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Abstract

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JEL Classification: C92, D62, D85, Q54

Keywords: Network formation

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Network formation with publicly noxious but privately profitable agents: an experiment *

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January 29, 2025

Abstract

We study experimentally a new model to study the effect of climate externalities and contractual incompleteness on network formation. We model a network where good/green firms enjoy direct and indirect benefits from linking with one another. Bad/brown firms benefit from having a connection with a good firm, but they are a cost to both direct and indirect connections. In efficient networks the green firms should form large connected components with very few brown firms attached. The equilibrium networks, on the other hand, have many more brown firms attached, and components are also smaller than the efficient ones. Our experiments show that empirical results are broadly in line with the theoretical equilibrium predictions, although the precise quantitative outcomes are different from the theory.

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Keywords: Network formation, climate change, contractual externalities, efficiency and equilibrium.

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1 Introduction

The interconnected structure of the economy plays a crucial role for social and economic outcomes. In many circumstances, economic shocks arrive from connections between different kinds of agents. Specifically, the world is already experiencing large shocks derived from climate change, and these shocks are going to get larger as the decades pass. Some of those shocks will arise directly form the climate, but others will come because of the transition and adaptation of the economy that will make some economic activities obsolete or undesirable. The effect of these expected or realized shocks will shape the pattern of linkages that the agents want to undertake.

We analyze experimentally the predictions of a model (derived from Cabrales and Gottardi 2024) to study this phenomenon. The model is applied to a production system where there are two types of firms who interact for the sale of their outputs. One type is that of sustainable (*green*) firms. Connections between *green* firms are beneficial for all the (*green*) firms that are directly or indirectly connected with them. The other type is that of (*brown*) firms, whose activity has adverse consequences for the environment. The connection between a *brown* and a *green* firm is beneficial for those two firms directly involved in the relationship. But the *green-brown* connections generate negative externalities for the rest of the firms with which they are connected.

The tractable nature of the model allows us to characterize and establish the properties of efficient and equilibrium networks. We refer to the green firms as the *firms*, and to the brown firms as the *investments*. The efficient networks in the context of our set-up have the property that every firm establishes a set of connections with an appropriate number of other firms, and those connections are organized in a set of minimally connected components that are symmetric (i.e. all of the same size). At the same time, each firm establishes connections with a number of *investments*, sometimes none. The number of the connections is shaped by the consideration that the costs of the connections between the firms and their investments are borne by all the firms of the component, and thus it is efficient to limit the number of *investments* for each firm.

Equilibrium networks are shaped by the incentives of any pair of firms to establish linkages. As in most of the network literature, we consider a notion of equilibrium that allows for bilateral deviations to avoid trivial coordination failures. Equilibrium and efficient network structures differ in several dimensions. First, the number of firms present in all components in equilibrium is smaller than the socially efficient one. In contrast, the number of *investments* formed by any firm in equilibrium is larger than at the social optimum. This is due to the fact that when an investment is made, the partners do not take into account the (negative) effects this linkage has on other firms in the component. Interestingly, this has additional effects on the network structure: it becomes in fact less profitable for a firm to form linkages with other firms, since such linkages expose the firm to an excessively large number of investments. As a result, firms establish too few connections among them.

1.1 Related literature

Our paper connects with several strands of the literature.

The classical economics networks literature already put a lot of emphasis on the tension between efficiency and stability/equilibrium in network formation (see e.g. Goyal 1993, Bala and Goyal 2000, Jackson and Wolinsky 1996). Those papers find the number of connections formed to be excessively large (small) because the agents forming the network do not take into account the negative (positive) externalities their linkages create on other agents.

More recently, there is a literature studying externalities in fixed networks. Bramoullé, Kranton,and D'Amours (2014) show that in a public goods context, contributions are determined by the minimal eigenvalue of the network. Elliott and Golub (2019) propose a model where agents create externalities in a network. They show that eigenvector centrality is essential to understand what are the contributions that lead to Lindahl outcomes. This allows them to identify essential players, efficient negotiations, and team formation. In contrast with that literature, our paper focuses on the interaction between the externalities and the formation of networks.

A relatively large literature deals with network formation under externalities (see e.g. Joshi, and Mahmud 2016, Buechel, and Hellmann 2012, Morrill, 2011, or Carayol, Roux and Yıldızoglu. 2008) . Our innovation lies in emphasizing how the externalities from one kind of link affect the creation of a different kind of link, and on the experimental nature of the work.

There is some literature dealing with firm networks and climate shocks (see e.g. Grover, and Kahn 2024, Pankratz and Schiller. 2024, König, and Zilibotti 2022, Hallegatte, and Tabourier 2012). This literature tends to focus on the value of networks for adaptation to exogenous shocks, and on supply chain endogenous formation in the presence of shocks. Our contribution is to understand the network formation implications of firms with different sustainability profiles and the emphasis on a tight experimental control.

Finally, we connect with the experimental literature on network formation (Rong and Houser 2015, Callander and Plott 2005, Corbae and Duffy 2008, Charness, Corominas-Bosch and Frechette. 2007, Charness, Feri and Meléndez-Jiménez 2014), which unlike us, tends to concentrate on empirical equilibrium selection and the shape of the networks that form. One exception is Chen, Lane, and McDonald (2024) which does focus on formation with local public goods, which is a little more related to our focus, although still somewhat distant as there is a single type of agent, and none of them cause an externality.

Our paper is organized as follows. Section 2 describes the theoretical model, together with its microfoundations, and characterizes efficient and equilibrium network structures. Section 3 describes the experimental design. Section 4 is devoted to the experimental results. Section 6 then concludes.

2 Model, equilibrium and efficiency

The model on which the experiment features firms who have a number of connections with one another, but they also have "investments". We should think that the firms provide services to customers who become the "investments". A linkage between the firms is beneficial for both, and the investments have direct benefits for the firm which does it. But a critical assumption of the model is that the investments of our firms create a negative externality on everyone that is connected to them. To understand this externality, note that our leading interpretation of the model is that the customers who represent the investments are climate-change-inducing, *brown* firms.[1] Each of them benefits from a contact with a clean *green* firm (which, say, supplies them an input or finance) but the partners of the green firms are in turn negatively affected by that investment. We expand on this explanation in the next subsection.

We denote the investments of a firm i, as y_i. The payoff from investments $I(y_i)$ has decreasing marginal returns:

$$I(y_i) = gy_i - \frac{c}{2}y_i(y_i - 1) \tag{1}$$

The key payoff relevant features of a network are then described by the following variables: for each firm i, N_i is the set of firms connected to i. Then $n_i^y = \sum_{j \in N_i} y_j$ is the number of "investments" of the contacts of i.The parameter g is the unit return of the investment, and c is the parameter associated to the quadratic the cost of the investemnts.

The payoff of each firm depends then on the properties of the network described by the above parameters Denote by Γ the network formed among the firms in the economy. The payoffs for a generic firm i is

$$u_i(\Gamma) = f(n_i) + I(y_i) - pn_i^y \tag{2}$$

The (concave) $f(.)$ function describes the benefits a generic firm i obtains from its linkages to other firms. All such linkages provide a benefit to i, there is also a linearly increasing cost in the total number of existing linkages with parameter p.[2] The firms are the "normal", non-externality inducing agents.

Microfoundation: sustainability As mentioned earlier, our preferred interpretation is that firms operate in a production network. Each firm can rely on supplies coming from - and going to - other firms in the network, which are sustainable (let's say "green"). The marginal benefits coming from the size of that network are decreasing, hence the decreasing returns in $f(.)$.

[1] Or they produce other environmental problems.

[2] We can interpret the linkages to other firms as providing risk sharing/trading possibilities among them (hence the concavity), something quite reasonable for big intermediaries in the financial markets, for example.

A firm can also rely on (or provide) supplies from/to other, firms. These are the "investments," and we think of them as unsustainable ("brown"). The contact with a brown "investment" generates a cost for the firm's contacts. This could be related with the fact that the "investments" are more susceptible to climate change risk (which could be transition risk or physical risk). The transition towards a greener economy means in fact a brown firm is more likely to disappear abruptly, either because people stop using GHG emitting technology (many technologies exhibit strong network complementarities, so changes can be abrupt), or because of regulation shifts. This means the "investments" are less reliable in their supply activities or as customers, and this generates a cost not only for their direct partners, but also other firms in the network.

Equilibrium To solve the game, we first think of the optimal number of investments each firm is going to make. Given the investment function is increasing and strictly concave, the optimal decision is:

$$\overline{y}_i = \frac{g + \frac{c}{2}}{c} \tag{3}$$

then, the utility of every firm as a function of n_i is

$$u_i(\Gamma) = f(n_i) + \frac{1}{8c}(c + 2g)^2 - pn_i\left(\frac{g + \frac{c}{2}}{c}\right) \tag{4}$$

and since $f(n_i)$ is assumed to be increasing and concave the desired $\overline{n}_i$ will solve

$$f'(\overline{n}_i) - p\left(\frac{g + \frac{c}{2}}{c}\right) = 0 \tag{5a}$$

Efficient networks We now compute the network structure that maximizes the sum of welfare for the network members.

$$\sum_i u_i(\Gamma) = \sum_i \left(f(n_i) + I(y_i) - pn_i^y\right)$$

Since all the agents are the same, it is equivalent to maximize the per capita payoff.

From this, it is easy to see that the optimal y_i, once the externality created by y_i on other network members, is taken into account will solve:

$$g + \frac{c}{2} - cy_i - pn_i = 0$$

so that

$$y_i^* = \frac{g + \frac{c}{2} - pn_i}{c} \tag{6}$$

and then n_i^* maximizes

$$\begin{aligned} & f(n_i) + g\frac{g - pn_i}{c} - \frac{c}{2}\left(\frac{g - pn_i}{c}\right)\left(\frac{g - pn_i}{c} - 1\right) - pn_i\left(\frac{g - pn_i}{c}\right) \\ = \; & f(n_i) + \frac{(g - pn_i)^2}{2c} + \frac{1}{2}(g - pn_i) \end{aligned}$$

Then, the efficient n_i^* solves:

$$f'(n_i^*) - p\left(\frac{g + \frac{c}{2} - pn_i^*}{c}\right) = 0 \tag{7}$$

Comparison of efficient and equilibrium networks. The following elementary proposition can be derived:

PROPOSITION 1. *$y_i^* < \overline{y}_i$ and $n_i^* > \overline{n}_i$*

Proof. $y_i^* < \overline{y}_i$ is immediate from comparing 6 and 3 and $n_i^* > \overline{n}_i$ is true because by comparing 7 and 5a one notices that the marginal benefit of n_i is the same in both cases, but the marginal cost is larger in equilibrium $p(((g+(c/2))/c))$ than in the efficient solution. $p(((g+(c/2)-pn_i^*)/c))$. □

The economic significance of this result is that in equilibrium there is an excessive level of intermediation $\overline{y} > y^*$ as each firm does not internalize the consequences that investing has, in terms of higher risk exposure, for all its contacts. We then see that firms respond to this by reducing the linkages among them. We thus have an inefficiently low level of risk sharing among firms, who anticipate the formation by each of them of a large number of harmful investments. This shows there is an interesting interaction between the departures from efficiency in the two layers of the network.

For the other interpretations of the model the implications are also interesting. In the production network case, the equilibrium features each sustainable firm having too many investments with cheaper and less sustainable partners. As a consequence of the risk and instability those connections bring to the groups of firms connected among them, these groups end up being smaller than optimality would prescribe.

3 Experimental Design

In the experiment, all the participants were firms who made investments and chose (up to 9) connections with other participants. These connections brought some revenues (the $f(.)$ function in the model. This function was specified as follows:

Connections	Points
1	10
2	19
3	27
4	34
5	40
6	45
7	49.5
8	53.5
9	57

Connecting with other participants also had costs, associated with the *investments* they had. If a participant connected to a participant who had y investments, she lost p points for each of them, for a total of yp points.

In each round of the game, the players decided how many investments they wanted to have and they could also propose to other participants to create a connection (and they may also have received connection proposals). In order for a connection to be created between participants, both had to agree.

Each round consisted of three phases. In the first phase they were simply asked how many *investments* they wanted to have. They then moved on to the second phase, where they decided how many proposals they wanted to make. Finally, they moved on to the third and final phase. In that phase, when there are matching proposals (two people had made mutual proposals), those connections were automatically established. Second, they saw information about proposals they had received and that they had not made, and they could decide whether to accept them or not. After that, they were taken to the round results screen, which showed the participants they had connected to and the profits made in the round.

All the groups had 10 participants, and there were 15 rounds.

Treatments and predictions There were 4 treatments in the experiment. All of them used the same $f(.)$ function described above, but the other parameters differed. We wanted to have sessions with high and low gains from investments, and with high and low externalities.

Treatment 1 $g = 9$, and $c = p = 6$

Prediction: $\overline{y} = 2, \overline{n} = 0, u_i\left(\overline{\Gamma}\right) = 12; y^* = 0, n^* = 8, u_i\left(\Gamma^*\right) = 53.5$

Treatment 2 $g = 5$, and $c = p = 4$

Prediction: $\overline{y} = 2, \overline{n} = 2$ or $3, u_i\left(\overline{\Gamma}\right) = 17; y^* = 0, n^* = 8, u_i\left(\Gamma^*\right) = 53.5$

Treatment 3 $g = 9$, and $c = p = 2$

Prediction: $\overline{y} = 5, \overline{n} = 0, u_i\left(\overline{\Gamma}\right) = 25; y^* = 0, n^* = 8, u_i\left(\Gamma^*\right) = 53.5$

Treatment 4 $g = 5$, and $c = p = 0$

Prediction: $\overline{y} = 9, \overline{n} = 8, u_i\left(\overline{\Gamma}\right) = 25; y^* = 0, n^* = 8, u_i\left(\Gamma^*\right) = 53.5$

Payoffs The show-up fee was 5 euros, and the exchange rates between points and monetary payments was 2 cents of a euro per point.

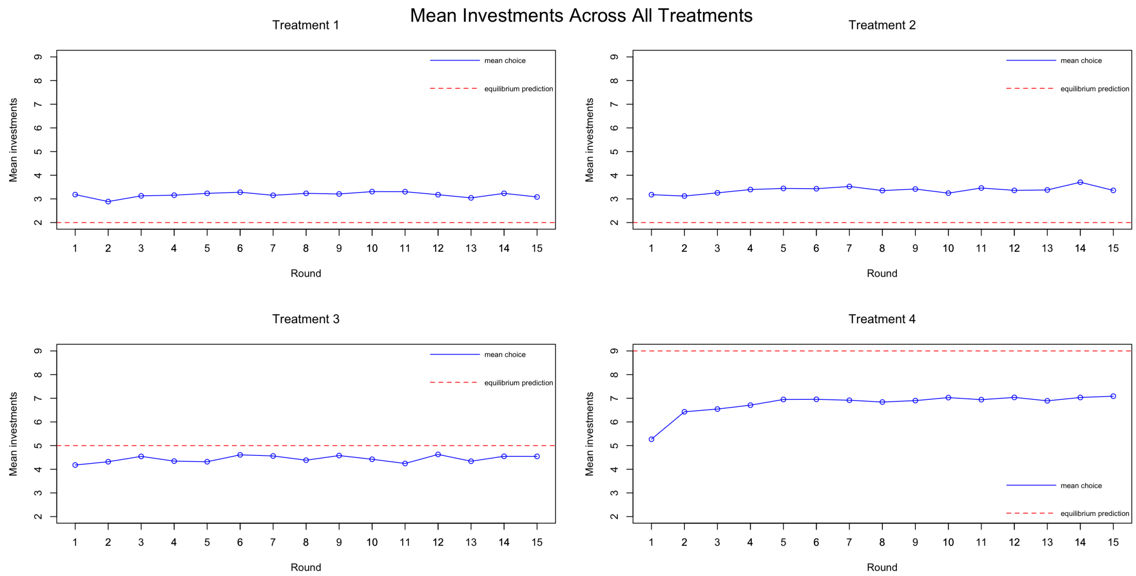

Figure 1: Evolution of investments in each treatment

4 Results

We begin with an overview of the dynamics of choices across the different treatments in the experiment. Figure 1 shows the evolution of choices of investments, while Figure 2 shows the dynamics of connections. In this latter figure we represent the number of active connections at the end of the round in the third phase.

Although participants do not choose the number of investments and connections as predicted in equilibrium, in general they increase or decreased as expected. Particularly, if the benefits of an investment are higher, we expect that the number of investments is higher and the number of connections are lower, since each individual expects that their connections have a higher number of investments that create a cost on them. Also for higher costs of investments, participants should choose fewer investments. Finally, for higher costs of connections, we expect that individuals choose fewer connections.

Considering the level of choices of the participants, we observe that in general they tend to smooth their decisions. That is, when the equilibrium predicts that they choose high levels of investments or connections, they choose lower levels than the equilibrium. Moreover, the opposite happens when the equilibrium quantity for investments or connections is low. This could be explained if participants make noisy/mistaken decisions. But when predictions are at the maximum or minimum, the mistakes can only go in one direction, so it biases the deviations down or up respectively. Palfrey and Prisbrey (1997) first noticed a similar phenomenon in VCM public good games where the equilibrium prediction was a zero contribution. They showed that when the equilibrium predictions for contributions were interior, they were on average in line with the observations, but when they were zero, the contributions were high. All these observations can be easily explained in a quantal

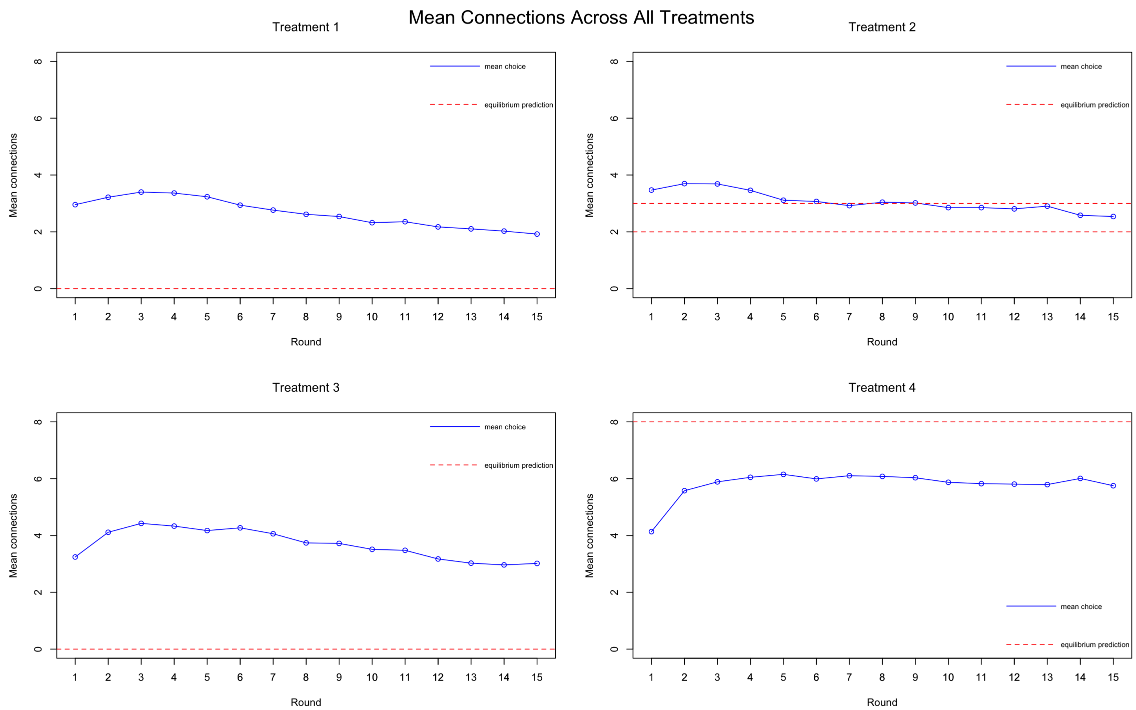

Figure 2: Evolution of connections in each treatment

response equilibrium framework (McKelvey and Palfrey 1995).

Table 1 shows the results of the Mann-Whitney tests for the first round, comparing the distributions of the choice of investments and connections across the different treatments. For the choice of investments, the test results are consistent with the model predictions, specifically that the number of investments in treatment 1 and 2 are equal and lower than in treatment 3, and the number of investments in treatment 4 is higher than in all the others ($t1 = t2 < t3 < t4$). In contrast, the findings for the choice of connections generally align our predictions but reveal some inconsistencies. Particularly, we fail to reject that the number of connections in treatments 1 and 3 is equal, as we expected. Moreover, we confirm that the number of connections in treatment 1 is significantly lower than in treatments 2 and 4, while treatment 3 exhibits a lower number of connections compared to treatment 4. However, we cannot reject the null hypothesis that the number of connections in treatment 2 is greater or equal to that in treatment 4, nor that in treatment 3 is greater or equal to that in treatment 2, which do not align with the model predictions.

Table 2 presents the regression analysis for the first round of the experiment. We can observe that there is a positive relationship between the benefits of investments and the number of investments that participants choose, although the effect is not significant. In addition, the relationship between the benefits of investment and the connections is negative and significant. This indicates that the participants take into account that the investments of the other participants connected to them create a negative externality on them.

Table 1: Mann-Whitney tests for the first round

	p value Investments	p value Connections
t1=t2	0.708	
t1<t2		0.020
t1<t3	0.000	
t1=t3		0.460
t1<t4	0.000	0.015
t2<t3	0.000	
t2<t4	0.000	0.266
t3<t2		0.117
t3<t4	0.000	0.079

Table 2: OLS regression of Choice in Equilibrium in the first round

	Investments	Connections
Benefits of investments (g)	0.056	−0.117***
	(0.183)	(0.001)
Cost of investments (c)	−0.388***	
	(0.000)	
Cost of connections (p)		−0.120***
		(0.000)
R^2	0.116	0.048
N	940	940

Standard deviations are given in parentheses.
***p<0.01

We also observe that the relationship between the cost of investments and the number of investments in negative, as we expected. Similarly, the cost of connections and the number of connections have a negative relationship.

5 Policy implications

Networks and network externalities underlie many global challenges, including climate change and biodiversity loss, and extend to any scenario where parties fail to account for the harm or risk their counterparties may pose. Policymakers are increasingly aware of connectivity, network topology, and diffusion dynamics, yet often struggle to address them effectively. This study's findings can inform the design of interventions that move equilibrium networks closer to efficient outcomes. We highlight two key policy areas where these insights are especially relevant: (i) supply chain legislation and (ii) bank prudential regulation.

5.1 Supply Chain Legislation

Laws such as the Corporate Sustainability Due Diligence Directive (CSDDD/CS3D), the French Due Diligence Law, and the German Supply Chain Act require companies to map their supplier links and address "adverse impacts" on the environment or human rights (Articles 8–9 CS3D). The experiment indicates that firms in equilibrium "over-connect," failing to account for the negative externality created by "brown" firms for indirectly connected players. Legislation that exposes and penalizes these indirect externalities is thus more likely to reduce such over-connection.

Crucially, the CSDDD covers "direct" and "indirect" business partners, unlike the German Act, which adopts more lenient rules for indirect links. Since the externality arises through indirect connections, laws that stress indirect responsibilities have a better chance of steering networks toward efficient outcomes.

In practice, however, supply chain legislation focus on cooperative measures: firms must address adverse impacts by, e.g., seeking contractual assurances accompanied by compliance mechanisms, increasing investments, providing financial support, etc. (Articles 10 (1) – (5) and 11 (1) – (6) CS3D) and treat termination of contracts as a "last resort" (Articles 10–11 CS3D). This logic assumes large firms can influence their suppliers "vertically." However, in "horizontal" networks (as modelled in this experiment), firms cannot turn "brown" partners "green." Instead, the efficient outcome involves "green" firms clustering together, connecting less with "brown" firms. Regulators and courts should recognize that in horizontal networks, termination (or not contracting) is the option when firms have limited influence over their counterparties' behaviour.

5.2 Bank Prudential Regulation

The Basel Framework (incorporated in the EU through the Capital Requirements Regulation (CRR) and Directive (CRD)) sets bank capital based on individual risk exposures (Pillar 1) and overall strategy, governance, and business model considerations assessed through Supervisory Review (Pillar 2). This places an excessive focus on direct links, while our study shows that indirect, network-level risks also matter.

Climate-Related FAQs and Reforms. There is an increasing awareness of climate change and nature-related risks (see Ramos Muñoz, 2024). The Basel Committee has recognized climate and nature-related risks, issuing Frequently Asked Questions (FAQs) to integrate them into Pillar 1, when assessing risk weights (RWs) for Credit Risk Exposures (CRE), i.e., to assess the risk of loss from default, among other things. The European CRR was reformed by the 2023 Banking Package, and it now includes a definition of ESG, environmental, transition, social and governance risks (new Article 4 (52d) to (52i) CRR). The European Banking Authority (EBA) has published guidelines for further reforms (EBA, 2023).

The underestimation of connectivity risk. However, these changes are modest relative to the overall Basel rulebook and still rely on banks to integrate climate risks "to the extent" they affect their regular risks, which means that banks may downplay their impact. Furthermore, the framework is largely focused on banks' most important risk, i.e., credit risk, which is measured as arising from direct exposures. This leaves indirect network risks underrecognized. In fact, Basel's Large Exposures Regime in Basel aims to avoid concentration with any single borrower or group. This makes sense to avoid idiosyncratic risk through diversification, but it inadvertently encourages more connections and potentially increases system-wide risk.

Thus, the study's implications go beyond climate and nature-related risks, suggesting that the Basel Framework may not only be unaware of climate- and nature-related risks, but about network dynamics. Some measures try to compensate for this, like systemic risk buffers, which use connectivity as a proxy for systemic risk. However, such systemic-risk buffers target large, systemically important banks (SIBs), not the broader connectivity problem of smaller players. Over-connection can spread risk even if no single institution is "too big to fail."

Pillar 2 and Climate Stress Tests. Pillar 2 addresses risks beyond direct exposures. Recently, both the Basel Core Principles and the European CRD have been updated to incorporate climate-related risks, in a more assertive way than under Pillar 1, including requiring banks to adopt "risk-based transition plans" (see Ramos Muñoz 2024). Supervisors are encouraged to use scenario analysis and stress testing (ECB, 2020), using the methodology of the Network for Greening the Financial System (NGFS) scenarios. The

"Fit-for-55" exercise by European authorities acknowledges that it is challenging to capture "all potential transmission channels of climate-related shocks, which might lead to an underestimation of losses especially in the adverse scenarios" (Fit-for-55, para. 10).

Pillar 2 measures are more assertive, but limited, as they can only focus on individual institutions. Instead of "climate stress tests" system-wide exercises are called "scenario analyses" or "exploratory" or "pilot" exercises (Fit-for-55, 2024, BoE, 2021, US Fed 2024) to avoid suggesting that they may trigger higher capital requirements for banks heavily exposed to climate risks (as a conventional stress test can do).

In light of our findings, authorities are right to model contagion and second-round effects. They should deepen network analyses to understand how "over-connection" can spread risk. The "Fit-for-55" study's suggestion that banks may finance the transition under benign conditions underscores a deeper need: banks and other institutions must reorganize their links to reduce network externalities. Policymaking that incorporates network dynamics more forcefully is crucial to avoid repeating the mistakes of the 2007–2008 crisis.

Summary Overall, these results highlight the importance of indirect links and network topology in both supply chain legislation and bank prudential regulation. Lawmakers and regulators should address over-connection more explicitly—exposing indirect externalities, encouraging the formation of "green" clusters, and refining macro-prudential measures to capture over-connectivity risks, and stress-test frameworks to capture second-round network effects. Only by acknowledging and correcting for these dynamics can policy interventions push networks toward more efficient and resilient outcomes.

6 Conclusions

We have analyzed a stylized model of link formation between agents who engage in intermediation activity with others, and do not internalize default contagion externalities. The main results we obtain are as follows. The efficient structure cannot be obtained as a result of individual decisions, because those decisions lead to excessive intermediation activity and this in turn limits the extent of connections in the system. Our experimental results validate the model in general lines, although there are some departures when predictions are at the boundaries.

These results suggest that regulatory interventions could be beneficial. It is unlikely that one can simply rely on contracts internalizing contracting externalities. A network is a very complex object and there is a limit to contract complexity. Further work should analyze the feasibility of different interventions in this kind of system.

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