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On the game of going green: How do consumers, firms, and banks struggle to escape environmental traps?

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ABSTRACT

This paper analyzes the complex interactions between consumers, firms, and banks within an evolutionary game model to understand pathways to green sustainability or environmental traps. Our dynamic model examines how individual decisions – consumers choosing green or brown products, firms investing in eco-friendly technologies or paying environmental taxes, and banks offering preferential loan rates for green initiatives – influence broader outcomes. Our findings indicate that environmental traps emerge when there are no initial green consumers in the economy. A steady state in which all consumers, firms, and banks adopt green strategies arises when banks' net gains from green consumers exceed the cost differential between green and brown firms. This cost differential is determined by the loans offered to each type of firm, weighted by their respective interest rates. Thus, if citizens show strong green preferences and monetary policy provides sufficiently preferential interest rates for green investments, the economy will eventually stabilize in green equilibrium, ensuring environmental sustainability. Numerical simulations support the analytical findings and demonstrate how different values of the model's parameters can lead to an environmentally responsible economic system against environmental traps.

1. Introduction

Sustainable development is the capacity of an economic system to meet present needs without compromising the ability of future generations to do the same. It rests on two pillars: a thriving economy that provides a decent standard of living for all, and an environment that is preserved to support long-term well-being. Therefore, environmental protection has become a key priority on public agendas in both developed and developing countries, achievable only through the implementation of production practices that guarantee responsible and durable growth. Given the polluting nature of any economic activity, it is essential to transition current production systems to more sustainable practices and promote consumer awareness of responsible consumption, an effort commonly referred to as the "green transition". Finance also plays a crucial role in this process by influencing the adoption of eco-friendly

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technologies when determining whether to grant loans to firms that implement sustainable production methods or not (Carrera et al., 2025; Bacchiocchi et al., 2024). From a policy standpoint, understanding how private incentives of the key economic agents such as firms, consumers, and financial intermediaries interact to shape sustainability outcomes is essential for designing effective environmental policies (Dijkstra and de Vries, 2006; Berlin et al., 2024; Rausch and Yonezawa, 2023). This knowledge, integrated with other socio-economic factors affecting ecology, is crucial for facilitating a green transition that minimizes the ecological impact of economic activity.[1]

Although the literature on environmental economics is extensive, a standard limitation is the lack of analysis of strategic interactions among actors, since most studies are based on the implications of macroeconomic relationships proposed by economic theory (Hassler et al., 2016). The theoretical literature on environmental economics and green transition can be categorized into two main strands. The first adopts a macroeconomic perspective, often using growth models, while the second is microfounded and typically employs a game-theoretic approach to analyze strategic interactions among agents that may drive transition.[2]

The first stream of theoretical literature is generally based on a seminal contribution from John and Pecchenino (1994), who developed an overlapping generations model incorporating environmental quality. Their analysis revealed the possibility of multiple steady states: one featuring sustained growth alongside environmental preservation, and another characterized by excessive environmental maintenance with inefficient capital accumulation. Over time, their model has been extended to explore various aspects of the environmental–economic relationship.[3]

Contributions to the second stream of theoretical literature are characterized by a microfounded analysis of environmental issues. In this strand of literature we find, among others, the works developed by Matsumoto et al. (2020), Matsumoto and Szidarovszky (2021), Cavalli et al. (2024), Feng and Ge (2024), and Wang et al. (2025). These papers propose (multi-stage) games and evolutionary games between firms and governments to analyze how fiscal policies and regulation can promote a green, low-carbon transition.

Although this second strand of literature is important to understand how firms react to environmental taxes set by the government, it fails to examine an important factor widely known to affect the transition to greener technologies and practices, that is moral values.[4] The research paper developed by Besley and Persson (2023) incorporates moral concerns in green values and explores their consequences for policy making and value transmission. By setting up a dynamic equilibrium model where consumption preferences are also driven by green moral values, transitions of values and technologies create a dynamic complementarity that can help or hinder a green transition.[5]

In this vein, the main contribution of our model to the existing literature lies in its novel perspective on the key factors influencing the green economic transition, specifically by integrating the strategic interactions of consumers, firms, and banks within an evolutionary game model. Although prior research on environmental economics and green transition often focuses on macroeconomic models or microfounded game-theoretic approaches, it typically overlooks the strategic interactions among the three key actors: consumers, firms, and financial intermediaries (banks). This paper addresses this gap by setting up a three-player game involving consumers, firms, and banks, each making strategic choices (green or brown) to maximize their payoffs. However, our model goes further by examining how moral values identified in the literature as critical for the transition, shape the dynamics toward ecological sustainability. Therefore, in this paper, we explicitly include the moral values of consumers in relation to the environment as a crucial factor, demonstrating how such values influence consumption choices and can drive a market-driven transition to sustainability, even without environmental taxes. Moral values enhance the utility that green consumers derive from the consumption of eco-friendly products, increasing their willingness to pay and making green firms more profitable. Consequently, the profitability of green firms positively affects banks that grant them loans at a preferential interest rate, thus promoting a virtuous cycle toward transition. Another poorly analyzed factor in the literature that we investigate in our model is the role of finance (i.e., banks) in promoting the transition and in supporting sustainable investments. As far as we know, the role of banks is often under-analyzed given that the most relevant studies have often relied solely on consumer preferences and/or in firm production practices. In our model, instead, we show how banks offering preferential loans to green firms and interacting with green consumers influence

[1] A country's socio-economic and political characteristics are other relevant factors affecting the environment (Policardo, 2015, 2016).

[2] The empirical literature mainly explores at the macroeconomic level the relationship between per capita income and various forms of pollution (see, for instance: Selden and Song, 1994; Grossman and Krueger, 1995; Pérez-Suárez and López-Menéndez, 2015; Shafik, 1994; Jaunky, 2011; Kaika and Zervas, 2013). The empirical literature that focuses on economic and environmental performance data at micro-levels, i.e., firm- or facility-level, generally analyzes firm performance, as measured by stock market returns, and environmental performance, as measured by emissions of pollutants or adoption of international environmental standards (see Dechezleprêtre and Kruse, 2018).

[3] For instance, Acemoglu et al. (2012) and Acemoglu et al. (2016) introduced endogenous and directed technical change within a growth model constrained by environmental limits and finite resources. Their findings suggest that sustainable growth depends on the substitutability between dirty and clean inputs, which, when sufficiently high, allows a green transition to low-carbon technology to be achieved through temporary policy interventions.

[4] Some scholars have tried to evaluate those moral values regarding willingness to pay for green products. For example, Dutta et al. (2008), in a comparative study of consumers' green practices in the US and India, found that consumers in the United States have a higher degree of involvement in environmentally and socially responsible practices in restaurants, which have the most significant effect on consumers' willingness to pay up to 10% or higher on menu prices for Green Practices (GP). In contrast, consumers in India have a higher degree of involvement in health and visibility than consumers in the United States, which is the major driver of their willingness to pay more than 10% or higher on menu prices for GP.

[5] Consumers' preferences are indeed shown to be crucial in driving the economy's green transition. For example, Tian and Sun (2022) examine this dynamic in a four-player game involving consumers, the government, producers, and a third-party certifier. Their findings suggest that consumers' preference for low-carbon practices is the primary transition driver, potentially influenced by whistle-blowing behavior. Many scholars have studied consumer-related issues to examine optimal production strategies (Du et al., 2016; Xia et al., 2020), particularly in terms of consumers' behavioral responses to low-carbon products (Liu et al., 2021), and have highlighted the role of consumer support schemes in establishing low-carbon markets (Gao et al., 2019; Liu et al., 2021; Tan et al., 2019).

profitability and the pace of adopting ecological practices in production, within a three-player evolutionary game where consumers, firms, and banks each affect the others' payoffs.

In our model, consumers, firms, and banks are randomly and simultaneously matched repeatedly over time. In each period, players update their strategy by imitating the most successful one, that is, the strategy expected to yield the highest payoff. All players revise their strategies at the same rate, so an equal fraction of consumers, firms, and banks adjust each period. Each player is assumed to benefit more when matched with counterparts of the same type. Green technology is more expensive than brown, making green products costlier. Although brown firms pay taxes for polluting capital, these taxes are assumed lower than the cost of clean technology, so brown consumers' dominant strategy is to purchase only brown products. To be profitable, then, green firms must set the prices of their products such that they are lower than consumers' willingness to pay for them.[6] Finally, green banks offer preferential interest rates to green firms, but brown banks apply the same interest rate to both brown and green firms.[7]

The model we set up predicts a range of equilibria, some of which can be stable under certain conditions. Specifically, our model predicts infinitely many equilibria characterized by environmental traps, where all consumers and firms adopt the brown strategy and banks can either be brown or green.[8] Moreover, it predicts two other equilibria in which all consumers and firms adopt the green strategy, and banks are either brown or green. It is important to emphasize that consumers, particularly through their moral values and purchasing decisions, act as a primary catalyst to initiate and sustain a virtuous cycle toward a green economy by making green firms profitable and incentivizing banks to engage in green finance. Our results indicate that consumers play a crucial and multifaceted role in driving or hindering green economic transitions, primarily through their strategic choices, moral values, and preferences, which in turn influence firms and banks. Specifically, consumers' preference for low-carbon practices is identified as a primary driver of the green transition. A higher proportion of green consumers can increase revenues for green firms. This, in turn, makes green consumption more appealing and helps accelerate the system toward a virtuous path. From their side, the banks' willingness to grant loans at preferential rates to green firms is motivated by their interactions with consumers. Our model's parameters suggest that if the additional benefits a green bank receives from serving green consumers/investors exceed the financial loss from offering lower interest rates to green firms, banks will converge to the virtuous equilibrium, meaning they also adopt green practices. Conversely, if the interest rate gap is too wide and offsets the benefits of attracting green consumers, banks may be less inclined to offer favorable terms to sustainable firms. In such a scenario, consumers and firms might still go green, but banks remain brown.

Through our model, we provide novel insights into the strategic interactions of key economic actors—consumers, firms, and banks. Depending on government intervention (or its absence), these interactions help explain how a green transition can be promoted by analyzing the main factors and incentives driving it. This is particularly important for designing policies that can accelerate the transition or prevent an environmental trap.

The remainder of the paper proceeds as follows. In Section 2, we present the consumers', firms' and the banks' non-cooperative game in strategic form, and we introduce their strategy profiles. We will generically define as "green" a strategy which acts in an environmentally responsible way, and as "brown" a strategy that neglects environmental considerations, regardless of whether the strategy belongs to a consumer, firm or bank. Assuming that each player chooses the strategy with the highest expected return given the other players' strategies, we will introduce the static game and compute the Nash equilibrium. In Section 3, we extend the model and present the evolutionary game, define the dynamics of the replicator, compute the dynamic equilibria, and analyze their stability properties. One important result is the emergence of a multiplicity of equilibria characterized by an environmental trap, but some parameter constellations allow us to overcome them. Section 4 corroborates our results with numerical simulations. Section 5 concludes with policy recommendations and proposes suggestions for future research.

2. Game setup

The economy is composed of three types of agents: consumers (C), firms (F), and banks (B). Each agent behaves according to two different strategies, namely "green", reflecting environmentally responsible behavior, or "brown", which neglects environmental

[6] The prices of green products play a crucial role in shaping consumers' strategies. Fewer consumers will opt for green products if these prices are too high, even though their moral values might encourage them. Furthermore, when green consumers interact with green firms, they experience additional utility as their moral values are aligned with their consumption choices. In this vein, a recent report by Thomas Husson and Melissa Chaudet found that consumers often want to support the environment against climate change. However, their actions sometimes do not match their intentions. This phenomenon is known as the "green consumer paradox". This means that even if consumers prefer green products, they can consume more polluting products because price is often the most significant barrier to environmentally conscious consumption. See: https://www.forrester.com/blogs/the-green-consumer-paradox/

[7] This hypothesis is supported by evidence from the euro area Bank Lending Survey (BLS), according to which climate change has had a net easing effect on credit standards for low-emitting firms and those in transition since banks apply a form of "climate discount" by lowering these companies' general credit risk premium, effectively encouraging sustainable investments. This assumption indeed aligns with the recent findings on bank lending conditions for financing green investment discussed in Nerlich et al. (2025). The authors show that European firms with low carbon emissions and those transitioning to greener practices benefit from more favorable lending conditions, including lower interest rates and more lenient credit standards. In contrast, high-emission companies face stricter requirements and higher borrowing costs. The authors conclude that, given the bank-centered financial structure of the euro area, banks play a crucial role in facilitating the transition to a greener economy.

[8] For the notion of environmental traps and empirical evidence, see, for example, Dioikitopoulos and Karydas (2024), Rodríguez-Pose and Bartalucci (2023) and Schlaepfer et al. (2002).

Table 1
Consumers' payoff matrix.

$C \setminus F\ B$	$F_g\ B_g$	$F_g\ B_b$	$F_b\ B_g$	$F_b\ B_b$
C_g	$u_{gg} + P_{B_g} - p_g$	$u_{gg} - p_g$	$u_{gb} + P_{B_g} - p_b$	$u_{gb} - p_b$
C_b	$u_{bg} - p_g$	$u_{bg} - p_g$	$u_{bb} - p_b$	$u_{bb} - p_b$

considerations.[9] We denote with C_g a consumer who consumes green products and by C_b a consumer who does not. Similarly, F_g is a firm that implements green technologies or uses green practices in the production process, and F_b, a firm that does not and prefers the available traditional and polluting technology for production. Finally, B_g is a bank that supports green investments; B_b, a bank that does not. Thus, each player has two pure strategies available, specifically: $\Gamma_C = \{C_g, C_b\}$, $\Gamma_F = \{F_g, F_b\}$, and $\Gamma_B = \{B_g, B_b\}$ are the sets of strategies available to consumers, firms, and banks, respectively. Agents are randomly chosen from each of these populations to play a game in which each player chooses their best response to the actions of the other two players. Details of the game are described as follows.

The consumers' game. Consumer preferences (green g or brown b) are measured by utility functions $u_i : \mathbb{R}_+ \times \mathbb{R}_+ : \ i \in \{g, b\}$ defined by $(x_b, x_g) \rightarrow U_i(x_g, x_b)$ where x_b corresponds to the consumption of brown goods and x_g to the consumption of green goods. Let $u_{c,f}$ denote the utility of a consumer with preferences $c \in \{g, b\}$ with respect to the consumption of x_f, $f \in \{g, b\}$, that is, the goods produced by green and brown firms, respectively. Thus, a green consumer of a green or a brown firm gets a utility equal to u_{gg} or u_{gb}, respectively. Similarly, a brown consumer of a green firm receives a utility of u_{bg}; and when dealing with a brown firm, they get a utility of u_{bb}. Each consumer gains higher utility when matched with a firm of their type, i.e., $u_{gg} > u_{gb}$ and $u_{bb} > u_{bg}$. Furthermore, a green consumer prefers to buy products made by a green firm rather than buying brown products from a brown firm, all else is equal. Similarly, brown consumers experience higher utility than green consumers when only brown goods are available. Furthermore, we consider that when a green consumer faces a green bank (i.e., the bank that finances the green firm at a preferred loan rate), he receives an additional benefit measured by P_{B_g} that is strictly positive. P_{B_g} represents a psychological benefit from knowing that the bank contributes to improving environmental quality by helping green firms finance their sustainable investments.[10] In contrast, when a green consumer faces a brown bank, he receives no additional satisfaction. Finally, brown consumers do not gain additional benefits regardless of whether they face a green or brown bank. We assume that information is complete, as consumers know product prices and competitive markets fully. As a result, the prices of green and brown goods denoted as p_g and p_b, respectively, are taken as given. We assume that $p_g > p_b$. Indeed, as we will discuss below, green products are made using more expensive and advanced technology, so their price is higher than that of brown products, all other things being equal.[11] Considering the above, the payoff matrix of consumers is represented in Table 1:

Let us note that green consumers will choose green products when $u_{gg} - p_g > u_{gb} - p_b$ or, equivalently when $p_g < u_{gg} - u_{gb} + p_b = p_g^*$. We define the price p_g^* as a threshold for green products, meaning that if the price of a green product exceeds this threshold, then green consumers will prefer brown products. Conversely, brown consumers have a strict dominant strategy and choose brown products as $u_{bb} - p_b > u_{bg} - p_g$ always holds, given the assumptions.

The firms' game. On the production side, we assume the economy consists of many firms that differ only in their choice of production technology: green or brown. Firms are assumed to be perfectly rational, maximizing profits within a competitive equilibrium where prices equal marginal costs. For any given output, however, the marginal cost of green technology is higher than that of brown technology. Therefore, green products incorporate more expensive technology, so their price is higher than that of brown products $p_g > p_b$, all else being equal.

Considering the existence of given taxes, subsidies, and the overall state of the economy, each firm decides on a production plan that maximizes its profits. Based on this principle, a firm can transition to a more sustainable production system and become green.[12]

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[9] Government intervention is assumed to be constant, exogenous, and even deemed zero to check whether a transition to low-carbon production schemes can be market-driven in the presence of moral values determining consumption and investment choices. Scholars (Coenen et al., 2024) have traditionally endowed the Government with the power to impose taxes or grant subsidies to firms to cope with economic activity's environmental costs or promote cleaner practices when pollution cannot be easily removed. We include this possibility, but we assume that the Government acts exogenously, imposing taxes on polluting capital and/or promoting green morale among citizens by investing in environmental education.

[10] In promoting green consumption, banks can play a crucial role not only by providing loans with favorable interest rates to producers but also by guiding consumers toward this type of consumption. To achieve this, they can offer information about their financial investments, including details in their monthly client reports on the kind of consumption they support, and highlight investment opportunities in companies that adhere to green technologies. See: https://thefintechtimes.com/67-of-consumers-want-their-bank-to-be-more-sustainable/, https://www.bi.team/blogs/should-banks-encourage-green-behaviours/

[11] That is, each consumer is a rational maximizing agent, assuming then that each has a fixed income equal to I, and such that he maximizes his preferences subject to the respective budget constraints:

$$B(p_g, p_b) = \left\{(x_g, x_g) \in \mathbb{R}_+ \times \mathbb{R}_+ : p_g x_g + p_b x_b \le I\right\}.$$

.

[12] Many firms indeed voluntarily choose to implement environmental international norms and get certifications of an environmental friendly production system: think for example to the ISO 14001 management standard, among others. The economic literature that studies the impact of these Environmental Management Practices (EMP) tends to accept the thesis according to which environmental marketing positively affects the operational and commercial performances of firms and this improvement will influence their economic results (Fraj-Andrés et al., 2009).

Table 2
Firms' payoff matrix.

$F \setminus C\ B$	$C_g\ B_g$	$C_g\ B_b$	$C_b\ B_g$	$C_b\ B_b$
F_g	$\pi_{gg} - (r_g + \gamma)L$	$\pi_{gg} - (r_b + \gamma)L$	$\pi_{gb} - (r_g + \gamma)L$	$\pi_{gb} - (r_b + \gamma)L$
F_b	$\pi_{bg} - r_b L - \tau K$	$\pi_{bg} - r_b L - \tau K$	$\pi_{bb} - r_b L - \tau K$	$\pi_{bb} - r_b L - \tau K$

We assume that each firm receives a loan from the bank, denoted $L > 1$, which is the same for all firms. On the one hand, firms that implement green technology in their production processes will allocate a fraction γ of the loan L to acquire new green technology. Thus, γL can be interpreted as the transition cost for companies adopting green production.

On the other hand, firms that choose not to implement green technology in their production are charged an environmental tax. For mathematical tractability, we assume that the environmental tax is proportional to the polluting inputs used in production. If we define τ as the tax rate and K as the quantity of polluting capital or input used in production, then τK represents the pollution cost of the firm that operates using conventional, non-green technology.

In addition to the costs associated with the green transition or the environmental tax (for green and brown firms, respectively), firms also bear the cost related to the loan L they receive. Specifically, they must pay interest on the borrowed capital. A brown firm incurs an interest rate $r_b \in (0,1)$, regardless of whether it is matched with a brown or green bank. In contrast, a green firm pays an interest rate $r_g \in (0,1)$ if matched with a green bank, but r_b if matched with a brown bank, and r_g is assumed to be strictly lower than r_b. Firms sell their products in the market, interacting with green and brown consumers.

Let us define with π_{fc}, where $f = \{g, b\}$, and $c = \{g, b\}$, the revenue that a firm of type f gets when facing a consumer of type c. The firms' payoff matrix is represented in Table 2:

Since there are strategic complementarities between firms and consumers of the same type, without loss of generality, we assume that: $\pi_{gb} = 0$ and $\pi_{bb} > 0$, $\pi_{gg} \geq 0$ and $\pi_{bg} \geq 0$. When faced with brown consumers, green firms obtain zero revenues. Indeed, as $u_{bb} > u_{bg}$ and $p_g > p_b$, from Table 1, we see that brown consumers have a strictly dominant strategy. In contrast, brown firms interacting with brown consumers earn positive revenues, while green firms paired with green consumers obtain non-negative revenues. As seen above, since the prices of green products are higher than those of their counterparts, green consumers will choose green goods if and only if $p_g < p_g^*$. For the same reason, brown firms facing green consumers also obtain non-negative revenues.

We assume that firms can choose not to produce, which occurs if expected payoff values are negative. Consequently, a firm will decide to produce when its payoff is strictly positive. This decision is based on potential subsidies, which are sufficient to cover its setup costs, production costs, loans, and interest rates. We consider that the unitary output revenue of a green firm is:

$$\pi_{gg} = \begin{cases} p_g & \text{if } p_g < p_g^* = u_{gg} - u_{gb} + p_b \\ 0 & \text{if } p_g > p_g^* \end{cases} \qquad \text{and} \quad \pi_{gb} = 0. \tag{1}$$

The unitary output-revenue of a brown firm is:

$$\pi_{bg} = \begin{cases} 0 & \text{if } p_g < p_g^* = u_{gg} - u_{gb} + p_b \\ p_b & \text{if } p_g > p_g^* \end{cases} \qquad \text{and} \quad \pi_{bb} = p_b. \tag{2}$$

Note that $\pi_{gg} = 0$ if $p_g > p_g^*$ because in this case $u_{gg} - p_g < u_{gb} - p_b$. That is, even when the consumer prefers green products, because $u_{gg} > u_{gb}$, if the price of the green product is too high the consumer will settle for buying a traditional brown product. Hence, in this case, $\pi_{gg} = \pi_{gb} = 0$, and $\pi_{bg} = \pi_{bb} = p_b$: the revenues of the brown firm will be the same regardless of the type of consumer it faces. The case where $p_g < p_g^*$ results in $\pi_{gg} = p_g$, $\pi_{bg} = 0$ if the consumer is of type g, while if the consumer is of type b, then $\pi_{gb} = 0$ while $\pi_{bb} = p_b$. If $p_g > p_g^*$, being brown is a strictly dominant strategy for all firms.

It is important to note that product pricing is closely tied to firms' production costs, which depend not only on technology but also on the terms of bank loans. Offering green firms favorable financing, such as preferential interest rates, can support more competitive pricing and encourage green consumption. Additionally, banks can promote sustainable consumer behavior by providing signals, incentives, or rewards for engaging in green financial activities.

The banks' game. Two types of banks in the economic system, green and brown, are matched to firms and consumers. All banks offer a loan L to all firms; however, green banks offer L at a preferential interest rate r_g only to those firms that adopt the green practices in production. Green banks that grant loans L to brown firms charge them an interest rate equal to r_b. Brown banks do not offer preferential interest rates and apply an interest rate equal to r_b to both green and brown firms. The preferential interest rate green banks provide to green firms is lower than the traditional or brown interest rate, i.e., $r_g < r_b$.

Banks' profits depend on the interest rate r_g or r_b at which they grant the loan $L > 0$ to firms.[13] The lending activity of each bank is risky. Indeed, banks' profits depend on whether firms will reimburse their loans or not, and there are different scenarios according to the various possible values of firms' revenue, as previously described. Thus, we model banks' payoff as follows, depending on the price of green goods.

[13] Generally, banks' profit can be represented as the sum of the intermediation margins/spreads on loans, deposits and bonds (taking also into account the riskiness of these activities), net of management costs, where the spread is the difference between their rate and the main refinancing rate r settled by the Central Bank through open market operations (Bacchiocchi et al., 2022). Without loss of generality, in our setting we focus on the loan market and r_g or r_b are closely related to the spread on loans to green and brown firms, respectively.

Table 3
Banks' payoff matrix.

$B \setminus F\ C$	$F_g\ C_g$	$F_g\ C_b$	$F_b\ C_g$	$F_b\ C_b$
B_g	$\alpha_{C_g}(1+r_g)L+$ $(1-\alpha_{C_g})(1-\gamma)L+P_{C_g}$	$(1-\gamma)L$	$(1-\alpha_{C_g})(1+r_b)L+$ $\alpha_{C_g}(L-\tau K)+P_{C_g}$	$(1+r_b)L$
B_b	$\alpha_{C_g}(1+r_b)L+$ $(1-\alpha_{C_g})(1-\gamma)L$	$(1-\gamma)L$	$(1-\alpha_{C_g})(1+r_b)L+$ $\alpha_{C_g}(L-\tau K)$	$(1+r_b)L$

When $p_g < p_g^*$, green consumers are willing to consume green products. In this case, green firms will earn enough revenues to repay the bank loan, L at the rate r_g or r_b. In contrast, when $p_g > p_g^*$ all consumers, both green and brown, choose brown goods. In this case, the green firm's revenues are equal to zero, and they will reimburse only a fraction $1-\gamma$ of the total loan L.

For modeling purposes, we define a dichotomous variable $\alpha_{C_g} \in \{0,1\}$ to represent the consumers' willingness to purchase green products. This variable influences the likelihood that loans granted by green banks to green firms will be fully repaid. Specifically, when $p_g < p_g^*$, we have $\alpha_{C_g} = 1$, meaning consumers choose green products. Conversely, when $p_g > p_g^*$, consumers opt for brown products, resulting in $\alpha_{C_g} = 0$. In this case, the green firm will only be able to repay the bank the value of its original loan, excluding the additional investment made for its transition to green production.

As for brown firms, we assume that $L \geq \tau K$, so that the bank loan covers the environmental tax. When the green consumer is willing to consume green products ($\alpha_{C_g} = 1$), the brown firm revenues are $\pi_{bg} = 0$ (see Eq. (2)). Therefore, brown firms only reimburse the fraction of their debt with the bank for an amount equal to $L - \tau K \geq 0$. To the contrary, when $\alpha_{C_g} = 0$, the brown firm revenues are positive, and the bank profit will be equal to $(1+r_b)L$.

When green banks encourage consumers to purchase environmentally friendly products through signals, incentives, or rewards ($P_{B_g} > 0$), their goal is to promote the success of green financial activities. Let $M_{C_g} > 0$ represent the gross benefit the bank gains from attracting green consumers. In this case, the net benefit derived by the green bank from having green consumers in the economy is given by $P_{C_g} = M_{C_g} - P_{B_g}$.

We can now define the banks' payoff matrix, as shown in the Table 3. We can infer the following observations from the banks' payoff matrix:

If $(1+r_g)L + P_{C_g} > (1+r_b)L$ or equivalently $0 < (r_b - r_g) < \frac{P_{C_g}}{L}$ to be green will be a weakly dominant strategy for banks. If, on the other hand, the inequality $(1+r_g)L + P_{C_g} < (1+r_b)L$ or equivalently $r_b - r_g > \frac{P_{C_g}}{L}$ holds, then being brown is a dominant strategy for banks when faced with green firms and consumers that consume green products ($\alpha_{C_g} = 1$).

As explained above, even if the rate r_b is higher than the green rate r_g, the potential to acquire a new customer provides sufficient incentive for banks to adopt green practices. This finding highlights the crucial role of consumers in guiding firms, banks, and the broader economy toward a sustainable system. However, if the interest rate gap is large enough to outweigh the benefits of attracting green consumers, banks may be reluctant to offer favorable terms to sustainable firms. This occurs when green consumers are insufficiently attractive to banks or when the potential gains from serving them do not justify lowering interest rates for firms pursuing sustainable production.

Expected payoffs. Let us proceed and construct the expected payoffs of each player (consumers, firms, banks) within each population. Each player's expected payoff depends on the profile distributions of the other players. Therefore, the expected payoff of each player's strategy will depend on the probability of encountering green or brown opponents. We consider the number of consumers N_C, firms N_F, and banks N_B to be given, but it can change over time. Therefore:

$$N_C = N_{C_g}(t) + N_{C_b}(t), \quad N_F = N_{F_g}(t) + N_{F_b}(t), \quad N_B = N_{B_g}(t) + N_{B_b}(t).$$

Note that the number of individuals in each subpopulation is time-dependent. That is, the percentage distributions among subpopulations will be affected by:

$$\begin{aligned}
(n_{C_g}(t), n_{C_b}(t)) &= (N_{C_g}(t)/N_C,\ N_{C_b}(t)/N_C),\\
(n_{F_g}(t), n_{F_b}(t)) &= (N_{F_g}(t)/N_F,\ N_{F_b}(t)/N_F),\\
(n_{B_g}(t), n_{B_b}(t)) &= (N_{B_g}(t)/N_B,\ N_{B_b}(t)/N_B),
\end{aligned}$$

respectively. To simplify the notation, we will avoid writing a temporary variable (t) when it is unnecessary for a clearer understanding.

2.1. Players' expected payoffs and their strategic choices

The probability that a player in the profile population $H \in \{C, F, B\}$ adopts a strategic behavior $i \in \{g, b\}$ corresponds to the percentage of individuals following that strategy, denoted as n_{Hi}. The expected payoffs for each player can then be defined based on their strategic profile and the distribution of strategies among the other players.

That is by using consumers' payoff matrix 1, and $n_{F_b} = 1 - n_{F_g}$ and $n_{B_b} = 1 - n_{B_g}$, we get:

$$\begin{aligned}
E(C_g) &= \left(u_{gg} - u_{gb}\right) n_{F_g} + n_{B_g} P_{B_g} + u_{gb} + (n_{F_g} - 1)p_b - n_{F_g}\, p_g.\\
E(C_b) &= \left(u_{bg} - u_{bb}\right) n_{F_g} + u_{bb} + (n_{F_g} - 1)p_b - n_{F_g}\, p_g.
\end{aligned} \tag{3}$$

If $E(C_g) > E(C_b)$, the consumers will prefer to consume green, while otherwise, they will prefer to consume brown products made with traditional (or polluting) methods. For $E(C_g) > E(C_b)$, we must have that either:

$$n_{F_g} > n^*_{F_g} = \frac{u_{bb} - u_{gb} - n_{Bg} P_{Bg}}{(u_{bb} - u_{bg}) + (u_{gg} - u_{gb})}$$

or,

$$n_{B_g} > n^*_{B_g} = \frac{n_{Fg}(u_{bg} - u_{gg}) - (1 - n_{Fg})(u_{bb} - u_{gb})}{P_{Bg}}.$$

The latter implies that consumers choose green products if the green firm share, n_{F_g}, or the green bank share, n_{B_g}, is large enough. Note that these thresholds, $n^*_{F_g}$ and $n^*_{B_g}$, are overcome as the banking incentives for green consumption, P_{Bg}, increase.

Using firms' payoff matrix 2 we get:

$$\begin{aligned} E(F_g) &= n_{C_g}\pi_{gg} + n_{B_g}(r_b - r_g)L - (r_b + \gamma)L. \\ E(F_b) &= n_{C_g}(\pi_{bg} - \pi_{bb}) + \pi_{bb} - r_b L - \tau K. \end{aligned} \tag{4}$$

Hence, firms will choose to be green if and only if $E(F_g) > E(F_b)$ and to be brown in the opposite case. Thus, firms supply green products when either:

$$n_{C_g} > n^*_{C_g} = \frac{n_{B_g}(r_g - r_b)L + \pi_{bb} - \tau K + \gamma L}{\pi_{gg} + \pi_{bb} - \pi_{bg}}$$

or,

$$n_{B_g} > \bar{n}_{B_g} = \frac{n_{C_g}(\pi_{bg} - \pi_{gg}) - (1 - n_{C_g})\pi_{bb} - \tau K + \gamma L}{L(r_b - r_g)}.$$

This implies that firms decide to offer green products if the proportion of green consumers, n_{C_g}, or the proportion of green banks, n_{B_g}, is large enough. This happens when the revenues of green firms facing consumers with green preferences, π_{gg}, increase enough to be more significant than any other revenues facing green or brown consumers. The green interest rates r_g also play a role in fostering green investment activities: if they are low enough, $r_g < r_b$, then there are incentives for green investment. Then, the thresholds $n^*_{C_g}$ and $\bar{n}_{B_g}$ are exceeded, and firms offer green products, i.e., $E(F_g) > E(F_b)$.

Like consumers and firms, as rational economic agents, banks choose their strategy based on their expected payoff. Using the payoff matrix 3, we obtain the banks' expected profits:

$$\begin{aligned} E(B_g) \quad &= \quad \left(\alpha_{C_g} L(r_g + \gamma + r_b) + \alpha_{C_g}\tau K\right) n_{C_g} n_{F_g} + \left(-\gamma - r_b\right) L n_{F_g} \\ &\quad + (-\alpha_{C_g}(r_b L + \tau K) + P_{C_g}) n_{C_g} + (1 + r_b)L. \\ E(B_b) \quad &= \quad \left(\alpha_{C_g} L(\gamma + 2r_b) + \alpha_{C_g}\tau K\right) n_{C_g} n_{F_g} + \left(-\gamma - r_b\right) L n_{F_g} \\ &\quad + (-\alpha_{C_g}(r_b L + \tau K)) n_{C_g} + (1 + r_b)L. \end{aligned} \tag{5}$$

So banks decide to be green instead of brown if $E(B_g) > E(B_b)$, and this happens when either:

$$n_{C_g} > \bar{n}_{C_g} = 0$$

or,

$$n_{F_g} > \bar{n}_{F_g} = \frac{P_{C_g}}{\alpha_{C_g} L(r_b - r_g)}.$$

The first case of threshold exceedance with n_{C_g} occurs when at least part of the population is green, that is when some consumers prefer green products to traditional or brown ones. For the second case n_{F_g}, the threshold is exceeded when both productive investment loans are high enough, and the green prime rate r_g is low enough. Conversely, the willingness to consume green products is high enough $\alpha_{C_g} \to 1$. Note that whenever $\alpha_{C_g} = 0$, meaning that green consumers do not consume green products, the equation $\alpha_{C_g} n_{F_g}\left(r_g - r_b\right) L + P_{C_g} = 0$ has no solution; Therefore, a necessary condition for $n_{F_g} \in (0, 1)$ is that green consumers consume green products, i.e., $\alpha_{C_g} = 1$. In the following, we consider $\bar{n}_{F_g} = \dfrac{P_{C_g}}{(r_b - r_g)L}$.

In the mixed strategic profile, the Nash equilibrium corresponds to a vector composed of three distributions, each corresponding to a population, indicating the percentages of agents in each population who adopt one behavior or another. The existence of a strictly mixed equilibrium pre-supposes the fulfillment of the equalities $E(C_g) = E(C_b)$; $E(F_g) = E(F_b)$; $E(B_g) = E(B_b)$, in the interior of the cube $C = [0, 1] \times [0, 1] \times [0, 1]$. Or, equivalently, the solutions of the following nonlinear system of equations:

$$\begin{aligned} f_1(n_{F_g}, n_{B_g}) &= E(C_g) - E(C_b) = 0, \\ f_2(n_{C_g}, n_{B_g}) &= E(F_g) - E(F_b) = 0, \\ f_3(n_{C_g}, n_{F_g}) &= E(B_g) - E(B_b) = 0. \end{aligned}$$

Let us denote this solution by:

$$n^e_C = (n^e_{C_g}, n^e_{C_b}),\ n^e_F = (n^e_{F_g}, n^e_{F_b}),\ n^e_B = (n^e_{B_g}, n^e_{B_b}).$$

Hence, whenever $(1+r_g)L+P_{C_g} < (1+r_b)L$ it is clear that $n^e_{F_g}$ is equal to $n^*_{F_g}$. At the same time if $(u_{gg}-u_{bg}) < ((r_b-r_g)L-1)(u_{bb}-u_{gb}) < (u_{gg}-u_{bg}) + P_{B_g}(r_b-r_g)L$, then $n^e_{B_g} = n^*_B$. Finally, under these conditions, solving the equation:

$$f_2(n_{C_g}, n^*_{B_g}) = E(B_g \mid n^e_{F_g}, n^e_{B_g}) - E(B_b \mid n^e_{F_g}, n^e_{B_g}) = 0, \tag{6}$$

we can conclude that:

$$n^e_{C_g} = \frac{n^e_{B_g}(r_g-r_b)L + \gamma L + \pi_{bb} - \tau K}{\pi_{gg}+\pi_{bb}} \tag{7}$$

is a solution of Eq. (6). Recall we are interested in the case in which $n^e_{C_g} \in (0,1)$, then, since by the assumptions $r_g - r_b < 0$ and $\gamma L < \pi_{gg}$, we can conclude that $n^e_{C_g}$ is strictly less than 1. Moreover, considering that $\alpha_{C_g} = 1$, $(1+r_g)L + P_{C_g} < (1+r_b)L$ and $P_{C_g}(u_{gg}-u_{bg}) < ((r_b-r_g)L - P_{C_g})(u_{bb}-u_{gb}) < P_{C_g}(u_{gg}-u_{bg}) + P_{B_g}(r_b-r_g)L$ hold, if $r_g+\gamma > r_b$ then $n^e_{C_g}$ defined by (7) is positive. Therefore, if the following conditions: $\alpha_{C_g} = 1$, $(1+r_g)L+P_{C_g} < (1+r_b)L$, together with $P_{C_g}(u_{gg}-u_{bg}) < ((r_b-r_g)L - P_{C_g})(u_{bb}-u_{gb}) < P_{C_g}(u_{gg}-u_{bg}) + P_{B_g}(r_b-r_g)L$ and $r_g+\gamma > r_b$ hold, then the profile distribution:

$$\left(n^e_{C_g}, n^e_{F_g}, n^e_{B_g}\right) = \left(\frac{n^e_{B_g}(r_g-r_b)L+\gamma L+\pi_{bb}-\tau K}{\pi_{gg}+\pi_{bb}}, \ \frac{P_{C_g}}{(r_b-r_g)L}, \ \frac{(1-n^e_{F_g})(u_{bb}-u_{gb}) + n^e_{F_g}(u_{bg}-u_{gg})}{P_{B_g}}\right) \tag{8}$$

defines a mixed strategy Nash equilibrium.[14]

We note that the probability distributions over the set of pure strategies, as a strategic profile, constitute a set of mixed strategies, one for each player. Therefore, the complete triad (n^e_C, n^e_F, n^e_B) is a strategic profile that corresponds to a Nash equilibrium in mixed strategies. However, this is a static concept. It tells us nothing about what would happen if a random change in the behavior of some individuals occurs. Next, we analyze the evolutionary dynamics of this economy.

3. The evolutionary game

The game described above, capturing the strategic conflict between green and brown activities among consumers, firms, and banks, can be modeled as a three-population evolutionary game, as it is continuously repeated. As noted in Section 1, in each period all populations revise their strategies at the same rate, potentially updating the entire population. This symmetry ensures consistent dynamics, as differing revision rates across populations could produce different outcomes. Therefore at each point in time, every population chooses between two strategies: green or brown. Although participants initially do not know their opponents' strategies, they form future strategies based on the expected value of each choice. This evaluation considers the overall state of the economy and the past behavior of opponents. The state of the economy is defined by the set of parameters at a given time, including prices, profits, interest rates, taxes, and subsidies.

Given the uncertainty about others' behavior, strategic profiles emerge through trial and error rather than strict profit maximization. It is reasonable to assume that players adopt strategies by imitating the most successful behaviors observed among their peers. These assumptions enable the analysis of social behavior evolution in this economy using the well-known replicator dynamics.

3.1. The replicator dynamics

Replicator dynamics (RD) explicitly model a selection process,[15] specifying how population shares associated with different strategies in a game evolve over time. Thus, it analyzes the evolution of each strategy, green g and brown b, for each population $H \in \{C, F, B\}$. Considering the strategic profiles of the populations $n_{H_g} = 1 - n_{H_b}$, then indicating their variation over time as $\dot{n}_{H_g} = -\dot{n}_{H_b}$, which results in the RD being defined by the following system of three differential equations:

$$\begin{cases} \dot{n}_{C_g} &= n_{C_g}\left(E(C_g) - \overline{E}_{C_g}\right) \\ \dot{n}_{F_g} &= n_{F_g}\left(E(F_g) - \overline{E}_{F_g}\right) \\ \dot{n}_{B_g} &= n_{B_g}\left(E(B_g) - \overline{E}_{B_g}\right) \end{cases} \tag{9}$$

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[14] Notice that $n^e_{B_g} \in (0,1)$, then since $\pi_{bb} > \tau K$ the following inequality holds:

$$n^e_{C_g} > \frac{(r_g-r_b)L + \gamma L}{\pi_{gg}+\pi_{bb}},$$

then the result $n_{C_g} > 0$ follows directly from the assumption $r_g+\gamma > r_b$. Moreover, we get n^e_F, $n^e_B \in (0,1)$, while n_{C_g} is also in the interval $(0,1)$. Then setting $n^e_C = (n^e_{C_g}, 1-n^e_{C_g})$, $n^e_F = (n^e_{F_g}, 1-n^e_{F_g})$ and $n^e_B = (n^e_{B_g}, 1-n^e_{B_g})$, thus definining the mixed strategy Nash equilibrium.

[15] This evolutionary process better captures the less far-sighted but more reactive manner in which green or brown strategies are adopted. Moreover, the evolutionary dynamics reflect players' bounded rationality, filtering out outcomes that are unlikely when errors occur randomly. This results in locally optimal equilibria that depend on credible actions, with the most successful behaviors being those most widely imitated over time (see, for example, Accinelli et al., 2015, 2021; Hofbauer and Sandholm, 2009; Weibull, 1997 and Weibull, 1998).

where $E(C_g)$ is the consumers' expected payoff when choosing strategy C_g, while $E(F_g)$ represents the firms' expected payoff when choosing strategy F_g (i.e., invest in environmentally friendly technologies), and $E(B_g)$ denotes the banks' expected payoff when choosing green financial activities. By $\overline{E}_{C_g}$, $\overline{E}_{F_g}$ and $\overline{E}_{B_g}$ we denote the average payoffs of consumers, firms and banks according to their initial distributions $(n_{C_g}, 1-n_{C_g})$, $(n_{F_g}, 1-n_{F_g})$ and $(n_{B_g}, 1-n_{B_g})$ over their possible behaviors (being green or brown). In other words, the proportion of agents using the green strategy increases if its payoff is larger than the average payoff of the population. From a direct calculation, the system (9) can be transformed into:

$$\begin{cases} \dot{n}_{C_g} &= n_{C_g}(1-n_{C_g})\left(E(C_g)-E(C_b)\right) \\ \dot{n}_{F_g} &= n_{F_g}(1-n_{F_g})\left(E(F_g)-E(F_b)\right) \\ \dot{n}_{B_g} &= n_{B_g}(1-n_{B_g})\left(E(B_g)-E(B_b)\right) \end{cases} \tag{10}$$

hence, using the expected payoffs (3), (4), (5), we obtain the RD system:

$$\begin{cases} \dot{n}_{C_g} &= n_{C_g}(1-n_{C_g})\left(n_{F_g}\left((u_{gg}-u_{gb})-(u_{bg}-u_{bb})\right)+n_{B_g}P_{B_g}+(u_{gb}-u_{bb})\right) \\ \dot{n}_{F_g} &= n_{F_g}(1-n_{F_g})\left(n_{C_g}(\pi_{gg}+\pi_{bb})+n_{B_g}(r_b-r_g)L+(\tau K-\gamma L-\pi_{bb})\right) \\ \dot{n}_{B_g} &= n_{B_g}(1-n_{B_g})n_{C_g}\left(n_{F_g}\left(r_g-r_b\right)L+P_{C_g}\right) \end{cases} \tag{11}$$

System (11) is a nonlinear three-dimensional dynamical system in continuous time. The first step to shed some light on its qualitative dynamic behavior is the study of the existence of equilibrium points: their localization (obtained by solving an algebraic system) and their local stability properties. Let us now analyze the dynamical equilibria of the RD system (11). Since the cube $C=[0,1]\times[0,1]\times[0,1]$ is an invariant set for the replicator dynamics if the initial conditions $N(t_0)=(n^G(t_0), n^F(t_0), n^G(t_0))$ belong to the cube; it follows that, for all $t>t_0$, the solution will remain in the cube.[16] To analyze the behavior of stationary points, we now consider two subsections: one for the behavior of stationary points on the edge and another for stationary points inside the cube.

3.1.1. The edges dynamics

To analyze the dynamically evolving economy described by system (11), we first identify the state where the rate of variation of the share of green preferences among the subpopulations are all zero. This state is denoted as $\dot{n}_{C_g}=\dot{n}_{F_g}=\dot{n}_{B_g}=0$. This condition indicates no changes in the preferences of customers, firms, or banks, whatever they are. Let $(n^*_{C_g}, n^*_{F_g}, n^*_{B_g})$ represent the solution to the right-hand side of system (11) when it equals zero:

$$\begin{cases} n^*_{C_g}(1-n^*_{C_g})\left(n^*_{F_g}\left((u_{gg}-u_{gb})-(u_{bg}-u_{bb})\right)+n^*_{B_g}P_{B_g}+(u_{gb}-u_{bb})\right) &= 0 \\ n^*_{F_g}(1-n^*_{F_g})\left(n^*_{C_g}(\pi_{gg}+\pi_{bb})+n^*_{B_g}(r_b-r_g)L+(\tau K-\gamma L-\pi_{bb})\right) &= 0 \\ n^*_{B_g}(1-n^*_{B_g})n^*_{C_g}\left(n^*_{F_g}\left(r_g-r_b\right)L+P_{C_g}\right) &= 0 \end{cases} \tag{12}$$

Next, we present Condition 1, which supports Theorem 1 to describe multiple low-level equilibria, and Condition 2, which supports Theorem 2, which characterizes green equilibria.

Condition 1. *When $n^*_{C_g}=0$, it implies that both $\dot{n}_{C_g}$ and $\dot{n}_{B_g}$ are always zero. Therefore, the dynamics occurs only in n_{F_g} at the edge $n^*_{C_g}=0$. If $n^*_{C_g}=n^*_{F_g}=0$ or $n^*_{C_g}=0$ and $n^*_{F_g}=1$, then we get the states $(0,0,n^*_{B_g})$ and $(0,1,n^*_{B_g})$ where $0\le n^*_{B_g}\le 1$ are the equilibrium manifold of (11). If $0<n^*_{F_g}<1$ and $E(F_g)-E(F_b)<0$, we can obtain that $\dot{n}_{F_g}$ will decrease. As a result, we can conclude that $(0,0,n^*_{B_g})$ is a stable manifold of equilibria, while $(0,1,n^*_{B_g})$ is an unstable manifold of equilibria.*

Hence, for the RD system (11) under Condition 1, we can state the following results (see Appendix A for proofs).

Theorem 1 (***Multiple Low-level Equilibria***). *Under the Condition 1, then there is a positive share of green banks, $0<n^*_{B_g}<1$, such that the system (11) supports the following equilibria.*

- *(a)* **Unstable low-level equilibria**. *Unstable Nash equilibria of the form $(0,1,n^*_{B_g})$ exist if and only if $u_{bb}>u_{gb}+P_{B_g}$, $u_{gg}\ge u_{bg}$.*
- *(b)* **Stable low-level equilibria, i.e. environmental traps**. *Asymptotically stable Nash equilibria of the form $(0,0,n^*_{B_g})$ exist if and only if $E(F_g)-E(F_b)<0$.*

[16] According to the Picard–Lindelöf theorem, once the initial conditions are known, that is, the distributions of each population over their possible strategies, the system will have a unique solution. Moreover, for the RD system (11), every stable steady state is a strict Nash equilibrium, and every Nash equilibrium is a fixed point or steady state (see, Bauer et al., 2019; Castro, 2018; Hofbauer and Sandholm, 2009; Weibull, 1997; van Damme, 1991). It is possible to analyze the stability of the equilibrium points of such a system starting from its linear approximation. The Hartman–Grobman theorem states that the behavior of a dynamical system in the vicinity of a hyperbolic equilibrium point is qualitatively the same as the behavior of its linearization near this equilibrium point. Hyperbolicity means that no eigenvalue of the linearization has a real part equal to zero. Therefore, we can use the linearization of the system to analyze its behavior around stationary points.

This Theorem 1 allows us to propose a definition for evolutionary environmental traps. We define an environmental trap as a situation in which economic conditions lead consumers to prefer polluting (brown) products. Therefore, firms favor polluting production, even when banks (or a number of them) are willing to finance green initiatives. Evolutionary environmental traps refer to Pareto-dominated equilibria—specifically, asymptotically stable equilibria of the RD system (11) in which brown consumers and firms dominate the economy. They are defined as traps because, once the system falls within their basin of attraction, the rational strategy of economic agents is to reinforce such traps (self-reinforcing mechanism according to Azariadis and Stachurski, 2005, and Sanchez-Carrera, 2019), making them more entrenched and difficult to overcome.

Definition 1 (***On Environmental Traps***)**.** *An environmental trap corresponds to an asymptotically stable Nash equilibrium where both consumers and firms are totally brown under the replicator dynamics.*

Therefore, escaping these traps requires significant changes in the parameters characterizing the economy, so that the basin of attraction of such equilibria is reduced, and the initial conditions remain outside.

On the other hand, when the initial conditions of the economy are such that consumers are completely green, then $n_{C_g} = 1$, this does not necessarily mean that $\dot{n}_{B_g}$ is zero. So, we have four vertices, which are $(1,0,0)$, $(1,0,1)$, $(1,1,0)$, and $(1,1,1)$, as equilibrium points. Let us analyze these situations.

Condition 2. *When $n^*_{C_g} = 1$, the dynamics of $\dot{n}_{C_g}$ and $\dot{n}_{B_g}$ depend on the signs of $E(C_g) - E(C_b)$ and $E(B_g) - E(B_b)$. Now, on the edges of the unit cube, we have as equilibrium points the four vertices ($(1,0,0), (1,0,1), (1,1,0), (1,1,1)$) and as a manifold of equilibria we get $(0,0,n^*_{B_g}), (0,1,n^*_{B_g})$, where $0 \le n^*_{B_g} \le 1$.*

Hence, for the RD system (11) under the Condition 2, we can state the following results (see Appendix A for proofs).

Theorem 2 (***Green Equilibria***)**.** *Under Condition 2, there exist two equilibria for the system (11) involving the green strategy, that is,*

(a) The equilibrium $(1,1,1)$ is a strict and asymptotically stable Nash equilibrium if $P_{C_g} > L(r_b - r_g)$. This equilibrium is characterized by all economic agents, that is, consumers, firms, and banks, converging in the long run toward green sustainability.
(b) The equilibrium $(1,1,0)$ is a strict and asymptotically stable Nash equilibrium if $P_{C_g} < L(r_b - r_g)$. This equilibrium is characterized by all consumers and all firms converging toward green sustainability in the long run, but the proportion of green banks is zero.

The Theorem 2 shows that when consumers have a total preference for green products, $n^*_{C_g} = 1$, then the economic system (11) should overcome environmental traps. Specifically, a stable green equilibrium $(1,1,1)$ is reached when bank lending considers that the spread between the standard interest rate r_b and the green interest rate for green investments r_g is not excessively large. That is, the inequality condition $P_{C_g} > L(r_b - r_g)$ is satisfied when the spread between interest rates is very low or even zero $(r_b - r_g) \to 0$, which can occur if both green interest rates and standard interest rates are sufficiently low, meaning that green monetary policy should be expansionary. The economy then converges toward long-term green sustainability. However, the Theorem 2 presents us with another, less efficient green alternative, in which both consumers and firms look for green options, even when there are no incentives on the part of banks that favor this option. In other words, monetary policy is not green. In this case, banks consider the difference between brown and green interest rates to be sufficiently high.

The following Fig. 1 analytically shows the cube's equilibria corresponding to the evolution of the pure strategies of each player in the game. Edges with arrows indicate the direction of convergence, while edges without arrows indicate the fixation of the equilibrium manifold.

Note that, according to Fig. 1, in the areas corresponding to the situations where banks face brown consumers and brown firms or green consumers and green firms, banks are disinterested in following a single strategy. This shows that the decision to consume green motivates banks to adopt a green policy.

3.1.2. The dynamics of the mixed Nash equilibrium

Unlike pure strategy equilibria, a mixed strategy Nash equilibrium corresponds to a profile of probability distributions. The equilibrium will be strictly mixed if it corresponds to a point inside the cube C. We begin our discussion of the stability of mixed equilibria given by (8) by estimating and evaluating the Jacobian of the system (11) at the equilibrium point (8). Thus, we obtain the following:

$$\begin{pmatrix} 0 & n^e_{C_g}(1-n^e_{C_g})B_C & n^e_{C_g}(1-n^e_{C_g})C_C \\ n^e_{F_g}(1-n^e_{F_g})B_F & 0 & n^e_{F_g}(1-n^e_{F_g})C_F \\ n^e_{B_g}(1-n^e_{B_g})(n_{F_g}A_B + B_B) & n^e_{B_g}(1-n^e_{B_g})n_{C_g}A_B & 0 \end{pmatrix} \tag{13}$$

where:

$$\begin{aligned} &A_B = (r_g - r_b)L < 0, \quad B_B = P_{C_g} > 0, \\ &B_C = u_{gg} - u_{gb} + u_{bb} - u_{bg} > 0, \quad C_C = P_{B_g} > 0, \quad D_C = u_{gb} - u_{bb} < 0, \\ &B_F = \pi_{gg} + \pi_{bb}, \quad C_F = (r_b - r_g)L > 0, \quad D_F = \tau K - \gamma L - \pi_{bb} < 0. \end{aligned} \tag{14}$$

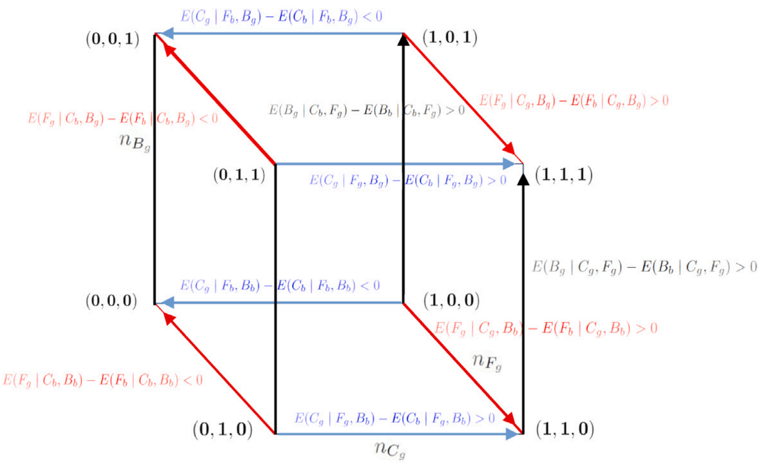

Fig. 1. The edges dynamics considering that $\alpha_{C_g} = 1$ and $1 > L(r_b - r_g)$.

Inequalities are consequences of the assumptions of the model. A direct computation allows us to conclude that the characteristic polynomial of the (13) is given by:

$$p(\lambda) = -\lambda^3 + A\lambda + B \tag{15}$$

where:

$$\begin{aligned} A &= n^e_{C_g} n^e_{F_g}(1 - n^e_{F_g})\left(n^e_{B_g}(1 - n^e_{B_g})A_B C_F + (1 - n_{C_g})B_C B_F\right), \\ B &= n^e_{C_g}(1 - n^e_{C_g})n^e_{B_g}(1 - n^e_{B_g})n^e_{F_g}(1 - n^e_{F_g})n_{C_g}\left(A_B B_F C_C + (n_{F_g} A_B + B_B)B_C C_F\right) \\ &= n^e_{C_g}(1 - n^e_{C_g})n^e_{B_g}(1 - n^e_{B_g})n^e_{F_g}(1 - n^e_{F_g})n_{C_g} A_B B_F C_C. \end{aligned}$$

Here we have used the fact that $n_{F_g} A_B + B_B = 0$, and the conditions of (8) and (14) hold. Then we have the following theorem about the stability of the mixed Nash equilibrium (see Appendix B for the proof).

Theorem 3. *The mixed Nash equilibria equilibrium* (8) *is an unstable state (a saddle point or spiral saddle point) of the RD system* (11).

The instability of the mixed Nash equilibrium suggests that small changes in consumer preferences, firm decisions, or banking policies can permanently shift the economy toward a green or brown state. In terms of the model's dynamics, the economy's evolution depends on its initial state – i.e., the population distribution at a given time – and the values of key parameters. Over time, the economy moves toward one of the stationary states at the vertices, reflecting a convergence toward widespread adoption of either green or brown strategies.

Given the initial conditions and parameter settings, we then perform numerical simulations showing the evolution of the economy (represented by the system (11)) to visualize the above. In this way, we can demonstrate that the interior mixed Nash equilibrium is unstable. On the contrary, in such an economy, environmental traps emerge in the face of the possibility of escaping them and moving toward an environmentally sustainable equilibrium.

4. Numerical simulations

To better understand the behavior of our economy represented by the system (11) and all the results predicted by the previous theorems, we perform several simulations providing different sets of parameters, trying to be consistent, when possible, with empirical evidence. The parameters r_b, L, K, π_{bb}, u_{bb}, u_{bg}, u_{gb} are designated as constant variables,[17] while the remaining parameters, as listed in Table 4, will be varied accordingly. Note that, according to Fig. 1, in areas where banks interact with either brown consumers and brown firms or green consumers and green firms, banks are neutral in their choice of strategy. This illustrates that consumers' choice of green products can motivate banks to adopt a green policy, offering preferential financing to green firms.

Parameters for which no data are available, such as consumers' utilities (typically expressed ordinally) or the profitability of green and brown firms, are chosen qualitatively. They take only two values, indicating whether a brown firm is more or less profitable than a green firm, or whether a green consumer derives higher utility from a green product than a brown consumer does from

[17] That is, $r_b = 0.05$, $L = 100$, $K = 100$, $\pi_{bb} = 140$, $u_{bb} = 200$, $u_{bg} = 0$, $u_{gb} = 0$.

Table 4
Parameter sets.

Parameter	r_g	γ	τ	π_{gg}	u_{gg}	P_{B_g}	M_{C_g}
Simulation I	0.045	0.3	0.3	160	230	2.1	2.2
Simulation II	0.045	0.3	0.4	160	200	3	3.1
Simulation III	0.045	0.3	0.4	140	230	3	3.1
Simulation IV	0.045	0.2	0.1	160	230	3	3.1
Simulation V	0.045	0.2	0.0	140	200	3	3.1
Simulation VI	0.045	0.3	0.3	140	200	3	3.1
Simulation VII	0.045	0.3	0.5	140	200	3	3.1
Simulation VIII	0.01	0.3	0.3	140	200	3	3.1
Simulation IX	0.045	0.3	0.3	140	200	3	−1

a brown product. This also applies to values such as profits and loans, Cellini et al. (2020) and Sanchez-Carrera (2019).[18] Their variation with respect to the single simulations is just made to change the consumers' and firms' incentives structure (see Table 4). The same has been done for those parameters for which we observe too large variability, such as capitalization of firms, that is, L and K, which are assumed, for simplicity, to be an amount equal to 100 in all the simulations. What is relevant in the choice of the parameters and in this simulation exercise is not the value each parameter takes but their reciprocal relationship that leads to the existence and stability of the various equilibria, as stated in Theorems 1 and 2 in Section 3. Conditions assumed in Theorems 1 and 2 are exhaustive as they cover all the cases under which an equilibrium exists. All the parameter sets that respect those conditions will eventually reach the stable equilibrium predicted by the model.

With those premises, consumers' utilities u_{bb} and u_{gg} take only two values, 200 and 230, in order to assess what happens to the results when green and brown consumers experience the same utilities when consuming their preferred product, or if green consumers experience higher utility when they consume green products in comparison to a brown consumer consuming a brown product. Similarly, the revenues of firms take only two values. Brown firms are taken as a benchmark and are always assumed to have the same revenues π_{bb}, while green firms are allowed to have the same revenues as the brown firms or higher (π_{gg}). Moreover, P_{B_g} and M_{C_g} are set to an arbitrary level consistent with the constraints imposed in the previous sections.

Regarding the taxation of polluting capital, we identified a range of values. Defining a tax based on capital stock rather than on actual pollution is challenging, as environmental taxes are typically tied to the amount of emissions produced—a variable not included in our model.[19] To address this, we used Italy as a reference, where such a tax is applied to capital despite differences in pollution intensity across assets. Road haulers with trucks featuring low-emission engines receive a carbon tax refund of about €0,21 per liter of diesel, while trucks with older or non-compliant engines receive no refund, paying the full €0,21 per liter. Assuming a diesel price of approximately €1,6 per liter, including the carbon tax, this corresponds to a carbon tax of roughly 14% of the fuel's value.[20] As parameters for simulation, then, we used a range of taxes on polluting capital from 0 (*laissez-faire* condition) to a maximum level of 0.5 (that is, 50%), which might be the value of taxes needed to lead the countries that are stuck in an environmental trap, toward a virtuous path. Most of the tax levels used in the simulation were around 30%–40%, consistent with the evidence provided by the most virtuous countries.

With regards to the interest rate levels, we set the brown interest rate at 5%, according to a study carried out by Confindustria, based on data released by the Bank of Italy.[21] We then examined the benefits that major Italian banks offer to firms making green investments.Specifically, we analyzed information sheets for two types of unsecured business loans offered by Banco BPM S.p.A., a bank with significant national presence. The bank provides loans at differentiated interest rates depending on the firm's intended use of funds. Although these rates are higher than those reported by Confindustria – since the loans are unsecured, whereas other Italian firm credit may be guaranteed – a standard loan of €100.000,00 with a three-year term carries an interest rate of %, including a spread of 11.5%. However, if the firm engages in green investments, the interest rate falls up to 11,24% with a repayment term of 5 years, €100.000,00 of capital and a spread equal to 9%. Considering that we set the brown interest rate equal at 5%, we re-proportioned the benefit for green investments at a half percent point, therefore setting the green interest rate at 0.045 (4.5%), which we believe it could be a fair approximation of the average benefit in the economy, as represented by our game.[22] In the case

[18] When possible, however, we tried to link the choice of our parameters to values that we believe are realistic. See: https://www.ecb.europa.eu/press/economic-bulletin/articles/2025/html/ecb.ebart202501_03~90ade39a4a.en.html and https://futurium.ec.europa.eu/en/promoting-enterprise/news/new-flash-eurobarometer-shows-smes-are-driving-green-transition

[19] For example, the carbon tax is usually computed on the amount of carbon emissions. Carbon taxes in Europe in year 2024 ranged from less than €1 per metric ton of carbon emissions in Ukraine to more than €120–130 in Sweden, Norway, and Switzerland. Italy had a carbon tax equal to €57 per ton of CO2 emissions. Data from https://carbonpricingdashboard.worldbank.org/compliance/price. Link accessed last time on March 13, 2025.

[20] Data relative to September 2024. Source https://sisen.mase.gov.it/dgsaie/prezzi-mensili-carburanti. This approach has limitations. Fuel prices, as well as the costs of other primary production inputs, can fluctuate due to exogenous and unpredictable factors such as shocks or wars, which may reduce the impact of taxes on polluting capital on green technology investments—sometimes increasing or remaining constant in percentage terms due to rising prices. Nonetheless, the model provides a reasonable approximation when price fluctuations are small. While it does not represent actual reality, under stable economic conditions it can help clarify the mechanisms that guide countries toward successful green transitions or into environmental traps.

[21] This study is available at https://www.confindustria.it/home/centro-studi/prodotti/previsioni/rapporto/highlights/rapporto-previsione-economia-italiana-autunno-2024/4450a521-615e-4af8-b5e0-d2a734796003. Basically, the average cost of money for firms recorded in September 2024, according to this study, is around 5%.

Table 5
In simulation I, for many initial conditions, the solutions go either to the equilibrium point $(1,1,0)$ or to the line of stable equilibria $(0,0,n_{B_g}(0))$.

Initial condition $\left(n_{C_g}(0), n_{F_g}(0), n_{B_g}(0)\right)$	Solution converge to $\left(n^*_{C_g}, n^*_{F_g}, n^*_{B_g}\right)$	Curve color in Figs. 2 or 3
$(0.5, 0.5, 0.5)$	$(1,1,0)$	Black
$(0.25, 0.5, 0.5)$	$(0,0,0.5)$	Red
$(0.5, 0.25, 0.5)$	$(0,0,0.5)$	Green
$(0.5, 0.5, 0.25)$	$(1,1,0)$	Blue

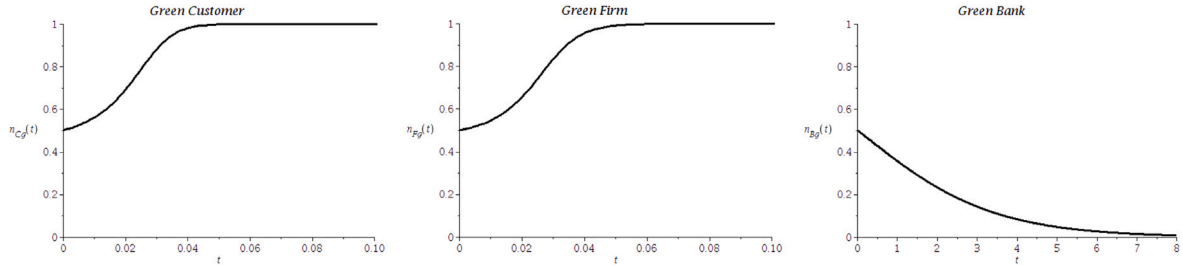

Fig. 2. The time series of n_{C_g}, n_{F_g}, and n_{B_g} with the initial conditions $\left(n_{C_g}(0), n_{F_g}(0), n_{B_g}(0)\right) = (0.5, 0.5, 0.5)$ in Simulation I.

of simulation VIII, we decreased the green interest rate up to 1% in order to verify whether the benefits of green interest rates, with all other parameters remaining constant, may lead to a virtuous path toward transition at a lower share of green consumers in the economy.

4.1. Simulations I, II III and IV

Simulation I, as shown in Table 4, is defined by a parameter set so that there is a balance between the capital borrowed by green firms for environmental sustainability investments L and the polluting capital taxed for brown firms K. This assumption is held constant for all the simulations. Moreover, brown firm taxes τ are set equal to the environmental investments γ made by green firms . The interest rate for brown firms is set at 5%, while green firms benefit from a slightly lower rate of 4.5%. Additionally, green firms are associated with larger sales than those of brown firms, as indicated by the revenue levels: $\pi_{gg} = 160$ compared to $\pi_{bb} = 140$. From a consumer perspective, green consumers obtain greater utility than brown consumers when purchasing products aligned with their respective preferences.

Taking this parameter into consideration, we observe a bi-stable condition in which the equilibrium point $(1,1,0)$ is an asymptotically stable equilibrium and the line of equilibrium $(0,0,n^*_{B_g})$ represents a line of stable equilibria. This point satisfies the condition $P_{C_g} < L(r_b - r_g)$ as stated in Theorem 2(b). The choice of initial conditions significantly influences the decisions, as shown in Table 5:

In Fig. 2, we can see that at $t = 0.05$, both green consumers and green firms have already reached a value of 1, while the green bank's value declines to 0 for $t > 8$. The black curve illustrates an initial condition where each sector of consumers, firms and banks begins with a 50% adoption rate of green practices. Over time, the system moves toward an equilibrium point of $(1,1,0)$, meaning that consumers and firms rapidly fully adopt green practices, while banks show little or no participation. If the initial percentage of banks adopting green practices is reduced to 25%, as shown by the blue curve in Fig. 3, the system still converges toward the same equilibrium point (1, 1, 0). However, suppose the initial adoption rates of green practices among consumers (represented by the red curves) and firms (green curves) are also lowered to 25%, while keeping the relative shares of firms and banks, as well as consumers and banks, constant. In that case, the system moves toward a different equilibrium line, represented by $(0,0,n_{B_g}(0))$, as depicted by the red and green curves. This suggests that banks consistently play a key role in supporting green sustainability over time.

It is worth noting that qualitatively similar results can be achieved with different parameter sets. Specifically, these results hold for the parameters listed in Table 4 under Simulations II, III, and IV.

Simulation II differs from Simulation I by assuming a higher pollution tax than the investment in sustainability, while the utility gained by green and brown consumers from their respective products remains equal. Interest rates are unchanged from Simulation I, and green firms continue to earn higher revenues than brown firms.

[22] Interest rate on unsecured loans to firms (for any purpose) can be found at https://www.bancobpm.it/DWN/trasparenza/Documenti/62428.pdf. Interest rate on unsecured loans to firms that invest in environmental sustainability can be found https://www.bancobpm.it/DWN/trasparenza/Documenti/62027.pdf. Last access on March 13, 2025.

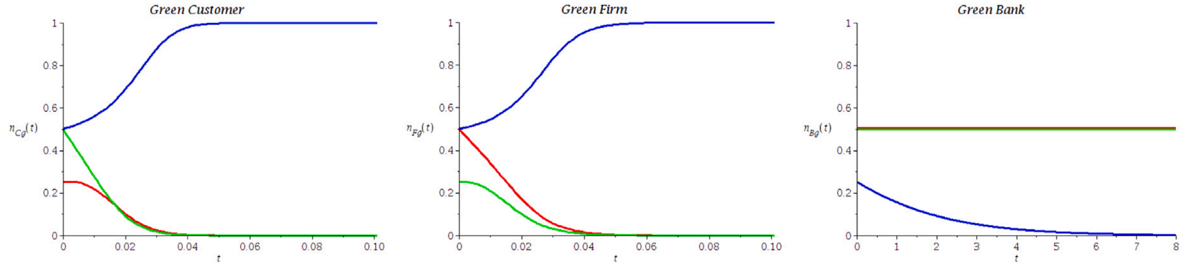

Fig. 3. The time series of n_{C_g}, n_{F_g} and n_{B_g} with some the initial conditions in Simulation I. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

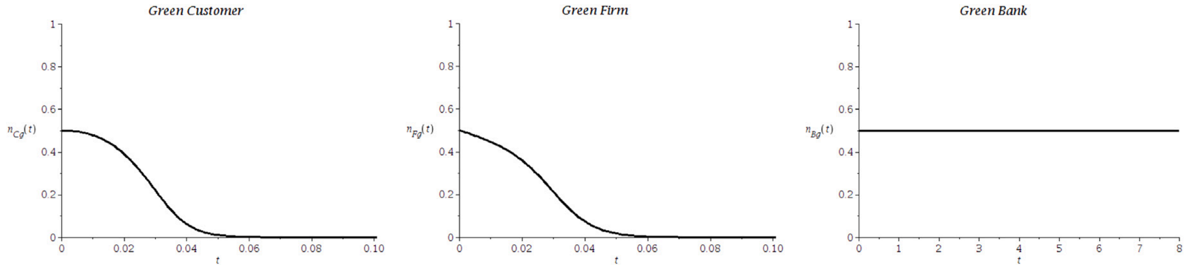

Fig. 4. The time series of n_{C_g}, n_{F_g}, and n_{B_g} with the initial conditions $\left(n_{C_g}(0), n_{F_g}(0), n_{B_g}(0)\right) = (0.5, 0.5, 0.5)$ in Simulation V.

Simulation III also assumes a higher pollution tax relative to sustainability investments, making pollution more costly, while equalizing the revenues of green and brown firms. As in Simulation I, green consumers retain moral concerns for the environment, deriving greater utility from green products than brown consumers do from brown products.

Simulation IV differs from Simulation I by introducing lower taxes τ on polluting capital than investments γ in green sustainability. Green firms continue to earn higher revenues than brown firms, and moral values for environmental responsibility remain, so green consumers still derive greater utility from green products than brown consumers do from brown products. To avoid redundancy, we present only the graphs for Simulation I, as the other simulations show qualitatively similar trends.

To avoid redundancy in graphical representation, we present only the graphs corresponding to Simulation I in the text, as the other simulations exhibit qualitatively similar trends.

4.2. Simulation V

Simulation V is particularly significant as it tests whether the previous results hold even in the absence of taxation on polluting capital—a scenario we refer to as the *laissez fare* case. As in the previous simulations, we impose the condition $P_{C_g} < L(r_b - r_g)$, as stated in Theorem 2(b). The interest rates for brown and green firms remain at 5% and 4.5%, respectively. The amounts allocated to green transition investments and polluting capital are assumed to be equal, as are the revenue levels of brown and green firms, along with the utilities derived by brown and green consumers when purchasing products of their respective types.

Consumer moral values toward the environment are reflected solely in the parameter P_{B_g}. As previously specified, this positive parameter indicates that consumers derive higher utility when matched with a green bank. On the other hand, M_{C_g} represents the gross benefit the bank gains from attracting green consumers, which is positive.

Using the same initial conditions as in the first simulation, we observe that all solutions converge to $(0, 0, n_{B_g}(0))$, as shown in Figs. 4. The results indicate that if 50% or fewer of the population initially adopt green practices – i.e., if the share of green consumers is low – the system will converge to an environmental trap in which all consumers and firms choose brown. In this case the conditions of Theorem 1, case b are satisfied, that is, $E(F_g) - E(F_b) < 0$. This result holds even when we decrease, one at a time, the share of consumers, firms, and banks to levels lower than 50% (results not shown).

On the other hand, if we increase the share of green consumers up to 75%, keeping the share of green firms and banks at 50% (green line), or increase the share of green firms at 75% keeping the share of green consumers and banks (blue line) constant at 50%, the system converges toward the equilibrium $(1, 1, 0)$ because the condition $E(F_g) - E(F_b) < 0$ ceases to hold, as shown in Fig. 5. Elevating the share of green banks to 75% and keeping the share of green firms and consumers (red line in Fig. 5) at 50%, does not allow the system to engage in a virtuous path toward sustainability since the system will drop to the polluted equilibrium $(0, 0, n_{B_g}(0))$.

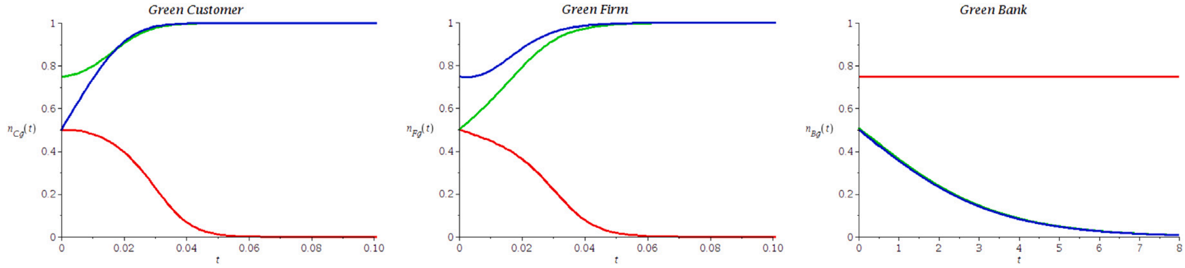

Fig. 5. The time series of n_{C_g}, n_{F_g}, and n_{B_g} in Simulation V, with initial conditions of 50% or more of customers, firms, and banks choosing green sustainability. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

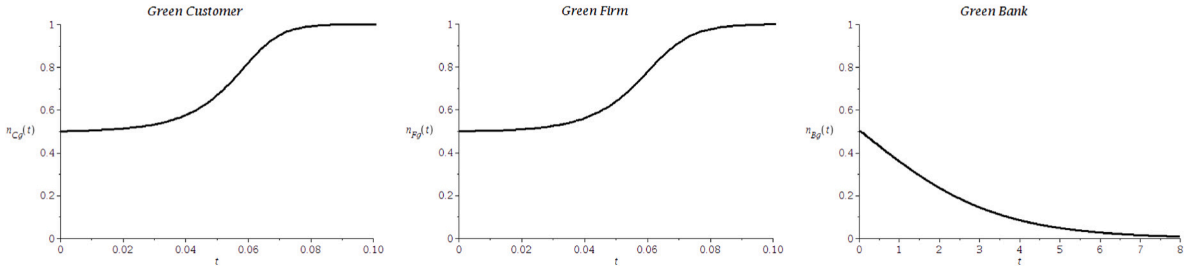

Fig. 6. The time series of n_{C_g}, n_{F_g}, and n_{B_g} with the initial conditions $\left(n_{C_g}(0), n_{F_g}(0), n_{B_g}(0)\right) = (0.5, 0.5, 0.5)$ in Simulation VI.

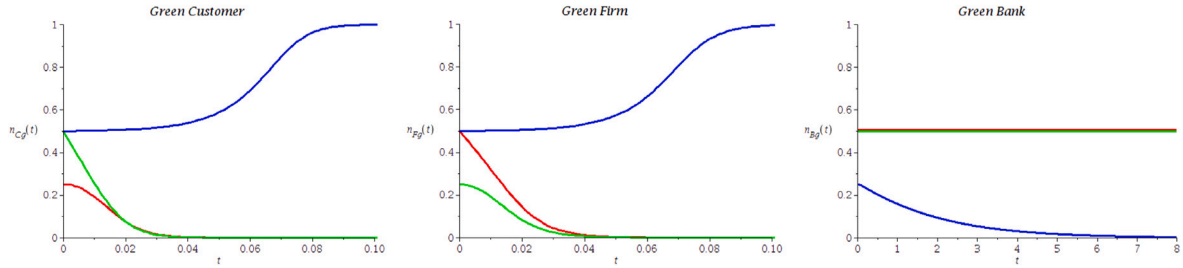

Fig. 7. The time series of n_{C_g}, n_{F_g} and n_{B_g} in Simulation VI with some initial conditions less than or equal to 50% choosing green sustainability.

4.3. Simulations VI, VII & VIII

Simulation VI assumes that the tax on polluting capital equals investment in green sustainability, while Simulation VII assumes the tax exceeds green investment. In both cases, green and brown consumers derive the same utility from their respective products, and green and brown firms earn equal revenues. Interest rates remain unchanged from previous simulations, with brown loans at 5% and green loans at 4.5%.

As before, moral values for the environment are captured solely by the P_{B_g} parameter, which reflects that consumers receive a higher additional utility when matched with a bank of their type. Given that the qualitative results of both simulations are highly similar, we here present only the results of Simulation VI to avoid redundancy in the figures. As previously observed, unlike the results from Simulation V, the system now converges to the virtuous equilibrium $(1, 1, 0)$ when starting with an initial condition of 50% green firms, consumers, and banks. This equilibrium is characterized by all firms and consumers adopting green practices, while banks remain brown. Compared to the *laissez-faire* scenario, the introduction of taxes on polluting capital allows the system to reach a high equilibrium even with a lower initial share of green consumers and firms (see Figs. 4 and 6).

Thus, when moral concern for the environment is not widespread, implementing or increasing taxes on polluting capital can help the system converge to a virtuous equilibrium, assuming all other parameters remain constant.

Qualitatively similar results occur when the share of green consumers or firms is increased to 75%, with the only difference being a faster convergence to the high equilibrium (1, 1, 0). Conversely, when the share of green consumers (red line) or green firms (green line) is individually reduced to 25%, the system shifts toward the vicious equilibrium $(0, 0, n_b(0))$ (see Fig. 7). However, decreasing the share of green banks to 25% while maintaining 50% green firms and consumers does not impact the system's convergence to the virtuous equilibrium (1, 1, 0).

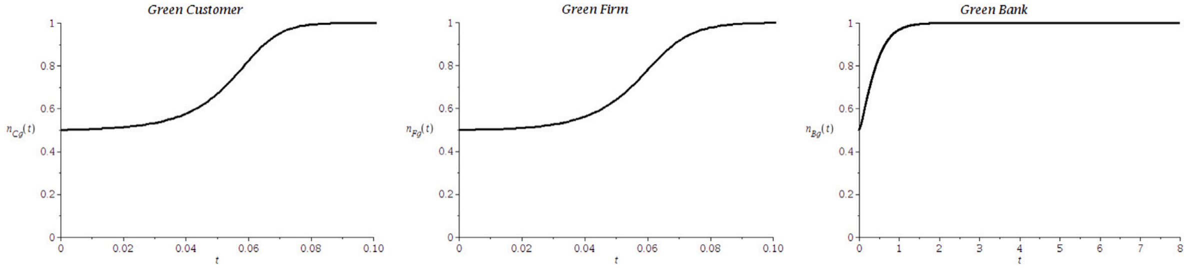

Fig. 8. The time series of n_{C_g}, n_{F_g}, and n_{B_g} with the initial conditions $\left(n_{C_g}(0), n_{F_g}(0), n_{B_g}(0)\right) = (0.5, 0.5, 0.5)$ in Simulation IX.

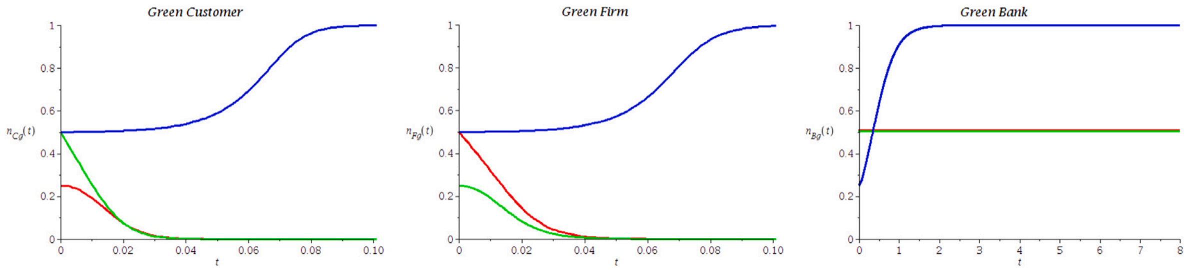

Fig. 9. The time series of n_{C_g}, n_{F_g} and n_{B_g} in Simulation IX with some of the initial conditions less than or equal to 50% choose green sustainability. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Notably, in Simulation VIII, reducing the green interest rate to 1% while keeping the brown rate at 5% and maintaining all other parameters from Simulation VI – equal revenues for green and brown firms, equal utility for green and brown consumers, and parity between pollution taxes and green investment – leads to faster convergence of banks toward the (1, 1, 0) equilibrium when the share of green firms and consumers is at least 50% (results not shown).

4.4. Simulations IX

In this simulation, we adopt the assumption from Theorem 2(a) that $P_{C_g} > L(r_b - r_g)$. Additionally, we assume $M_{C_g} < 0$, meaning that a green bank's extra utility when interacting with a green consumer is greater than the utility a green consumer derives from engaging with a green bank.

As shown in Table 4, the condition $P_{C_g} > L(r_b - r_g)$ is clearly satisfied, given that $P_{C_g} = 4$ and $L(r_b - r_g) = 0.5$. As in previous simulations, the brown and green interest rates remain fixed at 5% and 4.5%, respectively. Moreover, the amount of polluting capital subject to the carbon tax matches the loan amount firms allocate to environmental transition.

In this scenario, the carbon tax (or tax on polluting capital) is set equal to the investment in green sustainability. Additionally, there are no differences in revenues between brown and green firms, nor in the utilities that green and brown consumers derive when purchasing products of their respective types.

In keeping with this parameter, at 50% or higher share of green consumers, firms, and banks, all three populations converge to the adoption of green practices, that is, toward the equilibrium $(1, 1, 1)$ (see Fig. 8).

However, when the share of green consumers drops to 25%, while green firms and banks remain at 50% (red line in Fig. 9), both consumers and firms converge to brown strategies, whereas the share of green banks stays at its initial level. A similar outcome occurs when green firms decrease to 25% while consumers and banks remain at 50% (green line). In contrast, reducing green banks to 25%, with green consumers and firms at 50%, does not prevent banks from fully adopting green practices (blue line in Fig. 9).

The success of the green transition ultimately depends on the proportion of green firms and consumers, which creates a cycle of mutual reinforcement. More green consumers increase the revenues of green firms, and the success of these firms makes green consumption more attractive. Banks, however, play a secondary role. They adopt green practices only if the added value of engaging with green consumers outweighs the financial cost of offering lower interest rates to green firms. Otherwise, banks maintain standard "brown" rates, without affecting the choices of consumers and firms (see Figs. 6 and 8).

5. Discussion and policy recommendations

This paper analyzes a 2 × 2 × 2 symmetric game involving consumers, firms, and banks, each with two available strategies, one environmentally friendly and the other not. Consumers decide whether to prioritize environmental concerns in their purchasing choices, while firms must choose between investing in sustainability or paying a pollution tax. Banks can either support green investments by offering preferential interest rates or apply standard, higher rates to all investments.

A key finding of our model is the existence of multiple stable equilibria. Depending on parameter values, the system may converge to either an environmental trap or a virtuous equilibrium that supports the green transition. The environmental trap occurs when consumers and/or firms consistently choose non-green consumption and production, creating a stable state that impedes sustainable development. Importantly, with the same parameters, the economy's path toward either outcome depends on the initial share of environmentally conscious consumers and firms.

Numerical simulations support our analytical findings: moral values and environmental concerns accelerate the system's progression toward a virtuous path, where all consumers and firms adopt green consumption and production practices. However, when the spread of these moral values diminishes, meaning the proportion of green consumers and/or firms decreases, an increase in taxation may help bridge the gap. This makes it more financially attractive for firms to invest in green practices rather than pay the environmental tax (as shown in simulation VII).

Banks are also indirectly influenced by moral values. As long as the additional benefits a green bank receives from serving green consumers (represented in our model by the factor P_{C_g}) exceed the difference between brown and green interest rates on loans, the bank will also converge to the high equilibrium, as demonstrated in simulation IX. The greater this extra benefit, combined with a higher share of green consumers, the more likely the system will converge to the high equilibrium.

In our framework the environmental concerns of consumers are represented by the level of utility a consumer derives from consuming products produced according to environmental standards. Increasing the utility that green consumers experience from purchasing green products boost the proportion of green consumers. This, in turn, enhances the revenues of green firms and encourages the emergence of more green firms, leading to equilibria such as $(1, 1, 0)$ or $(1, 1, 1)$. The specific equilibrium depends on whether a green bank's additional payoff from serving green consumers is greater than or less than the differential between the returns on brown and green loans granted to firms.

When moral values are scarce among consumers, taxes on polluting capital can help the economy escape an environmental trap by making standard production more costly. Lowering interest rates on green investments can also encourage firms to adopt green production, but this is effective only if a sufficient share of banks is green. Thus, for green interest rates to support the transition, the economy must maintain a high share of green banks, which depends on the proportion of green consumers and the additional payoff banks receive from serving them.

Our model shows that outcomes can differ greatly depending on various factors, leading either to environmental traps or to virtuous equilibria. Many economies remain stuck in environmental traps, while others have successfully broken free, setting themselves on a path toward sustainability and ecological recovery. At the global scale, however, the picture is more troubling: the world's ecological footprint – measuring resource use – surpassed the planet's sustainable capacity as early as 1970 and has continued to rise ever since, while the biodiversity index has declined by more than half.[23] Emissions of greenhouse gasses are rising, and the impact of global warming is growing.[24] Acidification of rains and oceans is another example, along with plastic pollution which does not see an end. In 1950, the world produced more than 2 million tons of plastic per year. By 2015, annual production had surged to 419 million tons, further worsening the problem of plastic waste in the environment.[25] These are just a few examples of the environmental traps in which countries remain stuck. At the same time, there are also well-documented cases of nations that have implemented successful recovery plans. For instance, according to the U.S. Environmental Protection Agency (EPA), between the observation periods of 1989–1991 and 2009–2011, wet sulfate deposition – a major cause of acidification – fell by more than 55% on average across the eastern United States. The substantial emissions reductions achieved through the Acid Rain Program not only lowered atmospheric levels of fine particle pollution but also prevented numerous premature deaths. Toxic emissions from onroad and nonroad vehicles and engines are also dropping due to requirements for cleaner fuels and engines. These emissions are projected to decline by 80% from 1990 levels by 2030. Onroad and nonroad diesel particulate matter emissions decreased by about 27% from 1990 to 2005 and are projected to fall by an additional 90% between 2005 and 2030. Airborne levels of benzene, a carcinogen found in gasoline, declined by 66% from 1994 to 2009 based on available air quality monitoring information.[26] The success of some countries in reducing certain pollution indicators through environmental restoration plans demonstrates that our model provides a reasonably accurate reflection of reality. This underscores the importance of governments adopting strong environmental policies – ideally integrated strategies – that promote consumer awareness, implement effective taxation, and offer incentives for firms transitioning to greener production practices. Such measures represent the most effective path toward a successful transition.

As we learned from our model, the main drivers of this virtuous transition are often consumers' moral values encouraged by banks' lending policies, which contribute to the thriving of green firms.

Evidence shows that the main trends in green consumption habits are promising in some sectors of the economy, claiming that consumers do display moral values when they make consumption decisions. According to the Study Center for Circular Economy by CONAI which interviewed a group of Italian consumers in the food and beverage sector repeatedly from the year 2020 to 2024,[27] 86% of those consumers had implemented behaviors aimed at buying products from local producers, thus reducing emissions connected to the transport chain. The largest increase occurred between 2023 and 2024, with a rise of 10%. The authors of this study also

[23] United Nations Environment Programme (UNEP). Global Environmental Outlook 5 Report; UNEP: Nairobi, Kenya, 2012.

[24] Intergovernmental Panel on Climate Change (IPCC)

[25] https://earth.org/the-biggest-environmental-problems-of-our-lifetime/

[26] Content available at https://www.epa.gov/clean-air-act-overview/progress-cleaning-air-and-improving-peoples-health. Last access July 10th, 2025.

[27] The sample of consumers interviewed was not the same during the different waves of interviews, but the sample chosen was such that it was representative of the full consumers' cohort aged between 18 and 70. The full report, released in 2025, is available at https://www.conai.org/wp-content/uploads/2025/03/Report_Conai_Scelta_2025_Full-version_ITA.pdf. Last access July 10th, 2025.

observed more responsible buying habits aimed at reducing waste, such as buying more frequently food with a close expiration date (+54% in 4 years) or food with recycled packaging (+64%). With regards to other sectors of the economy like clothing, from 2020 to 2024 consumers that decided to opt for second-hand purchases increased by 42%, especially in the last year (+35% from 2023 to 2024). Moreover, 32% of consumers prefer buying products produced with renewable energy, and the trend is mainly constant throughout the period analyzed. This sentiment is confirmed by the PwC report of a survey carried out in 31 countries,[28] which estimated an additional willingness of consumers to pay up to 9,7% for green products. While the trend toward more conscious consumption on the part of consumers is undeniable, inconsistencies remain in the lending policies adopted by the financial sector. A recent study carried out by the European Central Bank from 2014 to 2020 reveals that despite banks disclosing their environmental initiatives, they tend to lend more to brown firms, and the more they disclose, the more they lend to brown firms.[29] The authors of this study find that the measure of banks' environmental disclosures increases over the sample period by about 27%. This is in line with the increasing focus on climate topics and the increasing attention shown to climate by stakeholders. Banks with more extensive environmental disclosures tend to discuss environmental issues with a positive sentiment or tone, although it is observed that the same banks when deciding their lending policy tend to specialize in extending loans to brown industries. This may be because banks with higher exposure to brown industries face increased pressure to disclose their environmental strategies and decarbonization plans, while simultaneously needing to minimize potential losses from these exposures. As a result, if borrowers in brown industries become unprofitable and lack alternative financing options, banks may choose to renew their loans in order to keep these borrowers operational and avoid losses on their balance sheets. Furthermore, the authors find that these banks also show a reluctance to lend to new firms in brown industries, those that could potentially drive innovation in cleaner technologies. On the production side, according to a study carried out by Confindustria,[30] in the manufacturing sector in Italy, emissions decreased by 17,1% from 2014 to 2023, showing that firms have been able to intercept the growing demand for green products. Moreover, Italy seems to be the leader in Europe for waste handling. In 2022 it recycled 53.3% of urban wastes in the key sectors of plastic packaging (54.6%), glass (80.8%) and metals (78.0%).

Given the reality of the facts just described, it is obvious that further research is needed to explore the role of government in this context. Our analysis suggests that a government must focus on three key variables to guide a country toward environmental sustainability:

- Firstly, moral values can be fostered within society through targeted educational programs that raise environmental awareness.
- Secondly, increased taxes on polluting capital. While this can effectively raise the cost of brown production, it mainly impacts the share of green firms and may have limited overall effects on consumers.
- Thirdly, subsidizing banks that offer loans at a lower interest rate for green investments to firms. This may help encompass the problem that we described above, which is mainly due to banks' fear of incurring losses on their balance sheets because of their high exposure to brown firms. Subsidies can take various forms, including measures designed to attract green consumers or investors, thereby providing banks with additional resources to lend to companies. Alternatively, subsidies may come in the form of government-backed guarantees for loans extended to firms investing in green technologies, ensuring repayment even if the firms cannot meet their obligations.

The role of governments in promoting and/or speeding the transition of actual production practices to processes that are sustainable from an environmental perspective is crucial to sustaining private support (Nerlich et al., 2025). Green investments are indeed particularly vulnerable to significant uncertainties, including potential failures of emerging green technologies and innovations, supply chain disruptions, and unexpected shifts in regulatory and policy frameworks. These factors heighten risks for banks and financial investors. Public sector intervention can be crucial in mitigating risks associated with green investments and encouraging private sector participation.

A final consideration that could be crucial for future research is that we have made some assumptions that might not be entirely realistic, although these assumptions have helped us simplify the mathematical feasibility of the problem. In our analysis, we assumed that all economic operators were willing to revise their strategy at the same rate each time. However, the evidence presented above might suggest that reality could be somewhat different, as some actors might be willing to revise their strategy more frequently than others. While the transition to greener consumption is easy for a consumer, converting a technology from brown to green (or vice versa) for a firm could be more problematic and time-consuming. If some populations are willing to revise their strategies at a different rate than others, the dynamics could be different, and further research might be required to analyze this issue. Therefore, if data availability allows, it is crucial to establish testable implications of the main results for statistical inference that corroborate all of the above.

[28] Results of the study are freely available at https://www.pwc.com/gx/en/news-room/press-releases/2024/pwc-2024-voice-of-consumer-survey.html. Last access July 10th, 2025.

[29] Content available at https://www.ecb.europa.eu/press/blog/date/2023/html/ecb.blog231206~fecd1d1634.en.html, last access July 10th, 2025.

[30] Source available at https://public.confindustria.it/repository/2025/04/30012639/Nota_CSC_Sostenibilita_100325_Confindustria.pdf, last access July 11th, 2025.

Table A.6
The eigenvalues of Jacobian of system (11) at four equilibrium points.

The equilibrium point	The eigenvalues of Jacobian matrix
$(1,0,0)$	$1,\ u_{bb}-u_{gb},\ \tau K - L\gamma - \pi_{gg}$
$(1,0,1)$	$-1,\ u_{bb}-u_{gb}-P_{B_g},\ \tau k - L\gamma - L(r_b-r_g)-\pi_{gg}$
$(1,1,0)$	$-[u_{gg}-u_{bg}],\ -[\tau K - L\gamma - \pi_{gg}],\ P_{C_g}-L(r_b-r_g)$
$(1,1,1)$	$u_{bg}-u_{gg}-P_{B_g},\ -[\tau K - L\gamma - L(r_b-r_g)-\pi_{gg}],\ -[L(r_b-r_g)-P_{C_g}]$

Declaration of competing interest

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Appendix A

Proof of Theorem 1. Respectively, the Jacobian of system (11) at $(0,0,n^*_{B_g})$ and $(0,1,n^*_{B_g})$ are

$$\begin{pmatrix} -(u_{bb}-u_{gb}-n^*_{B_g}P_{B_g}) & 0 & 0 \\ 0 & n^*_{B_g}(r_b-r_g)L+(\tau K-\gamma L-\pi_{bb}) & 0 \\ n^*_{B_g}(1-n^*_{B_g}) & 0 & 0 \end{pmatrix},$$

$$\begin{pmatrix} -(u_{bg}-u_{gg}-n^*_{B_g}P_{B_g}) & 0 & 0 \\ 0 & -[n^*_{B_g}(r_b-r_g)L+(\tau K-\gamma L-\pi_{bb})] & 0 \\ n^*_{B_g}(1-n^*_{B_g}) & 0 & 0 \end{pmatrix}$$

which have one zero eigenvalue and imply these equilibrium points are non-hyperbolic equilibria for $0<n^*_{B_g}<1$. The eigenvector of this zero eigenvalue is $(0,0,1)^T$. Assuming that $u_{bb}>u_{gb}+P_{B_g}$, $u_{gg}\geq u_{bg}$, we deduce that $u_{bb}-u_{gb}-n_{B_g}P_{B_g}>u_{bb}-u_{gb}-P_{B_g}>0$ and $u_{bg}-u_{gg}-n_{B_g}P_{B_g}<0$. This implies that $(0,0,n^*_{B_g})$ has one zero eigenvalue, one negative eigenvalue, and $(0,1,n^*_{B_g})$ has one zero eigenvalue, one positive eigenvalue. Thus, system (11) has infinite Nash equilibria of the form $(0,1,n^*_{B_g})$ and is unstable. Let us now focus on $(0,0,n^*_{B_g})$. The stability of this equilibrium depends on the value of the term $n_{B_g}(r_b-r_g)L+(\tau K-\gamma L-\pi_{bb})$, which is equivalent to $E(F_g)-E(F_b)$. If $E(F_g)-E(F_b)<0$, then the system (11) has infinite Nash equilibria of the form $(0,0,n^*_{B_g})$ which is asymptotically stable (or state it as the line of stable equilibria). In contraposition, if $E(F_g)-E(F_b)>0$ then system (11) has two unstable Nash equilibria of the form $(0,0,n^*_{B_g})$ and $(0,1,n^*_{B_g})$. □

Proof of Theorem 2. Consequently, the Jacobian eigenvalues of the system (11) in $(1,0,0)$, $(1,0,1)$, $(1,1,0)$, $(1,1,1)$ are shown in Table A.6:

Based on the assumptions in Section 2, we can derive the following inequalities: $u_{bb}>u_{gb}+P_{C_g}>u_{gb}$, $u_{gg}\geq u_{bg}$, $u_{gg}+P_{C_g}>u_{gb}$, $L\geq\tau K$, $\tau K\geq L\gamma+\pi_{gg}$ and $K(1+\tau)\geq L\gamma+L(r_b-r_g)+\pi_{gg}$. From these inequalities, we can conclude that

- $(1,0,0)$ is an unstable equilibrium point,
- $(1,0,1)$ is a saddle point,
- the stability of $(1,1,0)$ and $(1,1,1)$ depends on the $(P_{C_g}-L(r_b-r_g))$ term. If $P_{C_g}>L(r_b-r_g)$, then $(1,1,1)$ is a asymptotically stable equilibrium point, and $(1,1,0)$ is a saddle point. If $P_{C_g}<L(r_b-r_g)$, then $(1,1,0)$ is a asymptotically stable equilibrium point, and $(1,1,1)$ is a saddle point. □

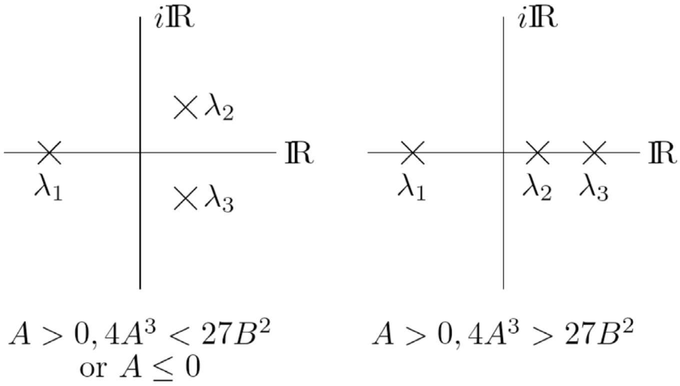

Fig. B.10. The roots of the characteristic polynomial (15). (Left) The eigenvalues for a spiral saddle point. (Right) The eigenvalues for a saddle point.

Appendix B

Proof of Theorem 3. Since the coefficient of the quadratic term of (15) is zero, and from Eq. (14) we can infer that B is strictly negative, we can conclude that:

$$\lambda_1 + \lambda_2 + \lambda_3 = 0,$$
$$\lambda_1 \lambda_2 \lambda_3 < 0.$$

Therefore, one of the λ's is negative, let us say λ_1, and the other two have a positive real part. The discriminant of the cubic polynomial (15) can be calculated using the Cardano formula: $D = 4A^3 - 27B^2$. If $A > 0$ and $4A^3 > 27B^2$, then $D > 0$ and as a result, we will have two real positive roots $\lambda_3 \geq \lambda_2 > 0$. Thus, the mixed Nash equilibrium point (8) is a saddle point, see Fig. B.10 (right). On the other hand, if $A > 0$ and $4A^3 < 27B^2$ or $A \leq 0$, then $D < 0$ and we will have a conjugate complex $\lambda_{2,3} = \alpha \pm i\beta$ where $\alpha > 0$. Thus, the mixed Nash equilibrium point (8) is a spiral saddle point; see Fig. B.10 (left). It is important to note that there is no case for $D = 0$ because $B < 0$. Hence, the strictly mixed Nash equilibrium (8) is either a saddle point or a spiral saddle point in a dynamical system (10).

Appendix C

In Theorem 2, we have already analyzed the dynamics when $P_{C_g} > L(r_b - r_g)$ or $P_{C_g} < L(r_b - r_g)$. For the case when $P_{C_g} = L(r_b - r_g)$, the mixed Nash equilibrium (8) becomes:

$$(n^e_{C_g}, n^e_{F_g}, n^e_{B_g}) = \left(\frac{n^e_{B_g} + \gamma L + \pi_{bb} - \tau K}{\pi_{gg} + \pi_{bb}}, 1, \frac{u_{bg} - u_{gg}}{P_{B_g}} \right).$$

It is important to note that $n^e_{F_g} = 1$ and the value of u_{gg} is greater than or equal to u_{bg}, resulting in a negative value for $n^e_{B_g}$, which means it is impossible to coalesce with any of the vertices equilibriums.

Data availability

No data was used for the research described in the article.

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