and fossil lending: Main test.

	Fossil loan		
	(1)	(2)	(3)
Home country carbon tax ×Foreign loan	0.0897***	0.0715***	0.0675***
	(0.0070)	(0.0069)	(0.0071)
Home country carbon tax	−0.0097**		
	(0.0043)		
Foreign loan	−0.0078***	−0.0035	−0.0044*
	(0.0022)	(0.0025)	(0.0025)
Host country×Year dummies	Yes	Yes	Yes
Home country×Year dummies	No	Yes	Yes
Bank fixed effects	No	No	Yes
No. Observations	2,141,998	2,141,960	2,136,679
R-squared	0.10	0.12	0.15

Note: The Table reports estimates from OLS regressions. The dependent variable is 'Fossil loan', a dummy variable equal to 1 if the loan is to a company in SIC sectors 12xx and 13xx. 'Home country carbon tax' is a dummy variable equal to one after the introduction of a carbon tax in the home country. 'Foreign loan' is a dummy variable equal to one if the loan is to a company domiciled in a foreign country. The sample period is 1988—2020. Data come from Dealscan, Carbon Tax Center, International Carbon Action Partnership (ICAP), and World Bank Group Carbon Pricing Dashboard. All regressions include fixed effects as specified. Standard errors clustered at the bank level appear in parentheses, where *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

to at home. Importantly, the coefficient of β_2 is still negative and significant at the 1% statistical level. The magnitude of the measured coefficient suggests that after a carbon tax is introduced in a country, foreign lending to fossil companies increases by about 7.2%.

Finally, in column (3), we introduce interactions of bank and year dummies. These are enormously important because any difference in banks' propensity to lend to fossil companies abroad, as opposed to in their domestic market, can be related to evolving circumstances at the bank level. We find that this is not the case. Once again, the coefficient of β_2 is negative and significant at the 1% statistical level. The point estimate suggests that after a carbon tax is introduced in a country, foreign lending to fossil companies increases by about 6.8%. The magnitude of the effect is therefore not dramatically different from columns (1) and (2), suggesting that the effect we measure is relatively stable across specifications.[16]

In all, our evidence is consistent with the idea that carbon taxes lead to a reduction in lending to fossil companies domiciled in the bank's domestic market, and to an increase in lending to fossil companies in the bank's foreign markets. The evidence is thus consistent with Hypothesis H1A which suggests that a carbon tax reduces domestic fossil firms' demand for credit, which leads creditors to reallocate fossil lending abroad.[17]

What is the implied aggregate effect? About 92.5% of all fossil loans in our dataset are domestic. As Table 2 makes it clear, domestic fossil lending declines by about 1% (column (1)), while foreign fossil lending increases by about 6.8% (column (2)). This suggests that the number of total fossil loans declines by about 0.4%.

In the Appendix, we present a number of alternative tests. In Appendix Table 5, we run the following simplified version of Eq. (1):

$$Share\ Foreign\ Loans_{b,t} = \beta_1 Carbon\,Tax_{i,t} + \gamma_b + \varepsilon_{b,t}, \tag{2}$$

$Share\ Foreign\,Loans_{b,t}$ is calculated as the ratio of foreign loans to total loans, for loans to fossil and for loans to non-fossil companies. This specification is not as tight as Eq. (1) because we cannot control for many unobservable factors, such as domestic regulation or voting preferences and foreign demand. We can, however, still control for unobservable bank-specific heterogeneity with bank fixed effects.

The evidence makes it clear that in the case of lending to coal, oil, and gas companies, the share of foreign lending increased by about 6 percentage point after the introduction of a domestic carbon tax (column (1)). This is a sizeable effect which is also significant at the 1% statistical level. In the case of non-fossil loans (column (2)), the share of foreign lending increases, too, but this increase is both economically and statistically indistinguishable from zero.

In Appendix Table 6, we attempt to control for heterogeneity that is time-invariant at the creditor-borrower level. To do so, we run a version of Eq. (1) where the dependent variable is the total loans extended by a bank to a firm in a given year, and we also

[16] To understand the role of potential omitted variable bias, we apply the method in Altonji et al. (2005) to gauge the relative importance of possible omitted variable bias. We measure coefficient stability by calculating the absolute value of the ratio between the coefficient in the regression including controls and the difference between this coefficient and the one derived from a regression on the same number of observation but without control variables. For the specification in Table 2, column (3), the coefficient with fixed effects is 0.0675, and the coefficient without fixed effects is 0.0897. Therefore, the ratio amounts to 3.04. This suggests that to explain the full effect of carbon taxes, the covariance between unobserved factors and carbon taxes needs to be twice as high as the covariance of the included controls. By way of comparison, Altonji et al. (2005) estimate a ratio of 3.55 which they interpret as evidence that unobservables are unlikely to explain the entire effect they document. We therefore conclude that it is unlikely that unobserved heterogeneity can explain away the positive effect of carbon taxes on foreign fossil lending.

[17] One caveat of our analysis is that a multinational bank can give a loan from any of its establishments in various countries. Hence, a multinational bank may choose not to originate a loan in a country with a high carbon tax, but instead to move origination to a country with a low carbon tax, in order to engage in window dressing, in which case the fossil firm still gets the loan, but from a different establishment.

control for bank-company dummy interactions. Because we want to gauge the evolution of lending from a bank to a firm over time, we only keep observations of repeat bank-firm lending relationships. This reduces the sample by around 70%. At the same time, this specification allows to include bank-firm fixed effects.[18] The evidence suggests that the total amount of foreign fossil lending increases significantly more after the introduction of carbon taxes than similar non-fossil loans, alleviating concerns that our results are driven by unobservable creditor-borrower heterogeneity.

In Appendix Table 7, we apply an alternative clustering scheme. As changes in carbon pricing take place at the level of the country, it may be more logical to cluster the standard errors at the country level, or to double cluster them at the country and year level, at the bank and year level, or at the bank, borrower, and year level. The evidence suggests that the main result of the paper is not sensitive to how we cluster the standard errors.

In Appendix Table 8, we control for economic development that may affect differentially the bank's propensity to lend abroad as opposed to at home. We do so by including on the right-hand side of Eq. (1) an interaction of the $Foreign\,Loan_{b,f,t}$ dummy with $Log\,(Home\,country\,GDP\,per\,capita)_{i,t}$, the natural logarithm of per-capita GDP in the country in which the carbon tax has been imposed. We continue to obtain a significant negative coefficient on β_2, suggesting that the cross-border reallocation of fossil lending in response to carbon taxes is not explained by contemporaneous shocks to domestic demand that are unrelated to the introduction of carbon taxes.

In Appendix Table 9, we report estimation from regression Eq. (1) performed on the matched sample of Dealscan-Compustat-BankFocus. This implies that we only look at loans in Dealscan that could either be matched to bank information in BankFocus or to firm balance sheet information in Compustat. This reduces the number of observations declines by 83.1%, from 2,112,834 to 359,641. Despite the substantially lower number of observations, the main result of the paper still obtains in this reduced sample.

Finally, in Appendix Table 10, we show that our main results are robust to controlling for bank-year fixed effects, thereby netting out the effect of time-varying unobservable characteristics at the level of the lender.

5.2. Parallel trend assumption

One of the underlying assumptions of our empirical approach is that there is no divergence between domestic and foreign fossil lending already before the introduction of the carbon tax. If this assumption were to be violated in the data, the test reported in Table 2 would simply capture a long-term trend that is independent of the timing of carbon taxes.

To address this issue formally, we now run the following version of Eq. (1):

$$\begin{aligned} Fossil\,Loan_{b,f,t} = {} & \beta_1 Foreign\,Loan_{b,f,t} + \beta_2 Carbon\,Tax_{i,t} \times Foreign\,Loan_{b,f,t} + \beta_3 Pre - Trend_{i,t} \times Foreign\,Loan_{b,f,t} \\ & + \gamma_{b,j} + \mu_{i,t} + \phi_{j,t} + \varepsilon_{b,f,t}, \end{aligned} \tag{3}$$

Eq. (4) differs from Eq. (1) in that it includes an interaction of the variable *Foreign Loan* with a pre-trend variable. The latter is constructed to be equal to 1 in 1988, 2 in 1989, and so on, until the year in which a carbon tax is introduced in the country, after which it is held constant. The sample period is the same as before, 1988–2020.

The estimates from this test are presented in Table 3, column (1). The point estimate of β_3 makes it clear that if anything, the share of domestic fossil loans was increasing prior to the introduction of the carbon tax. Therefore, the increase in the share of foreign fossil loans after the introduction of said tax reversed a trend that was going in the opposite direction. Moreover, the coefficient of β_2 continues to be significant at the 1% statistical level. The magnitude of the measured coefficient suggests that after a carbon tax is introduced in a country, foreign lending to fossil companies increases by about 7.7%. This is higher than in the specification in Table 2, column (3), where we do not control for a pre-trend. The fact that domestic lending declines significantly after the imposition of a carbon tax suggests that banks are not fully forward-looking and we are not capturing a simple reversion to the mean.

5.3. Falsification tests

Another potential concern with our results so far is that they are simply indicative of a general internationalization trend that took place at some point during the sample period. As part of this trend, banks expanded their geographic scope of operation, and as a result the share of foreign lending increased. It is possible then that this phenomenon is not confined to fossil lending, but the econometrician is erroneously attributing it to carbon taxes. We alleviate this concern somewhat in Appendix Table 5 where we show that in response to a carbon tax, the share of foreign fossil lending increases, while the share of non-fossil lending does not. However, the specification in Appendix Table 5 does not allow us to control for the full set of dummy interactions.

To neutralize this criticism, we now look at lending to firms with no fossil projects. Recall that according to the theoretical mechanism we have in mind, carbon taxes reduce the return to fossil-fuel projects, making banks less willing to lend to those.

[18] This is somewhat different from Khwaja and Mian (2008) and Jimenez et al. (2012) in the sense that we assume that there is a constant credit demand component by a firm with respect to its lender which we need to control for.

Table 3
Domestic carbon taxes and fossil lending: Pre-trend and placebo.

	Fossil loan	Wholesale or retail	Clean manufacturing
	(1)	(2)	(3)
Home country carbon tax ×Foreign loan	0.0765***	−0.0120	−0.0144
	(0.0076)	(0.0071)	(0.0108)
Foreign loan	0.0463***	−0.0265***	0.0711***
	(0.0074)	(0.0025)	(0.0050)
Pre-trend ×Foreign loan	−0.0023***		
	(0.0004)		
Host country×Year dummies	Yes	Yes	Yes
Home country×Year dummies	Yes	Yes	Yes
Bank fixed effects	Yes	Yes	Yes
No. Observations	2,127,049	2,136,679	2,136,679
R-squared	0.15	0.07	0.12

Note: The Table reports estimates from OLS regressions. The dependent variable is 'Fossil loan', a dummy variable equal to 1 if the loan is to a company in SIC sectors 12xx and 13xx (column (1)); 'Wholesale or retail', a dummy variable equal to 1 if the loan is to a company in SIC sectors 50xx—59xx (column (2)); and 'Clean manufacturing', a dummy variable equal to 1 if the loan is to a company in SIC sectors 20xx—39xx, excluding metallurgy and cement production (column (3)). 'Home country carbon tax' is a dummy variable equal to one after the introduction of a carbon tax in the home country. 'Foreign loan' is a dummy variable equal to one if the loan is to a company domiciled in a foreign country. 'Pre-trend' is a trend variable until the year of introduction of the carbon tax in the home country. The sample period is 1988—2020. Data come from Dealscan, Carbon Tax Center, International Carbon Action Partnership (ICAP), and World Bank Group Carbon Pricing Dashboard. All regressions include fixed effects as specified. Standard errors clustered at the bank level appear in parentheses, where *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

The same mechanism should not apply to sectors with little-to-no fossil assets. In the remainder of Table 3, we look at two such sectors: wholesale and retail trade (column (2)), and clean manufacturing (column (3)). The latter includes all manufacturing sectors with the exception of basic metals and cement production. In both cases, we fail to reject the null hypothesis that carbon taxes in the domestic market have no bearing on the foreign-domestic lending mix. The point estimate of β_2 in these falsification tests is both numerically and statistically indistinguishable from zero.

We conclude that the main mechanism which we have in mind—i.e., carbon pricing being relevant for fossil lending, but not for other type of lending—is validated in the data.

5.4. Robustness tests

To assess the validity of our main result, we now subject our main test to a number of robustness tests. Broadly speaking, we want to make sure that the main result of the paper is not sensitive to particular choices of empirical proxies for fossil lending and carbon pricing, as well as to a particular sample choice. We report the results of these estimations in Tables 4 and 5.

In Table 4, we look at robust definitions of the main dependent variable. In column (1), we aggregate the data differently. We calculate, for each year and each host-country, the share of fossil loans by a particular bank out of total loans by that same bank to

Table 4
Domestic carbon taxes and fossil lending: Dependent variable robustness.

	Share fossil lending	Including all mining	Including metallurgy and cement
	Aggregation at borrower-country level		
	(1)	(2)	(3)
Home country carbon tax×Foreign loan	0.0571***	0.0749***	0.0461***
	(0.0067)	(0.0078)	(0.0078)
Foreign loan	0.0058***	−0.0141***	−0.0076***
	(0.0022)	(0.0026)	(0.0026)
Host country×Year dummies	Yes	Yes	Yes
Home country×Year dummies	Yes	Yes	Yes
Bank fixed effects	Yes	Yes	Yes
No. Observations	229,166	2,136,679	2,136,679
R-squared	0.40	0.16	0.13

Note: The Table reports estimates from OLS regressions. The dependent variable is 'Share fossil lending', the bank-year-borrower country share of fossil loans (column (1)); 'Including all mining', a dummy variable equal to 1 if the loan is to a company in SIC sectors 10xx to and including 14xx (column (2)); and 'Including metallurgy and cement', a dummy variable equal to 1 if the loan is to a company in SIC sectors 12xx, 13xx, 32xx, and 33xx (column (3)). 'Home country carbon tax' is a dummy variable equal to one after the introduction of a carbon tax in the home country. 'Foreign loan' is a dummy variable equal to one if the loan is to a company domiciled in a foreign country. The sample period is 1988—2020. Data come from Dealscan, Carbon Tax Center, International Carbon Action Partnership (ICAP), and World Bank Group Carbon Pricing Dashboard. All regressions include fixed effects as specified. Standard errors clustered at the bank level appear in parentheses, where *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 5
Domestic carbon taxes and fossil lending: Sample robustness.

	Fossil loan					ETS-eligible sector
	Lead banks only	Dropping top-3 countries	5 years around carbon-tax event	3 years around carbon-tax event	All loans	Carbon-intensive sectors
	(1)	(2)	(3)	(4)	(5)	(6)
Home country carbon tax×Foreign loan	0.0468***	0.0273**	0.0846***	0.0729***		
	(0.0088)	(0.0129)	(0.0089)	(0.0094)		
Home country carbon tax or ETS×Foreign loan					0.0655***	
					(0.0052)	
Home country ETS×Foreign loan						0.2022***
						(0.0260)
Foreign loan	0.0063*	−0.0091***	−0.0012	0.0028	−0.0141***	−0.1527***
	(0.0035)	(0.0025)	(0.0026)	(0.0026)	(0.0026)	(0.0111)
Host country×Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
Home country×Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
Bank fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
No. Observations	820,764	1,788,796	1,787,657	1,687,190	2,136,679	424,326
R-squared	0.18	0.15	0.14	0.14	0.15	0.78

Note: The Table reports estimates from OLS regressions. The dependent variable is 'Fossil loan', a dummy variable equal to 1 if the loan is to a company in SIC sectors 12xx and 13xx (columns (1)–(5)); and 'ETS-eligible sector', a dummy variable equal to 1 if the loan is to a company in the fossil sector, cement production, metallurgy, or energy generation, and to 0 if the loan is to a company in transportation or agriculture (column (6)). 'Home country carbon tax' is a dummy variable equal to one after the introduction of a carbon tax in the home country. 'Home country carbon tax or ETS' is a dummy variable equal to one after the introduction of a carbon tax in the home country or after the home country joined an Emissions Trading Scheme (ETS). 'Home country ETS' is a dummy variable equal to one after a country joins the EU ETS scheme. 'Foreign loan' is a dummy variable equal to one if the loan is to a company domiciled in a foreign country. In column (1), only loan tranches by lead banks are included. In column (2), Japan, France, and the United Kingdom are excluded from the sample of home countries. In column (3), only the 5 years before and the 5 years after the introduction of a carbon tax are included, for countries with a carbon tax. In column (4), only the 3 years before and the 3 years after the introduction of a carbon tax are included, for countries with a carbon tax. In column (6), only loan tranches to carbon-intensive sectors are included. The sample period is 1988—2020. Data come from Dealscan, Carbon Tax Center, International Carbon Action Partnership (ICAP), and World Bank Group Carbon Pricing Dashboard. All regressions include fixed effects as specified. Standard errors clustered at the bank level appear in parentheses, where *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

that same country. This helps address the potential criticism that individual loan tranches are a noisy measure of actual lending. The estimates suggest that the share of fossil lending increases by around 5.7% for lending to foreign countries, as opposed to domestic lending.

In column (2), we modify the main dependent variable to be equal to one if the loan is not only to a coal, oil, or gas company, but also to a company in the mining sector. The point estimate of β_2 is still negative and significant at the 1% statistical level, and the magnitude of the measured coefficient is higher than the one in column (3) of Table 2. Numerically, it suggests that after a carbon tax is introduced in a country, foreign lending to fossil or mining companies increases by about 7.5%.

In column (3), the dependent variable is equal to one if the loan is not only to a coal, oil, or gas company, but also to a company in one of the two most carbon-intensive manufacturing industries. The first industry is "Other non-metallic mineral products" (sector code 32) and it includes cement production, which is responsible for around 7% of annual global carbon emissions. The second one is "Basic metals" (sector code 33) and it includes steel works and primary smelting, which is responsible for around 8% of annual global carbon emissions. The point estimate of β_2 is still negative and significant at the 1% statistical level, and the magnitude of the measured coefficient is around one-third smaller than the one in column (3) of Table 2. Numerically, it suggests that after a carbon tax is introduced in a country, foreign lending to fossil or mining companies increases by about 4.6%.

In Table 5, we repeat the main test using various robust samples. In column (1), we restrict the sample to lead banks only. The idea is that the lead bank is the most important player in the syndicate because it carries the negotiations and often sets the lending conditions. This is also consistent with the approach in some papers using syndicated lending data which attribute the whole loan to the lead bank (e.g., Giannetti and Laeven, 2012). We note that the main effect documented in this paper survives in this alternative specification, and the point estimate of β_2 is still significant at the 1% statistical level. At the same time, the magnitude of the measured coefficient is one-third smaller than the one in column (3) of Table 2. Numerically, it suggests that after a carbon tax is introduced in a country, foreign lending to fossil or mining companies increases by about 4.7%.

In column (2), we address the potential concern that our results are driven by a handful of countries. To that end, we exclude from the sample the three largest countries with a carbon tax, in terms of overall lending: Japan, the United Kingdom, and France. These three countries account for 40.2%, 12.3%, and 9.3%, respectively, of all syndicated loans by countries with a carbon tax. The evidence unequivocally suggests that the main result of the paper is not driven by these three outlier countries.

Next, we address the concern that while we conjecture that the effect of the carbon tax is immediate, the sample window is rather long. In columns (3) and (4), we restrict the main test to a window of 5 years and 3 years, respectively, around the introduction of a carbon tax in the respective country. The point estimate on the main variable of interest is still significant at the 1% statistical level, and the magnitude is numerically larger than the one in Table 2, column (3).

In column (5), we modify the variable 'Home country carbon tax' to be equal to one after the introduction of a carbon tax in the home country, or after the home country joined an Emissions Trading Scheme (ETS). An ETS represents an alternative way of forcing carbon-intensive firms to internalize the cost of the carbon externality. As Table 1 makes it clear, twice as many loan tranches (19.3% of all observations) are associated with banks from such countries as with banks from countries that have only imposed a carbon tax. Crucially, the point estimate of β_2 is still negative and significant at the 1% statistical level, and the magnitude of the measured coefficient is very similar to the one in column (3) of Table 2. Numerically, it suggests that after a carbon tax is introduced in a country, foreign lending to fossil or mining companies increases by about 6.6%.

One final concern we need to address is that the introduction of the carbon tax may be endogenous to the performance of carbon-intensive sectors. To address this issue, we employ a strategy inspired by the approach in Martin et al. (2014), who compare plants in the UK that are fully subject to plants that are only partially subject to the carbon tax. We notice that the EU ETS does not cover all carbon-intensive sectors. In particular, it covers the mining, oil, gas, dirty manufacture, and energy generation sectors, but it excludes agriculture and transportation.[19] In column (6), we focus only on carbon-intensive sectors in the EU, splitting them into EU ETS-eligible and EU ETS-ineligible, and we look at the differential effect on lending to such sectors after a country joins the EU ETS. Consistent with our prior, we find that after the home country joins the EU ETS, banks increase significantly more lending to foreign-domiciled carbon-intensive sectors, especially if they are covered by the EU ETS. This alleviates concerns about the endogeneity of carbon pricing to the overall performance of the domestic carbon-intensive sector.[20]

5.5. Loan characteristics

Our evidence so far suggests that the introduction of carbon taxes in one market leads banks to reduce the incidence of lending to fossil companies in that market, and to increase the incidence thereof in other markets. In Table 6, we examine three other characteristics of fossil loans: their size, maturity, and interest rate. This allows us to study whether banks not only extend more credit abroad, but they also increase the volume of foreign credit, as well as adjust the maturities of foreign loans in one or another direction. Furthermore, these tests allow us to distinguish between between credit supply and credit demand explanations of the main effect. To that end, we run the regression separately on fossil and non-fossil loans, and compare the coefficients across the two samples.

In column (1), we run a version of Eq. (1) where the dependent variable is the natural logarithm of the loan tranche amount. Because we do so only for the subsample of fossil loans, the number of observations is reduced to 87,180. The evidence suggests that the average loan amount increased significantly more in the case of foreign loans, following the introduction of a carbon tax in the domestic market. Because the dependent variable is a log transformation, and the independent variables are dummy variables, the interpretation of β_2 is that after the introduction of a domestic carbon tax, the difference in loan amount between foreign and domestic loans increases by $e^{\beta_2} - 1$ percent. Given a point estimate of 0.686, this suggests an approximate doubling in size of the average foreign fossil loan, compared to the average domestic fossil loan.[21] At the same time, we find no effect on the average size in the sample of non-fossil loans (column (2)), with the difference between the two coefficients being statistically significant.

What is the implied economic effect? The point estimates imply that after the introduction of a carbon tax, on average the size of a domestic fossil loan declines by 37%, and the size of a foreign fossil loan increases by 88%. Recall that according to the estimates in Table 2, the number of of domestic fossil loans declines by around 1%, and the number of foreign fossil loans increases by 6.8%. Finally, 92.5% of all fossil loans are domestic. Together, our estimates thus imply that after the introduction of a carbon tax, overall fossil lending, in terms of loan volume, declines by around 20.3%.[22]

In column (3), we re-estimate Eq. (1) with the natural logarithm of the loan's maturity as a dependent variable, for the sample of fossil loans. In this case, we find that the maturity of the average foreign fossil loan declines. The effect is significant at the 1% statistical level. The interpretation of β_2 is that after the introduction of a domestic carbon tax, the loan maturity of the average foreign fossil loan, compared with the average domestic fossil loan, decreases by about a quarter. However, loan maturities also

[19] To the best of our knowledge, the decision to include some sectors and not others is politically motivated, and it is independent of how polluting the sector is. For example, De Haas and Popov (2023) report that the energy sector (which the EU's ETS covers) is the most carbon-intensive, followed by water, air, and land transportation (which it does not cover), and then by metallurgy and cement production (which it covers). Therefore, regarding the sector's overall carbon footprint, coverage by the ETS appears to be random.

[20] One other potential source of endogeneity of carbon taxes is that their implementation coincides with changes in government. We are less worried about it, as for the mechanisms detected in the paper, it doesn't matter if carbon taxes are imposed by incumbent or by new governments. The more important assumption we make is that the government does not decide to implement a carbon tax in response to anticipated changes in the behavior of fossil firms or of banks lending to these firms.

[21] In Appendix Table 11, we replicate the analysis after imputing the missing loan shares in four different ways. In column (1), following Duchin and Sosyura (2014), lead banks are allocated the median loan share of lead banks in the sample when data is available, and the remaining loan share of non-lead banks is then split equally across the rest of banks. In column (2), following De Haas and van Horen (2012), lead banks and non-lead banks are each allocated 50% of the loan share and then shares are split equally across banks with the same role in the syndicate. In column (3), following De Haas and Van Horen (2013) and Dell'Aricci et al. (2021), missing values for the loan share are filled in based on a regression of the loan share when data is available. The main effect remains remarkably stable regardless of the imputation method used.

[22] By how much would fossil lending have declined absent cross-border reallocation? Assuming that in this case, domestic lending would have declined by exactly as much as it declined with the possibility to shift lending abroad, then total lending to fossil companies would have declined by about 30%.

Table 6
Domestic carbon taxes and fossil lending: Loan characteristics.

	Log (Loan amount)		Log (Loan maturity)		Loan rate	
	Fossil loans	Non-fossil loans	Fossil loans	Non-fossil loans	Fossil loans	Non-fossil loans
	(1)	(2)	(3)	(4)	(5)	(6)
Home country carbon tax ×Foreign loan	0.6780***	−0.0232	−0.2649***	−0.0608***	−2.9037***	−0.1505
	(0.1851)	(0.0429)	(0.0803)	(0.0184)	(0.4886)	(0.1250)
Foreign loan	−0.0492	0.2424***	0.0938***	0.0361***	2.0228***	8.0916***
	(0.0566)	(0.0178)	(0.0312)	(0.0068)	(0.1774)	(0.0559)
Host country×Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
Home country×Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
Bank fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
No. Observations	87,332	2,021,840	86,117	1,970,188	84,527	1,944,097
R-squared	0.54	0.67	0.48	0.22	0.63	0.58

Note: The Table reports estimates from OLS regressions. The dependent variable is 'Log (Loan amount)', the natural logarithm of the loan amount, in USD (columns (1) and (2)); 'Log (Loan maturity)', the natural logarithm of the maturity of the loan, in months (columns (3) and (4)); and 'Loan rate', the loan spread over the default base (columns (5) and (6)). 'Home country carbon tax' is a dummy variable equal to one after the introduction of a carbon tax in the home country. 'Foreign loan' is a dummy variable equal to one if the loan is to a company domiciled in a foreign country. 'Fossil loan' is a dummy variable equal to one if the loan is to companies in SIC 12xx and 13xx. The sample period is 1988–2020. In columns (1), (3), and (5), the sample is restricted to fossil loans, i.e., loans to companies in SIC sectors 12xx and 13xx. In columns (2), (4), and (6), the sample is restricted to non-fossil loans, i.e., loans to companies not in SIC sectors 12xx and 13xx. Data come from Dealscan, Carbon Tax Center, International Carbon Action Partnership (ICAP), and World Bank Group Carbon Pricing Dashboard. All regressions include fixed effects as specified. Standard errors clustered at the bank level appear in parentheses, where *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

decline for non-fossil loans (column (4)), and while the estimated coefficient for fossil loans is larger in absolute value, the difference between the two coefficients is not statistically significant.

Finally, in column (5), we replicate Eq. (1) with the loan spread as a dependent variable.[23] We find that the spread on the average foreign fossil loan declines, by about one-half of a sample standard deviation (column (5)). Once again, the effect is significant at the 1% statistical level. We document no such statistical relationship in the sample of non-fossil loans (column (6)), and the difference between the two coefficients is statistically significant.

The implication of the evidence in Tables 2 and 6 is that after the introduction of a carbon tax in the bank's domestic market, it extends more loans to fossil companies abroad, and these loans are on average of larger size and lower rates. This implies that banks increase foreign fossil lending both in terms of number of loans and in terms of loan size. Together with the decline in loan rates, this points towards a mechanism whereby credit demand by domestic fossil companies goes down following the introduction of a carbon tax, leading banks to increase the supply of credit to fossil companies abroad.[24]

6. Mechanisms

We now assess what factors at the bank, country, and company level amplify the effect of carbon taxes on banks' fossil lending. Identifying these would help shed light on the microeconomic mechanisms which we outlined in Section 2 and which could plausibly be behind the observed reallocation of fossil lending across national borders.

6.1. Bank-specific factors

We first look at mechanisms at the bank level whereby carbon taxes precipitates a cross-border reallocation of bank lending. One prominent such mechanism is bank specialization (Paravisini et al., 2015). Banks that already have significant experience in lending to the fossil fuel sector may have a higher incentive to continue lending to fossil companies. As long as the overall level of fossil lending stays constant, and the return to fossil lending at home declines, such banks will increase lending abroad. This mechanism requires the presence of fossil lending specialization, otherwise banks may simply switch from fossil to non-fossil lending in the home market, without any implications for fossil lending in foreign markets. In other words, as long as banks

[23] There are not enough observations of the variable "Spread over default base" in Dealscan in the case of loans to fossil companies. To circumvent this problem, in step 1 we first run the following regression on the full sample of loans:

$$Loan\,rate_{b,f,t} = +\ \beta_1 Log(Loan\,Amount)_{b,f,t} +\ \beta_2 Log(Loan\,Maturity)_{b,f,t} + \beta_3 Foreign\,Loan_{b,f,t} + \gamma_b + \mu_{i,t} + \phi_{j,t} + \varepsilon_{b,f,t},$$

Then, in step 2, we create a new variable, "Predicted loan rate" which is calculated based on the regression coefficients estimated in Step 1. As a result, the number of loan rates observations increases from 17,652 to 85,935, which enables us to run the second-stage regression.

[24] To get closer to the question of whether the effect we document is due to changes in domestic demand, in Appendix Table 12 we run a revised version of Eq. (1) on the sample of loans to domestic fossil companies. The evidence suggests that after the introduction of a carbon tax in a country, overall lending to fossil companies declines, and so do loan rates. This points to a decline in credit demand by fossil companies following the introduction of a carbon tax and is consistent with the notion that banks respond to lower demand for credit by domestic fossil firms by increasing the supply of credit to foreign fossil firms.

have a built-up expertise to provide fossil loans relative to other loans, a cross-border reallocation of fossil lending should be readily observed.

To test this mechanism, we construct a proxy for specialization based on the extent of banks' observed fossil lending prior to the introduction of a carbon tax. Banks with more exposure to a particular sector have more interactions with borrowers and are thus more informed (e.g., Dell'Ariccia et al., 1999; Winton, 1999). Thereby, when the price of carbon increases, banks with high levels of specialization in fossil lending will less likely switch to financing green technologies and more likely keep accumulating fossil assets than less exposed banks. As carbon taxes exogenously reduce the return to fossil lending in the primary domestic market, such banks will be more likely to increase fossil lending abroad.

We construct an empirical proxy for specialization that is based on the argument in Paravisini et al. (2015). In particular, we calculate, for each bank-year, the share of overall lending that is extended to the fossil sector. We then define outlier banks to be those for which that share is in the top-10% in a particular country. These are therefore banks that are the most extremely specialized in fossil lending, compared with banks in the same home market. We therefore define "Fossil lending specialization" as a dummy variable equal to 1 for banks that fall in this category. Finally, we interact this variable with the interaction of interest $Carbon\,Tax_{i,t} \times Foreign\,Loan_{b,f,t}$.

In column (1) of Table 7, we report a version of Eq. (1) which includes this triple interaction. The regression also includes the relevant double interactions. The evidence presented in column (1) suggests that banks with relatively higher specialization in fossil lending are significantly more likely to increase their foreign fossil lending in response to the introduction of carbon taxes at home.

Another possibility is related to banks capitalization and/or profitability. The reallocation to foreign lending may be stronger for less capitalized banks, to the extent that foreign loans are more risky and there exists a positive relationship between bank capital and risk taking (Holmström and Tirole, 1997; Ongena et al., 2013; Jimenez et al., 2014). Bank profitability could also play a role, albeit the link is theoretically ambiguous. On the one hand, more profitable banks may be less willing to engage in risk taking (Keeley, 1990), in this case by reallocating lending abroad. On the other hand, higher profitability may loosen bank borrowing constraints, and so more profitable banks may take risk on a larger scale (Martynova et al., 2020), including by increasing foreign lending.

We find that neither the level of bank capital (column (2)), nor that of the bank's return on assets (column (3)) affects the elasticity of foreign lending to domestic carbon taxes. The evidence is also inconsistent with the idea that a carbon tax is a primarily a shock to bank capital or profitability, leading banks in the direction of riskier lending.

Finally, we look at whether banks' green commitments matter for the mechanism we study. Kacperczyk and Peydro (2021) show that if a bank is a member of 11 banking groups that have made a net zero pledges, committing to reduce the greenhouse gas emissions of their clients, it typically reallocates the credit supply from carbon-emissions heavy firms to green firms. We note that 10 of the 11 banking groups are present in our sample, and there are 319 bank names in Dealscan that are associated with these 10 bank holding groups. We create a dummy variable equal to 1 if a loan tranche is given by a bank that is a member of one

Table 7
Domestic carbon taxes and fossil lending: Bank-level mechanisms.

	Bank factor = Fossil lending specialization	Bank factor = Capital	Bank factor = ROA	Bank factor = Green pledge
	(1)	(2)	(3)	(4)
Home country carbon tax ×Foreign loan	0.0600***	0.0890***	0.0882***	0.0682***
	(0.0073)	(0.0142)	(0.0153)	(0.0074)
Foreign loan	−0.0073***	−0.0214***	−0.0241***	−0.0045*
	(0.0024)	(0.0067)	(0.0072)	(0.0025)
Home country carbon tax ×Bank factor	0.0293***	0.0001	0.0007	−0.0099
	(0.0064)	(0.0001)	(0.0020)	(0.0067)
Bank factor ×Foreign loan	0.0295***	−0.0001	−0.0010	0.0002
	(0.0045)	(0.0001)	(0.0010)	(0.0037)
Home country carbon tax ×Bank factor ×Foreign loan	0.0484***	0.0000	0.0010	−0.0052
	(0.0145)	(0.0004)	(0.0050)	(0.0166)
Host country×Year dummies	Yes	Yes	Yes	Yes
Home country×Year dummies	Yes	Yes	Yes	Yes
Bank fixed effects	Yes	Yes	Yes	Yes
No. Observations	2,136,679	234,901	223,061	2,136,679
R-squared	0.15	0.13	0.13	0.15

Note: The Table reports estimates from OLS regressions. The dependent variable is 'Fossil loan', a dummy variable equal to 1 if the loan is to a company in SIC sectors 12xx and 13xx. 'Home country carbon tax' is a dummy variable equal to one after the introduction of a carbon tax in the home country. 'Foreign loan' is a dummy variable equal to one if the loan is to a company domiciled in a foreign country. 'Fossil lending specialization' is a dummy equal to 1 if the bank is in the top 10% in a country-year share of fossil loans before the introduction of the carbon tax. 'Capital' is the bank's total equity divided by total assets. 'ROA' is the bank's return on assets. 'Green pledge' is a dummy variable equal to one if the bank has explicitly signed up to a "green pledge" to reduce lending to carbon-intensive companies. The sample period is 1988–2020. Data come from Dealscan, Carbon Tax Center, International Carbon Action Partnership (ICAP), World Bank Group Carbon Pricing Dashboard, and BankFocus. All regressions include fixed effects as specified. Standard errors clustered at the bank level appear in parentheses, where *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

of these 10 bank holding groups. Then we include a triple interaction with this dummy variable in column (4). The evidence suggests that such green-pledge banks are less likely to extend more fossil loans abroad in response to the introduction of carbon taxes in the primary domestic market, but this effect is not statistically significant.

6.2. Borrower-specific factors

Next, we look at the role played by borrower-specific factors. There is a large literature on the role that borrower risk plays in creditors' lending decisions (e.g., Ongena et al., 2013; Jimenez et al., 2014). Borrower heterogeneity in terms of return-risk profile can conceivably be important in determining how fossil lending is reallocated across national borders following the introduction of a carbon tax. In addition, Ivanov et al. (2020) show that in response to the California cap-and-trade bill, banks restricted credit to high-polluting firms, and that this effect was significantly higher for private companies. This suggests that firm ownership can play a role, too.

In addition, banks may prefer to give a fossil loan to a company that has already obtained a fossil loan from the same bank, to maintain the value of the earlier loans and preserve valuable relationships. For instance, a large literature on the value of bank relationships has argued and shown that banks prefer to give credit to existing clients to preserve valuable relationships or to prevent defaults in their existing loan portfolios when these clients experience negative wealth shocks (e.g., Sharpe, 1991; Rajan, 1992; Petersen and Rajan, 1994; Berger and Udell, 1995; and Bolton et al., 2016). Such familiarity can therefore play an important stabilizing role when credit markets are hit by shocks (Beck et al., 2018). Furthermore, lack of strong relationships or creditor-borrower familiarity can result in a flight away from foreign lending (Giannetti and Laeven, 2012; De Haas and Van Horen, 2013). It is natural to hypothesize that such financial links may play a role when banks decide on the direction in which they reallocate fossil lending. Furthermore, Minetti (2010) argues that banks may continue funding mature technologies that they have experience with, because new technologies compromise the value of assets already on their balance sheets. While this does not necessarily imply that it make sense for a bank to internalize the benefit of an additional fossil loan for the value of all fossil loans, it does suggest that a bank will be more willing to give a fossil loan to a company that has already obtained a fossil loan from the same bank, to maintain the value of the earlier loans. Contrary to the previous arguments, this argument would imply that banks respond to firm-specific, as opposed to overall, fossil exposure.

In Table 8, we look at these aspects of borrower heterogeneity. We report versions of Eq. (1) which include a triple interaction with proxies for borrower-specific measures of ownership, profitability, risk, and familiarity. The regressions also include the relevant double interactions.

The first borrower-specific aspect that we look at is whether the borrowing company is publicly or privately owned. For example, private companies are subject to less scrutiny than public companies, and so more intense lending to these can be driven

Table 8
Domestic carbon taxes and fossil lending: Role of borrower-specific factors.

	Fossil loan				
	Borrower factor = Private firm	Borrower factor = Growth	Borrower factor = Debt	Borrower factor = Profit	Borrower factor = Repeat borrower
	(1)	(2)	(3)	(4)	(5)
Home country carbon tax ×Foreign loan	−0.0109	0.0784**	0.0200	−0.0605	0.0205*
	(0.0155)	(0.0313)	(0.0250)	(0.0404)	(0.0113)
Foreign loan	−0.0022	0.0249*	0.0593***	0.0655***	0.0072***
	(0.0038)	(0.0142)	(0.0104)	(0.0131)	(0.0024)
Home country carbon tax ×Borrower factor	−0.0121***	−0.0129	0.0520**	−0.3387***	0.0036**
	(0.0020)	(0.0111)	(0.0211)	(0.0620)	(0.0016)
Borrower factor ×Foreign loan	−0.1000***	−0.3208***	−0.0680	−0.2177	−0.0152***
	(0.0031)	(0.0359)	(0.0882)	(0.3376)	(0.0024)
Home country carbon tax ×Borrower factor ×Foreign loan	0.1186***	−0.4377***	−1.2471***	−0.0918	0.0579***
	(0.0157)	(0.0796)	(0.2537)	(0.1874)	(0.0110)
Host country×Year dummies	Yes	Yes	Yes	Yes	Yes
Home country×Year dummies	Yes	Yes	Yes	Yes	Yes
Bank fixed effects	Yes	Yes	Yes	Yes	Yes
No. Observations	1,777,618	93,604	158,910	137,342	2,136,679
R-squared	0.16	0.51	0.40	0.42	0.15

Note: The Table reports estimates from OLS regressions. The dependent variable is 'Fossil loan', a dummy variable equal to 1 if the loan is to a company in SIC sectors 12xx and 13xx. 'Home country carbon tax' is a dummy variable equal to one after the introduction of a carbon tax in the home country. 'Foreign loan' is a dummy variable equal to one if the loan is to a company domiciled in a foreign country. 'Private firm' is a dummy variable equal to one if the firm is privately owned, and to 0 if it is public. 'Growth' denotes the firm's average sales growth. 'Debt' denotes the firm's average debt, divided by assets. 'Profit' denotes the firm's average profit, divided by assets. 'Repeat borrower' is a dummy variable equal to 1 if the loan is not the first loan the borrower is taking from the same creditor. The sample period is 1988—2020. Data come from Dealscan, Carbon Tax Center, International Carbon Action Partnership (ICAP), World Bank Group Carbon Pricing Dashboard, and Compustat. All regressions include fixed effects as specified. Standard errors clustered at the bank level appear in parentheses, where *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

by banks' desire to avoid reputation loss. Private ownership can also signal higher ex-ante risk, e.g., because private firms are more opaque to a creditor. It can also signal higher ex-post risk, as private firms are smaller, have riskier projects, and have access to a less diversified pool of funding sources. At the same time, private firms being younger on average, tend to grow faster (e.g., Gompers and Lerner, 2001), and so lending to them can be more profitable. Therefore, knowing whether banks are more or less likely to reallocate lending abroad to private firms would be informative as to the exact microeconomic mechanisms at play.

The evidence presented in column (1) of Table 8 suggests that after a carbon tax is introduced in a bank's domestic market, banks are more likely to increase lending to a foreign fossil company, and relatively more so if this company is privately owned. The point estimate on the triple interaction is significant at the 1% statistical level. The coefficient implies that a foreign privately owned fossil company is around 12% more likely to receive a loan from a bank in a country that has introduced a carbon tax than a foreign publicly owned fossil company. This evidence is consistent with the idea that a carbon tax at home may drive banks to increase lending to riskier, less intensely scrutinized companies, resulting in higher lending to private fossil companies in foreign markets.

In the next three columns, we evaluate the role played by various proxies for return and risk. These proxies are the company's average sales growth (column (2)), the company's average debt-to-assets level (column (3)), and the company's average profitability (column (4)). We find that in response to the introduction of a carbon tax in the domestic market, banks are significantly more likely to grant a foreign loan to a low-growth, low-debt foreign company than to a high-growth, high-debt one. Ongena et al. (2013) show that in response to tighter regulation in home markets, banks increase risk taking abroad. The evidence here is inconsistent with the idea that domestic carbon taxes push banks to look for more risky opportunities abroad. On the contrary, banks seem to reallocate lending to companies with a more conservative risk-return profile.

Finally, we evaluate the effect of lending familiarity. Banks may prefer to give a fossil loan to a company that has already obtained a fossil loan from the same bank, to maintain the value of the earlier loans and preserve valuable relationships. To test whether banks respond to firm-specific or overall fossil exposure, we condition the analysis on whether a firm has obtained a loan from a that same bank in the past. If prior firm-specific lending turns out to matter independently of the overall fossil lending exposure of the bank, then this would lend support to the relevance of relationship-based theories.

In column (5) of Table 8, we take this question to the data. To do so, we augment Eq. (1) with a triple interaction of a home-country carbon tax dummy, a fossil loan dummy, and a bank-borrower measure of lending relationships (or familiarity). The latter variable is constructed as a dummy variable equal to one if that same borrower has already received a loan from that same bank in the past.

The point estimate on the triple interaction is positive and significant at the 1% statistical level. The interpretation of this result is that the introduction of carbon taxes is associated with an increase in foreign lending to fossil companies, and especially to companies with which banks have an existing lending relationship. This confirms the notion that banks adjust their lending on the intensive margin, within the sample of their existing customers.

The evidence presented in Table 8 thus supports the theoretical notion that bank-firm relationships play an important role in the reallocation of fossil lending across national borders in response to the introduction of a carbon tax. The role of borrower risk is more ambiguous. On the one hand, banks reallocate lending towards private fossil companies abroad, suggesting an increased appetite for risk taking and/or for avoiding public scrutiny in foreign markets in response to domestic carbon taxes. On the other hand, banks increase lending relative more to low-debt and low-growth companies abroad and reduce lending relative less to domestic fossil companies with high debt and high average growth. This is consistent with a mechanism whereby lenders reassert their support to existing borrowers whose creditworthiness is expected to decline, possibly to forestall credit losses (Giannetti and Simonov, 2013; Acharya et al., 2019).

6.3. Host country-specific factors

Finally, we turn to study the potential role that host country-specific factors play in the reallocation of fossil lending across national borders. One plausible margin is that of host-country regulation. The literature has already shown that regulatory arbitrage opportunities can be an important driver of cross-border lending (Houston et al., 2012; Ongena et al., 2013; Karolyi and Taboada, 2015). In our case, it is conceivable that the strictness of the borrower's country's environmental regulation[25] can play a role: banks would be less likely to reallocate lending to foreign markets where companies are subject to stricter green regulation. Another is the strictness of banking supervision in the host country. It is conceivable that banks would be more reluctant to increase lending in markets where loans are subject to more intense supervisory oversight. This will be the case even if supervisors have no “green” objectives per se, but are simply more likely to pay attention to changes in bank lending behavior.

We now push this argument further by asking whether differences in environmental regulation and in bank supervision across countries can explain the cross-border reallocation of loans to fossil companies. Our prior is that when a carbon tax is introduced in a country, banks will reallocate fossil loans to foreign countries that have relatively weak regulation, in the form of green laws and policies and bank supervision and regulation.

We study this question in Table 9. We augment Eq. (1) with a triple interaction of a home-country carbon tax dummy, a fossil loan dummy, and one of two variables: a variable that measures the extent of the host-country's environmental regulation

[25] While it would be natural to differentiate by whether the host country has a carbon tax or not, this test is complicated by the fact that in the early sample, there are very few foreign markets with a carbon tax.

Table 9
Domestic carbon taxes and fossil lending: Role of host country-specific factors.

	Fossil loan	
	Host country factor = Green policy	Host country factor = Bank supervision
	(1)	(2)
Home country carbon tax ×Foreign loan	0.1095***	0.1990***
	(0.0487)	(0.0538)
Foreign loan	0.0618***	−0.0011
	(0.0093)	(0.0010)
Foreign loan×Host country factor	−0.0122***	−0.0016
	(0.0032)	(0.0041)
Home country carbon tax ×Foreign loan×Host country factor	−0.0284**	−0.0912***
	(0.0101)	(0.0196)
Host country×Year dummies	Yes	Yes
Home country×Year dummies	Yes	Yes
Bank fixed effects	Yes	Yes
Host country×Home country	Yes	Yes
No. Observations	1,969,531	1,960,950
R-squared	0.15	0.14

Note: The Table reports estimates from OLS regressions. The dependent variable is 'Fossil loan', a dummy variable equal to 1 if the loan is to a company in SIC sectors 12xx and 13xx. 'Home country carbon tax' is a dummy variable equal to one after the introduction of a carbon tax in the home country. 'Foreign loan' is a dummy variable equal to one if the loan is to a company domiciled in a foreign country. 'Green policy' is a variable equal to the natural logarithm of the number of green laws and policies enacted up to the current year in the host country. 'Bank supervision' is a variable equal to the stringency of bank supervision in the host country. The sample period is 1988—2020. Data come from Dealscan, Carbon Tax Center, International Carbon Action Partnership (ICAP), World Bank Group Carbon Pricing Dashboard, EBRD, and Abiad et al. (2008). All regressions include fixed effects as specified. Standard errors clustered at the bank level appear in parentheses, where *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

(column (1)), and a variable that measures the extent of host-country bank supervision (column (2)). The first variable comes from the EBRD, and it is equal to the number of green laws and policies enacted up to the current year. The second variable comes from Abiad et al. (2008), and is averaged over the sample period. Because we are now interested in variation induced by differences across host countries, we also include interactions of home country and host country dummies in the regression.

The estimates from the regressions continue to show that the introduction of carbon taxes is associated with an increase in foreign lending to fossil companies. As before, the increase in foreign fossil lending in response to domestic carbon taxes is significant at the 1% statistical level. Importantly, this increase is smaller in countries with strict domestic environmental policy (column (1)). By the same token, the increase is larger in countries with less strict green policies. The point estimate on the triple interaction is significant at the 1% statistical level. Numerically, the point estimates imply that the effect of a domestic carbon tax on foreign fossil lending is positive as long as there are <132 green laws and policies in place in the foreign market. There is no reallocation of fossil lending to countries with >132 such regulations (or 18% of the bank-host country-year observations).

Analogously, the increase in foreign lending is smaller (larger) in countries with stricter (less strict) bank supervision and regulation (column (2)). Once again, the point estimate on the triple interaction is significant at the 1% statistical level. Numerically, the point estimates imply that the effect of a domestic carbon tax on foreign fossil lending is positive as long as the index of bank supervision in the foreign markets is <2.7, and negative if the index of bank supervision in the foreign markets is >2.7.

The results reported in Table 9 have two implications. First, in order to be effective from a global perspective, carbon pricing needs to be imposed, and environmental regulation needs to be sufficiently strict, throughout the world. Else, the effect of pricing carbon will be arbitraged away by large international banks, which will dampen the desired effect on global fossil lending. Second, even in the absence of strict environmental regulation in the foreign market, fossil lending to that market may increase less if bank supervision and regulation in general is sufficiently strict.[26]

7. Real effects

We have demonstrated that in response to carbon taxes, bank lending to fossil companies at home declines, likely because these companies now have a reduced demand for loans. Consequently, affected banks increase their supply of credit to foreign fossil companies. However, our analysis so far has been exclusively about bank lending, and we have not explored potential consequences for firms' economic activity. The latter is important because it would inform the debate on whether via changes in financial markets activity, carbon taxes have real consequences. This would be the case if in response to increased lending to

[26] In Appendix Table 13, we account for the possibility that the strictness of environmental regulation and/or bank supervision is a mere proxy for the level of host-country economic development. In other words, more developed economies also have more stringent regulation, and so we may be merely capturing a slower reallocation towards more developed markets. We including on the right-hand side an interaction of the $\textit{Foreign Loan}_{b,f,t}$ dummy and the double interaction thereof with carbon tax and $\textit{Log}(\textit{Host country GDP per capita})_{i,t}$, the natural logarithm of per-capita GDP in the host-country. We find that in response to carbon taxes, banks tend to reallocate fossil lending to more, not to less, developed economies. This is consistent with the idea that companies in countries with better institutional frameworks are more attractive to foreign investors (LaPorta et al., 1998). Importantly, the main effect still obtains: after a carbon tax is introduced, banks reallocate fossil lending relatively more towards markets with lower environmental protection and bank supervision.

Table 10
Domestic carbon taxes and fossil lending: real effects.

	Investment growth	Sales growth
	(1)	(2)
Home country carbon tax ×Foreign company	0.3033***	0.1725***
	(0.0730)	(0.0414)
Foreign company	−0.4015***	0.0716***
	(0.0774)	(0.0142)
Host country×Year dummies	Yes	Yes
Home country×Year dummies	Yes	Yes
Company fixed effects	Yes	Yes
No. Observations	5736	6221
R-squared	0.88	0.88

Note: The Table reports estimates from OLS regressions. The dependent variable is 'Investment growth', the annual change in firm investment (column (1)), and 'Sales growth', the annual change in firm sales (column (2)), during the year after receiving a loan. 'Home country carbon tax' is a dummy variable equal to one after the introduction of a carbon tax in the home country. 'Foreign company' is a dummy variable equal to one if the company is domiciled in a foreign country. The sample is restricted to fossil loans, i.e., loans to companies in SIC sectors 12xx and 13xx. The sample period is 1988—2020. Data come from Dealscan, Carbon Tax Center, International Carbon Action Partnership (ICAP), and World Bank Group Carbon Pricing Dashboard. All regressions include fixed effects as specified. Standard errors clustered at the bank level appear in parentheses, where *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.
We declare that we have no material interests to disclose pertaining to the research in this paper.
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foreign fossil companies, these companies increase their activity, with potentially negative consequences for their own (as well as for aggregate) carbon emissions.

To address this question, in Table 10 we study the response of fossil firms' investment and sales over time, depending on their market of operation and on the bank they receive a loan from. We find that after the introduction of a carbon tax in one market, during the year after receiving a loan, fossil companies in the home market (in foreign markets) experience a relative decline (increase) in investment (column (1)) and in sales (column (2)). In both cases, the point estimate is significant at the 1% statistical level. Taking the point estimates in column (1), investment growth by foreign fossil companies is relatively higher by 0.30 (or one-third of a sample standard deviation). This result is consistent with the idea that increased lending to foreign fossil companies in response to a tightening in domestic carbon pricing leads these foreign fossil companies to invest relatively more and to grow relatively faster. Our evidence thus suggests that in addition to bank lending effects, there are also real effects associated with the reallocation of fossil lending across geographic borders.

Because the analysis reported in Table 10 is based on differences-in-differences estimation, it is unclear whether the relative effect is driven by domestic or by foreign fossil companies. Appendix Figs. 1–4 provide further visual evidence to answer this question, and they suggest that it is both. Following the introduction of carbon taxes in one market, investment by fossil companies in that market declines (Appendix Fig. 1), and it increases in foreign markets in each of the following three years (Appendix Fig. 2). A similar pattern is observed in the case of sales (Appendix Figs. 3 and 4). The figures also suggest that there are no pre-trends in real activities, strengthening the overall identification strategy.

8. Conclusion

There is a broad consensus among economists and policy makers that taxing carbon is the most cost-efficient way to price the externality associated with carbon emissions. Increasing the effective price of carbon should reduce emissions, stunting the growth of atmospheric carbon and slowing down climate change. At the same time, few countries in the world tax carbon-intensive activities at the levels recommended by economists. This hesitancy is partially driven by fear of free-riding: national authorities are concerned that imposing carbon taxes unilaterally would hurt their economies as carbon-intensive activities migrate to different jurisdictions.

In this paper, we show that such carbon tax arbitraging can indeed happen because of adjustments in multinational banks' lending portfolios. Our main finding is that following an exogenous increase in the price of carbon in their domestic market (as a result of the introduction of a carbon tax), banks reduce their lending to coal, oil, and gas companies at home, and increase such fossil lending abroad. This reallocation of fossil lending across national borders is immediate, economically meaningful, and statistically significant. Our analysis suggests that after a carbon tax is introduced in a country, bank lending to foreign fossil companies increases by 6.8%. At the same time, because domestic fossil lending declines, overall fossil lending goes down by about 0.4%. We find a similar effect of joining an ETS, as well as in the case of lending to other carbon-intensive sectors, such as metallurgy and cement production. At the same time, such effect is absent in the case of lending to non-fossil sectors, such as retail, wholesale, and clean manufacturing.

Our second finding is that there are significant differences within the group of banks, firms, and countries affected by the carbon tax. Banks are much more willing to reallocate lending across national borders if they already have substantial fossil lending. This speaks to theories of lender specialization, with some banks having a comparative advantage in making fossil loans. Such banks are also more likely to increase the amount of fossil lending to countries which have less stringent environmental regulation and less strict supervision. This finding confirms the idea that when subject to changes in carbon prices in one market, banks react by engaging in cross-border regulatory arbitrage. Finally, banks in markets hit by carbon taxes are more likely to increase lending to private firms, to low-growth and low-debt companies, and to companies they already have a lending relationship with. This evidence speaks to theories of the value of firm information and the incentives to increase risk taking in response to changes in bank balance sheet conditions.

Finally, we also find that after the introduction of a carbon tax in one market, fossil companies in that market (in foreign markets) experience a relative decline (increase) in investment and in sales. Our evidence thus suggests that in addition to bank lending effects, there are also real effects associated with the reallocation of fossil lending across geographic borders.

The facts we document in this paper have a number of implications. First, carbon taxes work, not only in directly affecting the cost of production for carbon-intensive firms, but also by impacting the willingness of banks to extend credit to carbon-intensive projects. Second, to engineer a meaningful reduction in the funding of fossil companies, a carbon tax needs to be global. Third, an effective global carbon tax will hit the hardest the most exposed banks, which calls for acute attention by bank regulators and supervisors.

Data availability

Carbon Taxes and the Geography of Fossil Lending (Original data) (Mendeley Data)

Declaration of Competing Interest

We declare that we have no material interests to disclose pertaining to the research in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jinteco.2023.103797.

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