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The Environmental Responsibility of Firms and Insurance Coverage in an Evolutionary Game

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Abstract
Climate change can deeply impact a company's business performance, therefore insurance is an important tool to mediate such a risk, helping firms to remain on the market. Polluting companies want to maximize profits according to different business strategies and that appeal to their risk attitude. Firms are Nash players in an oligopoly market adopting two production technologies, brown or green. Climate change loss is a function of the firms' emissions and is considered endogenous in the maximization problem of the players. We study firms' behavior in choosing their more profitable strategy through a random matching evolutionary context. Analysis of the model reveals that the dynamic system admits at most seven stationary states. The paper focuses on the regime in which all the possible strategies coexist, due to its economic relevance. Moreover, the results of the sensitivity analysis show interesting policies to nudge an ecological transition.

Keywords Evolutionary game dynamics · Environmental damage · Insurance coverage · Environmental firms responsibility · Oligopoly market

1 Introduction

Insurance is the main way to transfer risks on a company's business, in particular when the risk referred to is climate change, namely in this paper the economic impact of pollution. The research wants to concentrate on the analysis of the possible impact of climate risk insurance policies on the behavior of a polluting company that operates according to the criterion of profit maximization.

There is a lot of specialized literature that proposes empirical evidence of climate changes effects caused by polluting behavior [5]. Air pollutants have an evident relationship with climate change: some pollutants induce warming while others have a cooling effect on the climate. This phenomenon could be represented by the double face of a coin. Climate change

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mitigation actions can help reduce pollution, furthermore, reducing air pollution levels have immediate and significant effects, decreasing the possibility of triggering dangerous climate tipping events. It has been highlighted in numerous studies that the distribution of emissions in the air is not strictly connected to the place where harmful climatic events have occurred based on meteorological phenomena. For this reason, some authors [16] have proposed models that present a sharing of costs according to various countries' payments. Many countries have found introducing laws that impose cleaning costs for companies with polluting businesses to be an effective persuasion. In some countries, banks that finance polluting activities have been considered equally responsible and consequently some of them now prefer to finance investments in green assets. There are models (see for example [9]), in which the insurance sector covers the risk of pollution and the banking sector provides financing for "clean" activities. The clean-up fees are so high that a possible strategy could be the use of insurance coverage. Merrifield [27] proposes an insurance bonding approach to pollution threats. Freeman and Kunreuther [18] present models in which private insurance can be used as a useful tool for achieving compliance with environmental policy directives.

Insurance company support is necessary to reduce the risk of business loss of a polluting company. Recent studies have also analyzed the potential of insurance regarding the coverage of production losses due to weather events [10]. In 2013 the European Commission published the Green Paper on the insurance of natural and man-made disasters to stimulate insurers to manage climate change risks. However, climate change in recent years has had adverse impacts on the affordability and availability of the insurance industry [28, 29]. Herweijer et al. [19] show that, in the long run, the concept of insurability could be put at risk, as it is difficult to adapt the quantification of the damage in areas with increasing risk, consequently limiting the economic availability of private insurance coverage or the accessibility of its price. Recent studies use the adaptive cycle in climate change risk to reduce the costs of insurance [13]. Insurance indeed plays a vital role in helping to develop understanding about the risk associated with climate change and in promoting measures to protect against losses caused by climate change itself.

We know that climate change is causing more and more economic losses connected to natural disasters and unfortunately these risk variables are increasing. Bostrom et al. [8] study self-efficacy measures to demonstrate the possibility of reducing climate change riskness according to different compliant firm's actions. The risk mitigation measures adopted and how they are communicated to the different stakeholders can have varying impacts on the real reduction of the risk. Insurance can support a firm's reduction strategies.

Very recent studies have focused on the effects of different financial incentives, on the different probability levels, and deductibles in a natural disaster insurance market under the assumption of mandatory coverage [30]. In particular, the authors analyzed how investments are influenced by different financial incentives coming from the insurance market. Some studies site in evidence that a wide class of environmental risks are now strongly subject to moral hazard behaviors [25]. This condition could lead us to believe that covering a firm's business with insurance allows it to operate with complete disinterest to that same risk. Different authors [21, 30] also present in their study the influence of behavior, due to the different inclinations toward risk. The analyzed sample in Mol et al. [30] shows that the green investments increase when the expected value of the damage increases. The result is affected by moral hazard, but it is detected only in the scenarios with a high probability of occurrence, and not in the low ones. Moral hazard appears to be of lesser magnitude in an insurance market where the odds are relatively low. Recent studies [3, 4] show how polluting companies operate in a regulated market through the purchase of permits to pollute. Companies that adopt non-polluting technology do not need permits to operate, while companies that use polluting technology can purchase permits and continue to pollute. Only the regulator can try to drive out companies without permits out of the market, but an overall equilibrium can only be reached under particular model conditions.

It has been highlighted above that the insurance sector plays an essential role in mitigating climate change loss. In our paper, we analyze whether it is possible for insurance to play an active role towards an overall improvement in pollution. Since the insurance market is in continuous evolution, insurers are always interested in creating flexible policies in order to reach more specific segments of the market in which they operate [1, 6, 12, 26, 32] to gain greater possibility of expansion of their market share and greater efficiency of the coverage using information relating to policyholders' behavior, which allows for shaping individual profiles to base an insurance policy on. The insurer could propose coverage that takes into account the polluting behavior of the insured company according to different premiums. Polluting firms, through their insurance coverage, can mitigate their climate change losses, reducing their negative impact on profits. In such a way, different business strategies can coexist on the market. Therefore, it will be interesting to study whether an insurance policy results in the strategic leveraging of a polluting company to carry on polluting behavior or instead be an incentive to favor a more voluntary environmentally friendly business without the interaction of the regulator.

This paper will first present a static game in which polluting companies want to maximize their profit under three different business strategies. Firms can be risk averse or risk neutral and can adopt brown or green technology for their production activities. To protect themselves against climate change loss, firms can choose the optimal level of insurance coverage under the expected utility paradigm. Companies operate in a Cournot oligopoly game as Nash players and consider climate change loss as endogenous in the profit maximization problem. In a second stage, firms can select their strategy through a random matching evolutionary context. The dynamics is determined by the replicator equation, a learning process where agents compare the payoffs of the alternative existing strategies adopted on the market and choose the most remunerative one (for further details, see, among others, [14, 33, 36].

The paper is structured as follows. In Sect. 2 we introduce the model and the static game, while Sect. 3 deals with the evolutionary dynamics. Numerical sensitivity analysis will be presented to study the evolution of firms' strategies in Sect. 4. Concluding remarks and highlights will be proposed in Sect. 5.

2 The Model

Let us suppose that a polluting company wants to maximize its profit according to three different strategies: being risk averse and completely disinterested in the environmental impact caused by its behavior (hereafter called D-firm), being risk averse and aware that its behavior contributes to a potential environmental disaster and for this reason adopts a less polluting, but more expensive, technology (A-firm), or, finally, being as in the previous case but risk neutral (C-firm). Each type of firms is subject to the following climate change potential loss:

$$\widetilde{L} = (l, \eta; 0, 1 - \eta) \tag{1}$$

where $l > 0$ represents the value of the loss and $\eta \in [0, 1]$ its probability. From 1 we infer that the expected loss is:

$$\mathbb{E}\widetilde{L} = \eta l$$

Risk averse firms can cover the potential loss (1) subscribing an insurance climate change policy, when economically convenient, according to the choice of a coinsurance rate. Moreover, the three types of firms play in an oligopoly market composed of N firms that produce a unique homogeneous good. We designate m as the number of A-firms and s as the number of C-firms, therefore $N - m - s$ represents the number of D-firms. Denoting A, C, and D-firms with subscripts $i = a, c, d$ respectively, we assume their random profits to be as follows:

$$\begin{aligned} \pi_a &= (R_a - \widehat{P}\gamma_a - (1-\gamma_a)l)\eta + (R_a - \widehat{P}\gamma_a)(1-\eta) \\ \pi_c &= R_c - \eta l \\ \pi_d &= (R_d - \widehat{P}\gamma_d - (1-\gamma_d)l)\eta + (R_d - \widehat{P}\gamma_d)(1-\eta) \end{aligned} \tag{2}$$

where $\gamma_j \in [0, 1]$ (with $j = a, d$) is the coinsurance rate mentioned above, $\widehat{P}$ is the premium for full coverage and R_i represents the market revenues (denoting "brown" and "green" technology costs with subscript $k = b, g$, respectively):

$$R_i = [p - c_k]q_i \tag{3}$$

where

$$p = \overline{p} - mq_a - sq_c - (N - m - s)q_d$$

is the inverse demand function, with $\overline{p} > 0$ representing the reservation price, namely the higher price that the representative consumer is willing to pay and q_i are the output quantities. The costs c_k are strictly positive parameters remembering that A-firms and C-firms adopt the same green technology, while D-firms adopt the brown one. We assume that the green technology is more expensive than the brown one, namely $c_g > c_b$.

According to Schlesinger [34], we define the premium for full coverage as

$$\widehat{P} = (1 + \lambda)\eta l \tag{4}$$

where $\lambda \geq 0$ is the premium loading factor of the coverage given by the insurance market. If the premium is fair, namely $\lambda = 0$, then the optimal coinsurance rate is equal to 1, that is $\gamma_j^* = 1$ (see [31]). Conversely, if the premium is unfair, namely $\lambda > 0$, then $\gamma_j^* \in [0, 1)$. We assume that the loss is a function of the production activities:

$$l = [(N - m - s)q_d + (1 - \theta)(mq_a + sq_c)]\delta \tag{5}$$

where $\theta \in (0, 1)$ captures the reduction of emissions due to the use of green technology (higher θ, lower emissions) and $\delta > 0$ represents the impact of emissions on loss (a measure of the economic severity of the climate change loss).

We assume that firms first choose the coinsurance rate and then the production quantities, as in Seog [35]. A-firms and D-firms choose the coinsurance rate that maximizes the expected utility of their random profit function ($H_j(\gamma_j) = Eu(\pi_j)$, with $H'(\gamma_j) > 0$ and $H''(\gamma_j) < 0$). Adopting a logarithmic utility function, the problem becomes:

$$\max_{\gamma_j \in [0,1]} H_j = \eta \ln(R_j - \widehat{P}\gamma_j - (1-\gamma_j)l) + (1-\eta)\ln(R_j - \widehat{P}\gamma_j) \tag{6}$$

Maximizing (6) and substituting $\widehat{P}$ with (4), we obtain the optimal values of the coinsurance rate:

$$\gamma_j^* = \frac{\lambda R_j - (1-\eta)(1+\lambda)l}{[(1+\lambda)\eta - 1](1+\lambda)l} \tag{7}$$

From (7) we can infer that, if the revenues increase, then the optimal insurance coverage also increases (i.e., $\frac{\partial \gamma_j^*}{\partial R_j} > 0$). We can now move on to the profit maximization problem. As standard in oligopoly theory, each firm takes as given the output quantity chosen by the other firms. Moreover, we assume that companies know that the loss is a function of their emissions. By rearranging the random profits (2), the problem becomes:

$$\begin{aligned}
&\max_{q_a \in [0,+\infty)} \pi_a = R_a - (1+\lambda\gamma_a^*)\eta l \\
&\max_{q_c \in [0,+\infty)} \pi_c = R_c - \eta l \\
&\max_{q_d \in [0,+\infty)} \pi_d = R_d - (1+\lambda\gamma_d^*)\eta l
\end{aligned} \tag{8}$$

The following proposition holds.

Proposition 1 *The optimal values of q_a, q_c, q_d, are given by:*

$$\begin{aligned}
q_a^* &= \{\overline{p} - c_g + (N-m-s)(c_b - c_g) + (2-\theta+\lambda)\delta\eta s^2 + [N^2 - (3-\theta)Nm - 2Ns \\
&\quad + (2-\theta)m^2 + 2ms - (1-\theta)m](1+\lambda)\delta\eta\}\left(\frac{1}{N+1}\right) \\
q_c^* &= \{\overline{p} - c_g + (N-m-s)(c_b - c_g) + [N^2 - 2Nm + (2-\theta)m^2 + 2ms](1+\lambda)\delta\eta \\
&\quad + [(2-\theta+\lambda)s - (3-\theta+\lambda)N - (1-\theta)]s\delta\eta\}\left(\frac{1}{N+1}\right) \\
q_d^* &= \{\overline{p} - c_b - (m+s)(c_b - c_g) + [(2-\theta)m^2 + 2ms + m - Nm - Ns - N + s](1+\lambda)\delta\eta \\
&\quad + (2-\theta+\lambda)\delta\eta s^2\}\left(\frac{1}{N+1}\right)
\end{aligned} \tag{9}$$

Proof The first order conditions of the maximization problem (8) are:

$$\begin{aligned}
\frac{\partial \pi_a}{\partial q_a} &= \frac{\partial R_a}{\partial q_a} - \frac{\partial l}{\partial q_a} - \left(\frac{\partial \gamma_a^*}{\partial q_a} l + \frac{\partial l}{\partial q_a}\gamma_a^*\right)\eta\lambda = 0 \\
\frac{\partial \pi_c}{\partial q_c} &= \frac{\partial R_c}{\partial q_c} - \frac{\partial l}{\partial q_c}\eta = 0 \\
\frac{\partial \pi_d}{\partial q_d} &= \frac{\partial R_d}{\partial q_d} - \frac{\partial l}{\partial q_d} - \left(\frac{\partial \gamma_d^*}{\partial q_d} l + \frac{\partial l}{\partial q_d}\gamma_d^*\right)\eta\lambda = 0
\end{aligned} \tag{10}$$

where:

$$\begin{aligned}
\frac{\partial R_a}{\partial q_a} &= \overline{p} - (m+1)q_a - sq_c - (N-m-s)q_d - c_g \\
\frac{\partial R_c}{\partial q_c} &= \overline{p} - mq_a - (s+1)q_c - (N-m-s)q_d - c_g \\
\frac{\partial R_d}{\partial q_d} &= \overline{p} - mq_a - sq_c - (N-m-s+1)q_d - c_b \\
\frac{\partial l}{\partial q_a} &= (1-\theta)\delta \\
\frac{\partial l}{\partial q_c} &= (1-\theta)\delta \\
\frac{\partial l}{\partial q_d} &= \delta
\end{aligned}$$

$$\frac{\partial \gamma_a^*}{\partial q_a} = \frac{\frac{\partial R_a}{\partial q_a}[(1+\lambda)\eta-1](1+\lambda)l\lambda - \frac{\partial l}{\partial q_a}[(1+\lambda)\eta-1](1+\lambda)\lambda R_a}{[(1+\lambda)\eta-1]^2(1+\lambda)^2 l^2}$$

$$\frac{\partial \gamma_d^*}{\partial q_d} = \frac{\frac{\partial R_d}{\partial q_d}[(1+\lambda)\eta-1](1+\lambda)l\lambda - \frac{\partial l}{\partial q_d}[(1+\lambda)\eta-1](1+\lambda)\lambda R_d}{[(1+\lambda)\eta-1]^2(1+\lambda)^2 l^2}$$

Solving (10), we obtain the values (9). □

Notice that the quantities are a function of the market composition, namely of parameters m and s. For this reason, in the following section we will endogenize firms' business strategies.

3 Evolutionary Dynamics

We assume now an infinite population of firms that are randomly matched in pairs playing a Cournot duopoly game (see, among others, Droste et al. [17] and, more recently, Kopel et al. [23]). Therefore, the payoffs (namely the profits) of adopting a strategy are a function of the type of firm matched. We denote $x_a \in [0, 1]$ as the probability of being matched with an A-firm, $x_c \in [0, 1]$ as the probability of being matched with a C-firm, and $x_d \in [0, 1]$ as the probability of being matched with a D-firm, with $x_a + x_c + x_d = 1$. Moreover, as above, the subscript denotes the strategy chosen, while the superscript refers to the strategy adopted by the market competitor. For instance, π_a^a represents the profits of an A-firm if it is matched with another A-firm. The expected random profits are:

$$\begin{aligned}\mathbb{E}\pi_a &= x_a\pi_a^a + x_c\pi_a^c + x_d\pi_a^d\\ \mathbb{E}\pi_c &= x_a\pi_c^a + x_c\pi_c^c + x_d\pi_c^d\\ \mathbb{E}\pi_d &= x_a\pi_d^a + x_c\pi_d^c + x_d\pi_d^d\end{aligned}$$

Since the shares of the market composition must equal to 1, we can reduce the variables to x_a and x_c, with $x_d = 1 - x_a - x_c$. The dynamic system is assumed to be given by the following replicator equations (see, among others, recent applications of [2, 7, 11, 15, 20, 22, 24]):

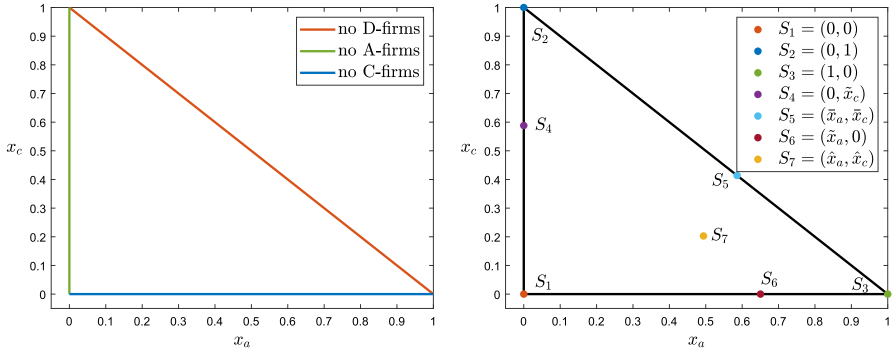
$$\begin{aligned}\dot{x}_a &= [\mathbb{E}\pi_a(x_a, x_c) - \overline{\pi}(x_a, x_c)]x_a\\ \dot{x}_c &= [\mathbb{E}\pi_c(x_a, x_c) - \overline{\pi}(x_a, x_c)]x_c\end{aligned} \tag{11}$$

where $\overline{\pi}(x_a, x_c) = x_a\mathbb{E}\pi_a + x_c\mathbb{E}\pi_c + (1 - x_a - x_c)\mathbb{E}\pi_d$ is the average payoff. The dynamic system (11) is defined in the triangle given by the vertices of coordinates $(0, 0)-(0, 1)-(1, 0)$. In Fig. 1a there is a graphical representation of the three-dimensional simplex. The green line is the invariant axis where $x_d = 0$ (therefore, $x_a + x_c = 1$), the red line is the invariant axis where $x_a = 0$ and the blue line is the invariant axis where $x_c = 0$.

The dynamic system (11) admits at most seven stationary states (see Fig. 1b):

- the point $S_1 = (0, 0)$ in which only D-firms exist;
- the point $S_2 = (0, 1)$ in which only C-firms exist;
- the point $S_3 = (1, 0)$ in which only A-firms exist;
- the point $S_4 = (0, \widetilde{x}_c)$, with $\widetilde{x}_c \in (0, 1)$, in which C and D-firms coexist;
- the point $S_5 = (\overline{x}_a, \overline{x}_c)$, with $\overline{x}_a + \overline{x}_c = 1$, in which C and A-firms coexist;
- the point $S_6 = (\widetilde{x}_a, 0)$, with $\widetilde{x}_a \in (0, 1)$, in which A and D-firms coexist;
- the point $S_7 = (\widehat{x}_a, \widehat{x}_c)$, with $\widehat{x}_a + \widehat{x}_c < 1$, in which all three types of firm coexist.

The points S_1, S_2, and S_3 always exist. Due to the complexity of the model we concentrate our analysis on the most relevant economic scenario: where all the three strategies coexist



(a) Simplex. **(b)** Stationary states.

Fig. 1 Graphical representation of the simplex and of the stationary states

Table 1 Parameter set

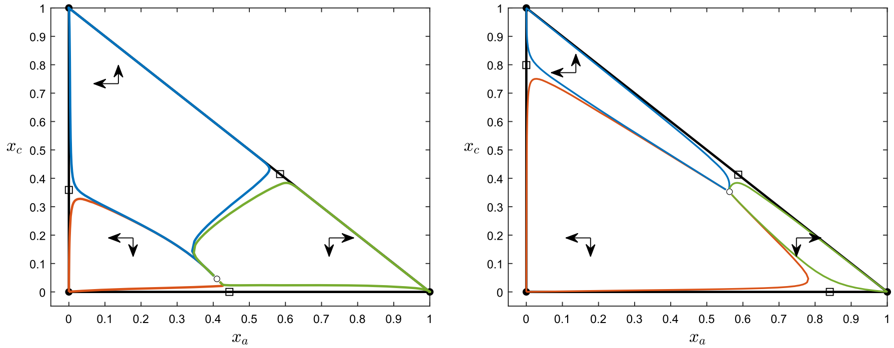
Function	Description	Value
$\overline{p}$	Output market reservation price	5
c_b	Marginal cost of brown technology	1
η	Loss probability	0.2
c_g	Marginal cost of green technology	1.5
θ	Abatement share of green technology	0.75
δ	Severity of loss	3.5
λ	Premium loading factor	0.15

at the equilibrium. Therefore, we consider a parameter set such that all the seven stationary states exist, see Table 1. From the numerical stability analysis it emerges that the states S_1, S_2 and S_3 are stable, the states S_4, S_5 and S_6 are saddle points, and, finally, the state S_7 is unstable (see ”Numerical stability” in the Appendix). We are aware that a numerical analysis does not cover all possible regimes that may arise from the dynamic system (11). However, we focus on an economically significant case where all the seven stationary states exist. Moreover, the parameter set used complies with several constraints, as non-negative quantities and coinsurance rates between 0 and 1. Even if a different parameter set, such that the seven stationary states exist, should be used, the stability nature of the equilibria does not change, so the simulations performed are even representative of alternative parametric scenarios.

Having defined the market business strategies, the model and the possible stationary states that may arise, we now introduce in the next section a numerical sensitivity analysis to study the firms’ behaviors and to derive policy implications to nudge an ecological transition.

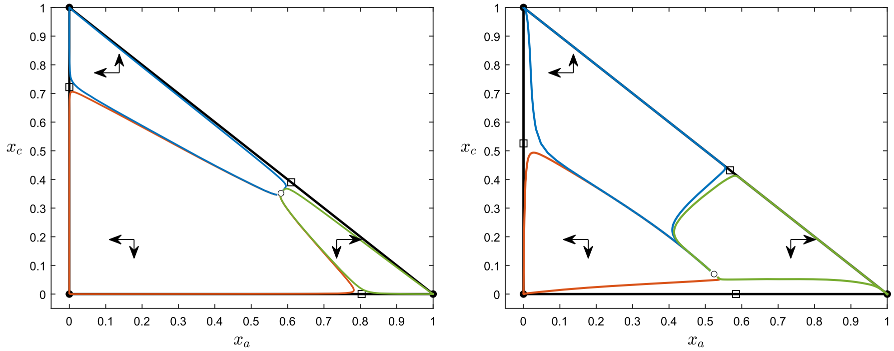
4 Sensitivity Analysis

In the present section we perform numerical simulations to analyze firms’ behavior varying some key parameter values, namely the green technology cost, the reduction share of emissions on the environmental damage, the impact of production activities on the loss and the insurance coverage premium loading. The dynamics presents three basins of attraction



(a) $c_g = 1.35$. **(b)** $c_g = 1.65$.

Fig. 2 Basins of attraction for relatively low and high values of green technology cost. Legend: • attractor, ∘ repellor, □ saddle point

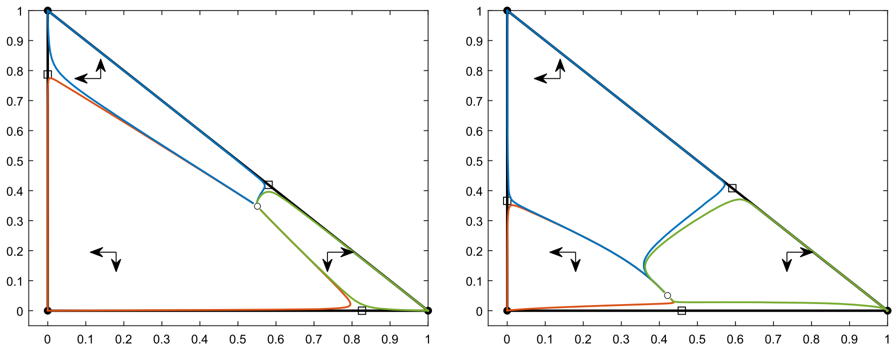


(a) $\theta = 0.4$. **(b)** $\theta = 0.88$.

Fig. 3 Basins of attraction for relatively low and high values of emissions' reduction technology. Legend: • attractor, ∘ repellor, □ saddle point

according to which we can observe the change when implemented into the firm's strategies and, consequently, the composition of the market. We show the basins of attraction according to different parameter values.

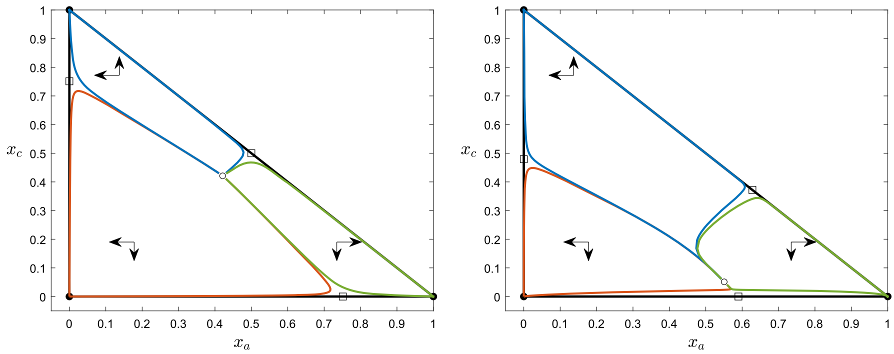
Consider the possibility that green technology evolves and becomes more accessible to firms at a lower cost (c_g). This situation can arise, for example, with new innovative methods for the production of goods, their distribution and use, or simply, as incentives given by institutions nudging towards an ecological transition that leads to lower overall costs. Figure 2 shows three attractor points (0, 0), (0, 1) and (1, 0), which correspond respectively to points S_1, S_2 and S_3 of the stationary states in Fig. 1b. In these points only a single type of firm is present on the market for each of them: D, C or A respectively. We can see even three saddle points lying on the invariant axes where only two strategies exist that correspond to the states S_4, S_5 and S_6 (see Fig. 1b). Finally, notice that there is a repulsive point (S_7 of Fig. 1b) from which the trajectories representing the basins of attraction start. If you look at the arrows in Fig. 2a, you can observe the movement of C, D and A strategies due to the reduction of green technology cost while the brown one remains the same. Figure 2b shows the opposite case in which we have an increment in green cost. Comparing the two graphs Fig. 2a, b it is evident that the basin of attraction of D-firms (red trajectories) presents a bigger dimension



(a) $\delta = 2.75$.

(b) $\delta = 4.5$.

Fig. 4 Basins of attraction for relatively low and high values of environmental damage severity. Legend: • attractor, ∘ repellor, □ saddle point



(a) $\lambda = 0$.

(b) $\lambda = 0.25$.

Fig. 5 Basins of attraction for relatively low and high values of premium loading factor. Legend: • attractor, ∘ repellor, □ saddle point

in the case of high level green technology costs with respect to the other two firm typologies, C (blue trajectories) and A (green trajectories), which both have to support the same change in green technology costs.

It is also evident that a green cost containment policy will therefore favor transition towards a more sustainable economy. It is frequent news that large companies, which contribute the most to pollution levels rising, are engaged in campaigns to reduce their emissions and act towards climate change containment.

Will investments in effective emission reductions impact the type of companies on the market? Will there be a consequent increase in companies compliant with environmental standards on the market? In our model we modify the level of emissions reduction (θ). We provide two different graphs where a lower efficiency share is considered in Fig. 3a and vice versa in Fig. 3b. Greater emissions reduction (see Fig. 3b) reduces the basin of attraction of D strategy (i.e., the point (0, 0)) towards a bigger presence on the market of A and C-firms. Reducing emissions consequently reduces damage and the expected loss decreases. If the efficiency of green technology increases, the environmental damage decreases, so that the insurance premium will be lower and the probability of finding A-firms on the market will be higher. Less damage implies higher profits in general, so we have a positive effect even on C-firms. If the companies do not undertake to favor a reduction in emissions, the negative impact on the damage is so considerable that it determines little basins for the survival of environmentally engaged companies, whether they are risk averse or not. The higher expected value of the damage, and consequently the higher price of the insurance policy, reduces the profitability of the D business.

Let's now analyze the impact of emissions on the loss. The parameter δ measures the impact of production on climate change that determines the damage. Climate change accelerates as the overall output quantity produced by companies A, C and D increases. The higher the δ impact is, the greater the speed of climate change is. The parameter δ can therefore be interpreted as the economic severity that the production of the good has on climate change.

Figure 4a shows a lower δ than in Fig. 4b, highlighting how the basin of attraction of D strategy is reduced in favor of C (i.e., the point (0, 1)) and A strategies (i.e., the point $(1, 0)$). If the severity is very high, climate change is accelerated, resulting in a higher expected loss. This eventuality, since the companies still have to remain on the market, would force them to be more environmentally compliant. The basins of attraction of the A and C strategies increase in Fig. 4b with respect to Fig. 4a in an attempt to slow down the climatic change that would cause unsustainable losses. While D-firms enjoy higher average profits than A and C, these profits, if the severity is high, will no longer cover the expected loss and the strategy will be a business conversion to A and C. Under the parameter set used, if a D-company decides to change its strategy to adopt a pro-environmental behavior, the C strategy could be more profitable.

Now consider the market evolution for different values of the premium loading factor λ. Insurance coverage is essential in the model to encourage the coexistence of the three strategies, by playing an active role in sharing the risk of losses induced by climate change.

It can be seen from Fig. 5a how, at a low λ value, there is a greater likelihood that companies will be insured (remember that for $\lambda = 0$ risk averse firms have full insurance coverage). The C basin in Fig. 5a is strongly reduced particularly in favor to the D-firms who are not interested in the impact of their production on the expected losses on account of their insurance coverage. A low λ results in an insurance premium that, despite a high expected value of the loss, does not compromise the profitability of the business. On the other hand, if the loading of the premium is relatively high, the insurance cost significantly reduces the profit, therefore, in this situation, it could be convenient to change the business strategy towards more pro-environmental behavior (see Fig. 5b). The analysis above enables reflecting on the role that the insurance market can play in relation to a desired ecological transition. A high loading factor, and therefore a high insurance premium, favor the presence of companies A and C on the market. However, if λ is too high then $\gamma_a^* = 0$, so adopting strategies A or C would make no difference. Without the loss mitigation of the insurance market, the model would not reach a regime where all three types of companies coexist.

5 Conclusions

The model studies the behavior of companies with polluting businesses whether or not they adopt green technologies and whether or not they cover the cost of potential pollution damage through insurance coverage. It is clear that the premium influences the behavior of the companies regarding the polluting strategy adopted. This paper aims to analyze if there may be a possible synergy between the insurance market and polluting companies and, in particular, if the premium can be a strategic leverage to induce companies to behave proactively towards reducing pollution and/or if policy interventions are necessary.

The model allows us to understand how different typologies of companies, coexisting on the market, could change their behavior according to different basins of attraction. These basins are strongly influenced by the parameter settings, so we presented a sensitivity analysis performed on the green technology cost, the reduction share of emissions on the environmental damage, the impact of production activities on the loss and the insurance coverage loading factor.

Studying the evolutionary dynamics, the model presents seven stationary states; three of them in which only D, C or A-firms survive on the market, three in which firms are present in a couple (D,C), (C,A) and (A,D) and one where all types of firms play together. From the numerical analysis, it emerges that the equilibria where only one strategy exists are stable, the equilibria where two strategies exist are saddle point, and, finally, the equilibrium where all three strategies coexist is unstable.

The model is interesting to understand how the business strategies can change according to different market conditions, namely different values of key parameters. A sensitivity analysis has been performed to study the evolution of firms' strategies.

In the case where green technology cost decreases through innovative methods for good production, new typologies of distribution or, for example, due to incentives given by institutions nudging an ecological transition, the basins of attraction of D strategy is consistently reduced. The model suggests this is an effective leverage to force sustainable behavior. If the investment in green technology is really carried out to its full extent, then the expected loss can be reduced and, consequently, the insurance market can offer a policy with a lower premium.

Furthermore if companies are engaged in campaigns to reduce their emissions, the environmental damage decreases and consequently their insurance premium, so that the probability of finding A-firms on the market will be higher and the lower expected loss will have a positive effect even on C-firms. The basin of attraction of the D strategy will be significantly reduced.

A similar result can be seen when conducting the sensitivity analysis on the impact of emissions on climate change parameters. If the economic severity is relatively high, climate change is accelerated and a higher expected loss can be expected. The basins of attraction of A and C strategies increase to balance the production of D's. In this situation, profits are no longer capable of counteracting the expected loss and, thus, an ecological transition must occur.

We previously suggested that the insurer could potentially to nudge the transition to a more environmentally friendly strategy. Well, let's analyze the behavior of the basins of attraction if there should be an increment in the coverage premium charge. D-companies, that are aware of their polluting behavior, are insured. If the premium rises, we observed that dirty companies are forced to change their strategy towards a more green behavior. From the sensitivity analysis, when the insurance premium is higher due to the increment of the loading factor, it emerges that environmentally-friendly companies A and C will remain on the market.

Policy interventions to favor the use of green technology at low cost and/or opening up to green investments associated with the benefits coming from the insurance market can trigger the environmentally aware firms' sense of responsibility.

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Appendix: Numerical Stability

From Figs. 6, 7, 8, and 9 it emerge that, under the parameter set used, the stationary states S_1, S_2, and S_3 are always stables, since the trace of the Jacobian matrix is always negative, the determinant is always positive, and the roots are real and distinct $(tr^2 > 4det)$. Conversely, the stationary states S_4, S_5, S_6 are always saddle points, since the determinant is always negative (again with real and distinct roots). Finally, the stationary state S_7 is always unstable since both the trace and the determinant are always positive (again with real and distinct roots).

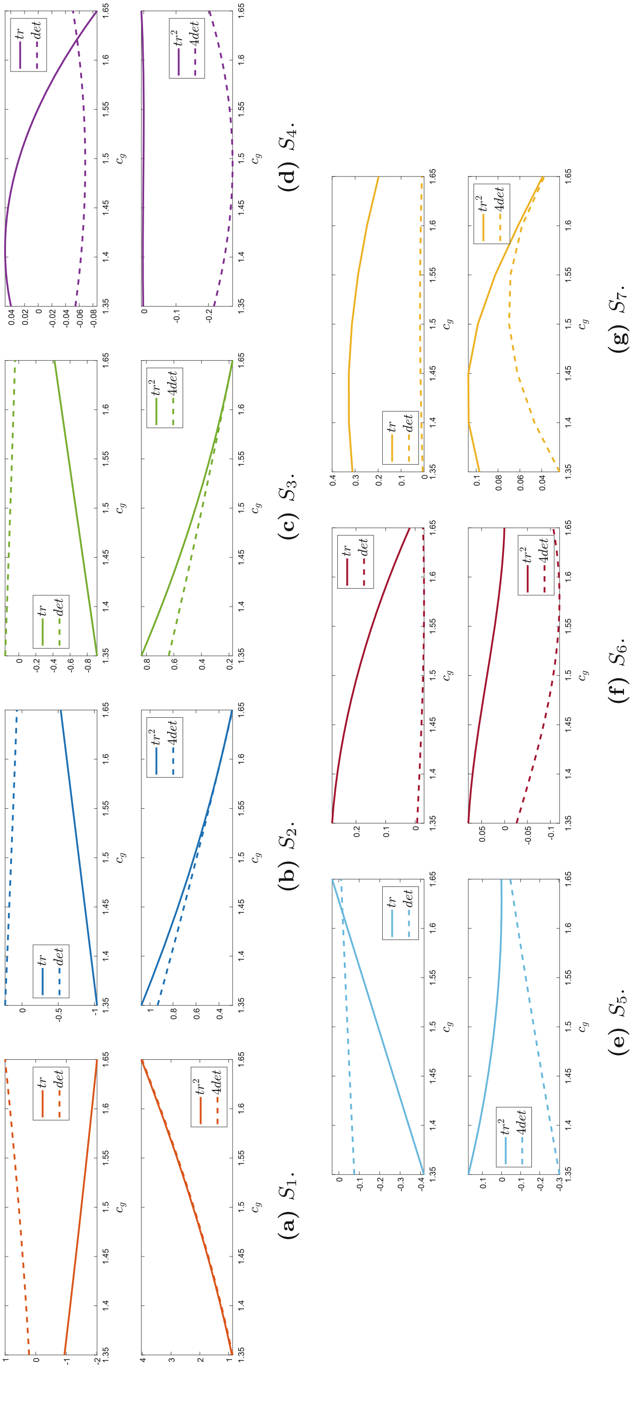

Fig. 6 Trace and determinant for changing value of the green technology cost

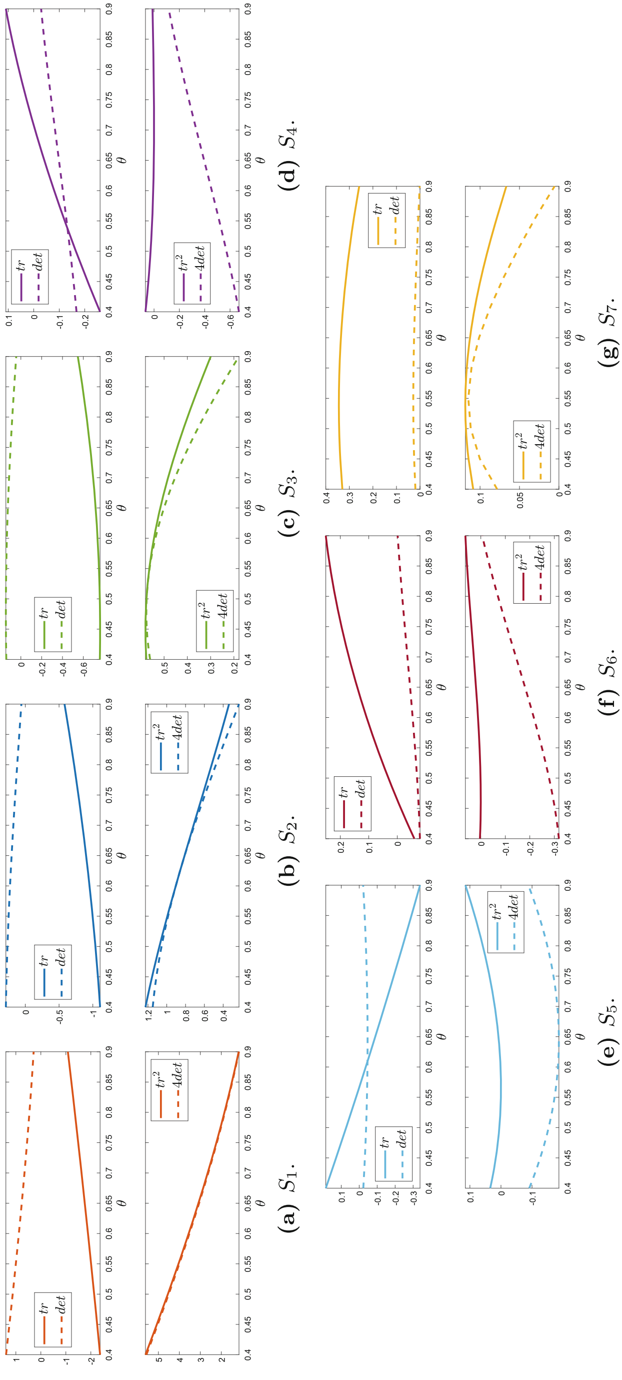

Fig. 7 Trace and determinant for changing value of the emission's reduction technology

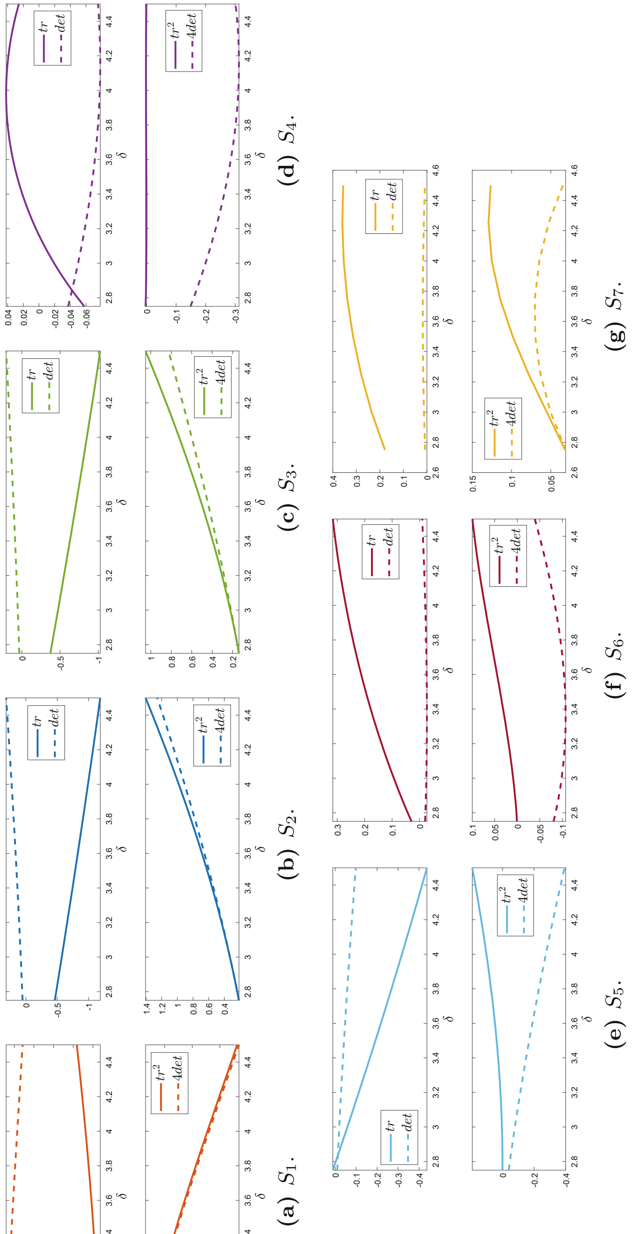

Fig. 8 Trace and determinant for changing value of the environmental damage severity

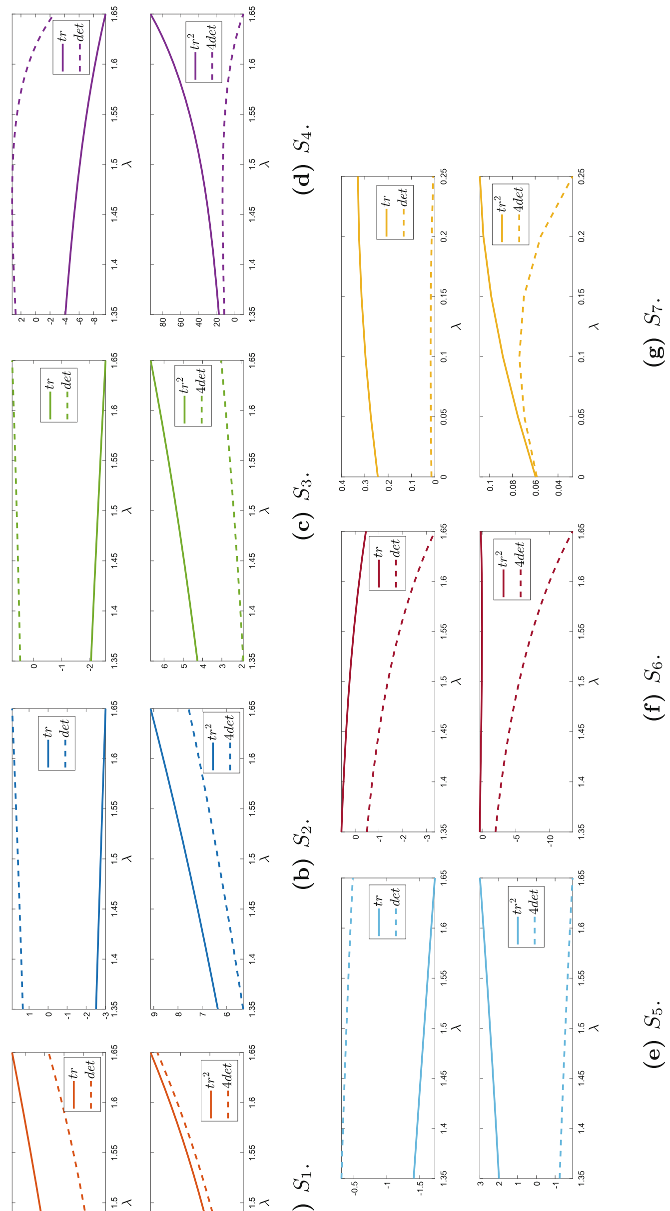

Fig. 9 Trace and determinant for changing value of the premium loading factor

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