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Green licenses and environmental corruption: a random matching model

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Abstract

This paper studies environmental corruption via a random matching evolutionary game between a population of firms and a population of bureaucrats who have to decide whether to release a "green" license to the firms. A firm obtains the license if the bureaucrat checks that it complies with environmental regulations, otherwise it is sanctioned. The model assumes that there are two types of bureaucrats (honest and dishonest), two types of firms (compliant and non-compliant), and two possible crimes (corruption and extortion). Corruption occurs when a dishonest bureaucrat accepts a bribe from a non-compliant firm, while extortion occurs when a dishonest bureaucrat claims a bribe from a compliant firm. When there is no dominance of strategies, we show that there exist two bistable regimes, in which two attractive stationary states exist, and two regimes with an internal stable equilibrium, corresponding to the mixed strategy Nash equilibrium of the one-shot static game, surrounded by closed trajectories. From comparative statics analysis performed on the latter two dynamic regimes, it emerges that policy instruments may help the Public Administration reduce both corruption and extortion, although increasing sanctions and detection probability do not always get the desired results.

Keywords: Bureaucratic corruption, Evolutionary games, Environmental regulations, Economics of crime.
JEL classification: C73, D21, D73, K42, Q52.

1 Introduction

Recently, the media have focused a lot of attention on compliance with environmental regulations by industrial enterprises and on inspection by bureaucrats, especially after the so called *Volkswagen scandal*.[1] However, these issues have attracted the attention of economists for a

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[1]In September 2015, the German automaker Volkswagen Group has received a notice of violation of the Clean Air Act from the United States Environmental Protection Agency (EPA). It was found that the enterprise had used a software applied to some diesel engines to activate certain emissions controls only during laboratory emissions testing. The software caused the compliance with U.S. environmental standards for nitrogen oxide (NO_x) output during laboratory tests, but produce up to 40 times higher NO_x output in real-world driving. See, for further details, both links: Financial Times and The New York Times.

long time. The incentive to comply with environmental regulation is obviously reduced if the inspection effort is insufficient or not properly done. This may depend on many reasons, including lack of financial resources to perform proper controls, inability of inspectors to discover violations or corruption of inspectors. In particular, several studies have analysed the negative effects of corruption on environmental degradation. In this regard, it is possible to identify two main strands in the literature on this issue. The first strand has examined the effects of bureaucracy and lobbying groups on the efficacy of environmental policy (Lopez and Mitra, 2000; Damania et al., 2003; Fredriksson et al., 2003; Fredriksson and Svensson, 2003; Cole et al., 2006; D'Amato and Zoli, 2012, 2013; D'Amato et al., 2015). The second strand, instead, has analyzed the effects of corruption on environmental degradation through economic growth, investigating how corruption affects the shape of the so-called *Environmental Kuznets Curve* (Welsch, 2004; Cole, 2007; Leitao, 2010).[2]

The link between corruption and economic growth is the object of a heated debate in the literature. Several studies (Mauro, 1998; Mo, 2001; Blackburn et al., 2006) consider bribery as a "grabbing hand" and, therefore, as an evil for economic growth. This seems to be confirmed by the fact that the most corrupt countries have generally low income level (Svensson, 2005), which is usually explained by the literature via the negative role that bad institutions can play for economic growth (Lipset, 1960; Demsetz, 1967; Treisman, 2000; Glaeser et al., 2004; Acemoglu et al., 2012).[3] Some authors, however, propose a different viewpoint that conceives corruption as a "helping hand" and argue that bribes may lead firms to allocate their resources more efficiently, in an economy afflicted by slow bureaucracy and rigid laws (see, e.g., Leff, 1964; Huntington, 1968; Lui, 1985). Finally, some contributions take a more intermediate position emphasizing that corruption has non-linear effects on economic growth that depend on the quality of the institutions (Méndez and Sepúlveda, 2006; Aidt, 2009; Méon and Weill, 2010).

Corruption has attracted much attention also in game theory that generally models this phenomenon as the result of a strategic interaction between at least two kinds of players.[4] Among game theoretic models on corruption, a particularly interesting contribution is provided by the so-called *inspection games*,[5] where one player, a policeman, must decide whether to inspect the other player, who in turn must decide whether to infringe a regulation (Tsebelis, 1989, 1990). According to Holler (1993), the inspection games have no Nash equilibrium in pure strategies since both players have the possibility to improve their payoff values by choosing an alternative strategy, given the strategy of the other player. Therefore, there is a single mixed strategy

[2]As it is well-known, the Environmental Kuznets Curve (EKC) is an inverted U-shape relationship between environmental degradation and per capita income, which suggests that environmental degradation first increases at early stages of economic growth and then decreases when income exceeds a certain level. The name was coined due to its similarity to the work of Kuznets (1955) on the relationship between income inequality and per capita income (cf. Grossman and Krueger, 1991; Shafik and Bandyopadhyay, 1992; Panayotou, 1993). See Borghesi (2001), Dinda (2004) and Kijima et al. (2010) for extensive reviews and in-depth discussions on the EKC.

[3]More precisely, corruption is generally found to have detrimental effects on economic growth, both directly and indirectly through lower levels of investments, openness, schooling and political stability (Pellegrini and Gerlagh, 2004). See Dreher and Herzfeld (2008) for a survey on the economic costs of corruption and a discussion of its transmission channels.

[4]An alternative (non-game theoretic) approach that is sometimes used to study crime deterrence in general is *decision theory* that involves only one actor (see, for further details, Becker, 1968; Garoupa, 1997; Polinsky and Shavell, 2000). We will not adopt this approach here since we focus more specifically on corruption that is an agreement between at least two actors: a player who decides to infringe a regulation and, to avoid being sanctioned, offers a bribe to another player who accepts the bribe and decides not to sanction the former player.

[5]Another way to model corruption adopting a game theoretic framework is the *principal-agent theory*, where crime occurs due to the presence of asymmetric information between the principal, usually the Public Administration, and the agent, a public official (see, for further details, Bardhan, 1997; Acemoglu and Verdier, 2000; Di Gioacchino and Franzini, 2008). We do not use this setting here since the focus of the present analysis is not on the existence of asymmetric information across agents but on the mechanism underlying the choices of randomly matched agents in an evolutionary context.

Nash equilibrium that has counter-intuitive comparative statics properties (Andreozzi, 2004). In fact, these models show that increasing sanctions and the probability of being discovered for the player who must decide whether to infringe a norm, have no effects on law enforcement.[6] The only way to reduce crimes is to increase the inspection incentives for the policemen. Andreozzi (2004) proposes a variant of the 2x2 simultaneous-move inspection game originally set forth by Tsebelis (1989), namely, a sequential version in which the inspector acts as a Stackelberg leader and shows that in that case the opposite result applies: in order to reduce crimes policy-makers should decrease (rather than increase) the inspector's incentive to catch the transgressor. However, as Friehe (2008) has shown, if the enforcer and the offender payoffs are correlated, increasing the catch bonus cannot increase crime while the latter can be decreased by increasing the severity of the sanction, thus contradicting the counterintuitive results that emerged from both the simultaneous and sequential versions of the game described above.

In this paper we adopt the framework of the inspection games using an evolutionary context (see, e.g., Andreozzi, 2002). The *evolutionary game theory* assumes that large populations of players with bounded rationality learn, imitate, and adopt the relatively more rewarding strategies. As pointed out by Cressman et al. (1998), this context seems particularly appealing for the study of crime, since it captures the positive influence of good role models in society that is often stressed as an important factor for reducing crime.

Differently from other evolutionary models on corruption that study the dynamics of only one population, either of firms playing a public contracting game or of public officials (cf., Antoci and Sacco, 1995, 2002, respectively), we propose a random-matching evolutionary game between a population of firms and a population of bureaucrats.[7] In each instant of time, there is a large number of random pairwise encounters between firms and bureaucrats. In each encounter a bureaucrat checks the compliance with environmental regulations by a firm. When the environmental laws are respected, the firm obtains a "green" license, a sort of a "sticker" that firms can show to prove their customers that they comply with environmental laws.[8] Otherwise, the firm receives a penalty. There are two kinds of firms, compliant and non-compliant, and two kinds of bureaucrats, honest and dishonest. Moreover, we suppose the existence of two crimes: corruption and extortion. Corruption occurs when a dishonest bureaucrat accepts a bribe from a non-compliant firm, while extortion occurs when a dishonest bureaucrat claims a bribe from a compliant firm. Finally, we introduce the existence of an anti-corruption agency that monitors the behaviour of bureaucrats and firms. The agency can be regarded as an exogenous player that affects the choices of the two populations.[9]

When there is no dominant strategy, four dynamic regimes can arise in the economy: two bistable dynamic regimes (i.e. with extreme equilibria and no inner equilibrium) and two with an internal stable equilibrium. In the first two dynamic regimes, similar economies (same rules, same sanctions, etc.) can converge to different stationary states, depending on the initial shares

[6] See Di Vita (2014) for a discussion of the deterrence effects of sanctions of environmental crimes from the perspective of law and economics.

[7] A random-matching approach has been used in several other economic contexts to describe the numerous and heterogeneous situations in which agents interact during pair wise casual meetings. These situations include, among others, the random matching between buyers and sellers in housing transactions, between unemployed workers who look for a job and entrepreneurs who want to hire new workers, or the matching between firms that apply for a loan and banking executives who have to decide whether to grant the loan. See Rogerson and Shimer (2011), Han and Strange (2015) and Dong et al. (2016) for updated surveys and in-depth discussions on the use of random matching models in housing markets, labour markets and credit allocation, respectively.

[8] For instance, one can think of ecolabels as an application of the notion of green license described here. See the interesting contribution by Blanco and Lozano (2015) for an evolutionary model examining how the transitional dynamics deriving from certification practices may improve or worsen natural resources.

[9] See Di Vita (2007) who examines how agents respond to exogenous changes in (dis)incentives to corruption coming from an authority that is not part of the game.

of the strategies in the two populations. In the other two dynamic regimes, instead, the shares of the two populations oscillate around an internal stable equilibrium. This implies that similar economies that differ only for their initial conditions can lie on different trajectories, therefore, they can have different "orbital periods", describing circles of different lengths around the internal equilibrium.

The comparative statics analysis of the dynamic regimes with an internal stable equilibrium shows that policy instruments (sanctions, probability of being discovered by the anti-corruption agency and inspection effort) may reduce both corruption and extortion. The effectiveness of policy instruments depends on their impact on the payoffs of the alternative strategies and on the initial shares of the strategies in the two populations.

Our model differs from other inspection games (both static and evolutionary ones) in several respects. While inspection games, as described above, have a single mixed strategy Nash equilibrium, (therefore, they only allow dynamic regimes with oscillating trajectories), the present game has Nash equilibria both in pure and in mixed strategies, which enriches the dynamics that can arise from the model. Moreover, as it will be shown below, in the present context not only the enforcer's effort but also higher sanctions and detection probability can effectively reduce crimes. In addition, we broaden the possible cases of corruption as compared to other inspection games allowing for both bribery and extortion. Finally, differently from previous inspection games, in the present model inspectors choose whether to be honest or dishonest rather than their inspection effort. The latter here is captured by the detection probability that encompasses also other factors (e.g. the technologies the inspector has at disposal to perform proper controls). Such probability is initially assumed to be exogenously given in order to focus the analysis on the binary choice (being honest/dishonest) described above, and then properly modified to see the effects of a change in the corresponding parameter on environmental compliance.

The paper is organized as follows. Sections 2 and 3 describe the model, Section 4 shows the basic results, Section 5 deals with the dominance relationship between strategies, Section 6 analyses the dynamic regimes, Section 7 contains the effectiveness of policy instruments, and Section 8 concludes.

2 The model

Let us assume that in each instant of time $t \in [0, +\infty)$, many pairwise random matchings occur between firms and bureaucrats. Each firm has to choose *ex ante* between two possible strategies: (C) comply with environmental regulations and incur compliance cost C_C, or (NC) not comply with environmental laws. Each bureaucrat has to choose *ex ante* between two possible strategies: (H) be honest and do her job properly, or (D) be dishonest and accept a bribe from a non-compliant firm or claim a bribe from a compliant firm. Tables 1 and 2 describe the firm's and the bureaucrat's payoff matrix, respectively.

If a compliant firm encounters an honest bureaucrat, it obtains the green license, while if it encounters a dishonest bureaucrat it may be victim of extortion; if that is the case, the compliant firm has to pay an extortion bribe (b_e). However, this crime could be discovered by the anti-corruption agency with probability θ; in that case, the public administration will compensate the firm for the extortion bribe by offering a refund (η). If a non-compliant firm encounters an honest bureaucrat, it will be sanctioned (s_1) for not being compliant with a probability p, that depends on the honest bureaucrat's capacity to discover the firm's violation.[10] Otherwise, if a non-compliant firm encounters a dishonest bureaucrat, it will pay a corruption bribe (b_c).

[10] Such a capacity will obviously depend not only on the bureaucrat's monitoring effort but also on the efficacy of the control instruments that she has at disposal.

Table 1
Payoffs of strategies C and NC

	H	D
C	$\pi_C^H = -C_C$	$\pi_C^D = -C_C - b_e + \theta\eta$
NC	$\pi_{NC}^H = -ps_1$	$\pi_{NC}^D = -b_c - \theta s_2$

Table 2
Payoffs of strategies H and D

	C	NC
H	$\pi_H^C = w$	$\pi_H^{NC} = w$
D	$\pi_D^C = w + b_e - \theta\sigma_1$	$\pi_D^{NC} = w + b_c - \theta\sigma_2$

In this case, it will take the risk of being sanctioned (s_2) by the anti-corruption agency with probability θ. In this case, the firm will be sanctioned both for the corruption crime and for not being compliant with the environmental laws. We suppose that $C_C > 0$, $b_c > b_e > 0$, $\eta \geq 0$, $s_2 > s_1 > 0$, $1 > \theta > 0$, $1 > p > 0$. Let us turn now out attention to the payoff matrix of the bureaucrat. Empirical studies suggest that incentives in wages to bureaucrats may be ineffective in reducing corruption, whereas bribery may be discouraged by the extension of liability rules for the Public Administration and the civil servants (e.g. Di Vita, 2011). For this reason, we will assume that no incentive wage is offered to the honest bureaucrat (i.e. her payoff is independent of the type of firm she encounters) whereas proper sanctions are levied on corrupted bureaucrats. More precisely, if a bureaucrat is honest, she will obtain the wage (w), regardless of the kind of firms she encounters. If a dishonest bureaucrat encounters a compliant firm, she will obtain an extortion bribe in addition to wage, but it will run the risk of being sanctioned (σ_1) by the anti-corruption agency with probability θ.[11] Finally, if a dishonest bureaucrat encounters a non-compliant firm, she will obtain -beyond her wage- the corruption bribe but will take the risk of being sanctioned (σ_2) by the anti-corruption agency with probability θ. We suppose that $w > 0$, $b_c > b_e > 0$, $\sigma_1 > 0$, $\sigma_2 > 0$, $1 > \theta > 0$.

3 The Dynamics of the game

Let $c(t) \in [0, 1]$ represent the share of firms adopting strategy C and let $h(t) \in [0, 1]$ represent the share of bureaucrats adopting strategy H, at time t. Consequently, $1-c(t)$ and $1-h(t)$ represent, respectively, the shares of firms playing strategy NC and of bureaucrats playing strategy D.

The firms' expected payoffs from playing strategies C and NC are:

$$\Pi_C(h) = \pi_C^H \cdot h + \pi_C^D \cdot (1 - h)$$

[11] Notice that a dishonest bureaucrat might hypothetically decide not to ask any extortion bribe ($b_e = 0$) if she meets a compliant firm, in which case she would obviously get no sanction ($\sigma_1 = 0$). In what follows, however, we will focus attention on the more interesting case in which both b_e and σ_1 are strictly positive.

$$\Pi_{NC}(h) = \pi_{NC}^{H} \cdot h + \pi_{NC}^{D} \cdot (1-h)$$

where h and $1-h$ represent the probabilities that a firm is matched with a bureaucrat who plays, respectively, strategy H or D.

The bureaucrats' expected payoffs from playing strategies H and D are:

$$\Pi_H(c) = \pi_H^C \cdot c + \pi_H^{NC} \cdot (1-c)$$

$$\Pi_D(c) = \pi_D^C \cdot c + \pi_D^{NC} \cdot (1-c)$$

where c and $1-c$ represent the probabilities that a bureaucrat is matched with a firm who plays, respectively, strategy C or NC.

The average payoffs in the population of firms and of bureaucrats are:

$$\overline{\Pi}_F = c \cdot \Pi_C(h) + (1-c) \cdot \Pi_{NC}(h)$$

$$\overline{\Pi}_B = h \cdot \Pi_H(c) + (1-h) \cdot \Pi_D(c)$$

We assume that the time evolution of c and h is described by the standard replicator dynamics, a learning-by-imitation model of evolution widely used in economics (see, among others, Hofbauer and Sigmund, 1988; Weibull, 1995). The replicator dynamics postulates that players are bundled rational and update their choices by adopting the relatively more rewarding behaviour that emerges from available observations of others' behaviours. The shares c and h will increase (decrease) the more, the higher (lower) their payoff differential with respect to the population average payoff. Accordingly, in our two-strategy context the dynamic system is:

$$\begin{aligned} \dot{c} &= c[\Pi_C(h) - \overline{\Pi}_F] = c(1-c)[\Pi_C(h) - \Pi_{NC}(h)] \\ \dot{h} &= h[\Pi_H(c) - \overline{\Pi}_B] = h(1-h)[\Pi_H(c) - \Pi_D(c)] \end{aligned} \tag{1}$$

where $\dot{c}$ and $\dot{h}$ represent the time derivatives dc/dt and dh/dt of the shares c and h, respectively. The factors $c(1-c)$ and $h(1-h)$ are always non-negative, so the signs of $\dot{c}$ and $\dot{h}$ will depend respectively on the signs of the payoff differentials.

4 Basic results

The system (1) is defined in the unit square S:

$$S = \left\{(c,h) \in R^2 : 0 \le c \le 1, 0 \le h \le 1\right\}$$

The graphs of the payoff differentials $\Pi_C(h) - \Pi_{NC}(h)$ and $\Pi_H(c) - \Pi_D(c)$ are shown in Figs. 1(a) and 1(b). Strategy C (H) is dominant when the graph of $\Pi_C(h) - \Pi_{NC}(h)$ ($\Pi_H(c) - \Pi_D(c)$) lies entirely above the c-axis (h-axis) in the interval $[0,1]$. Conversely, strategy NC (D) is dominant when it lies entirely below the c-axis (h-axis) in the interval $[0,1]$. Finally, if it intersects the interior of the interval $[0,1]$, then no dominant strategy exists. Figs. 1(a) and 1(b) show the possible cases that can be observed.

The payoff differentials can be written as follows:

$$\Pi_C(h) - \Pi_{NC}(h) = b_c - b_e + \theta\,(\eta + s_2) - C_C - [b_c - b_e + \theta\,(\eta + s_2) - ps_1]\,h \tag{2}$$

$$\Pi_H(c) - \Pi_D(c) = \theta\sigma_2 - b_c + [b_c - b_e + \theta\,(\sigma_1 - \sigma_2)]\,c \tag{3}$$

According to the dynamic system (1), $\dot{c} = 0$ holds if either $c = 0, 1$ or if the value of the share h is such that $\Pi_C(h) - \Pi_{NC}(h) = 0$, that is:

$$h = \bar{h} := \frac{b_c - b_e + \theta\ (\eta + s_2) - C_C}{b_c - b_e + \theta\ (\eta + s_2) - ps_1} \tag{4}$$

Considering (2), we can distinguish between two cases.

Case (a):

$$b_c - b_e + \theta\ (\eta + s_2) - ps_1 < 0,\ \textit{that is},\ s_1 > \bar{s}_1 \tag{5}$$

where $\bar{s}_1 := \frac{b_c - b_e + \theta\ (\eta + s_2)}{p}$.

Case (b):

$$b_c - b_e + \theta\ (\eta + s_2) - ps_1 > 0, \textit{that is},\ s_1 < \bar{s}_1 \tag{6}$$

The graph of the payoff differential $\Pi_C(h) - \Pi_{NC}(h)$ is a line with positive slope (i.e., $\Pi_C(h) - \Pi_{NC}(h)$ is an increasing function of h) in Case (a), while it is a line with negative slope (i.e., $\Pi_C(h) - \Pi_{NC}(h)$ is a decreasing function of h) in Case (b). This implies that, in the context of Case (a), the strategy C becomes relatively more remunerative (compared to the strategy NC) when the share of honest bureaucrats h increases; the opposite occurs in Case (b).

Analogously, according to the dynamic system (1), $\dot{h} = 0$ holds if either $h = 0, 1$ or if the value of the share c is such that $\Pi_H(c) - \Pi_D(c) = 0$, that is:

$$c = \bar{c} := \frac{b_c - \theta\sigma_2}{b_c - b_e + \theta\ (\sigma_1 - \sigma_2)} \tag{7}$$

Taking into account (3), we can distinguish between two cases.

Case (c):

$$b_c - b_e + \theta\ (\sigma_1 - \sigma_2) > 0,\ \textit{that is},\ \sigma_1 > \bar{\sigma}_1 \tag{8}$$

where $\bar{\sigma}_1 := \sigma_2 - \frac{b_c - b_e}{\theta}$.

Case (d):

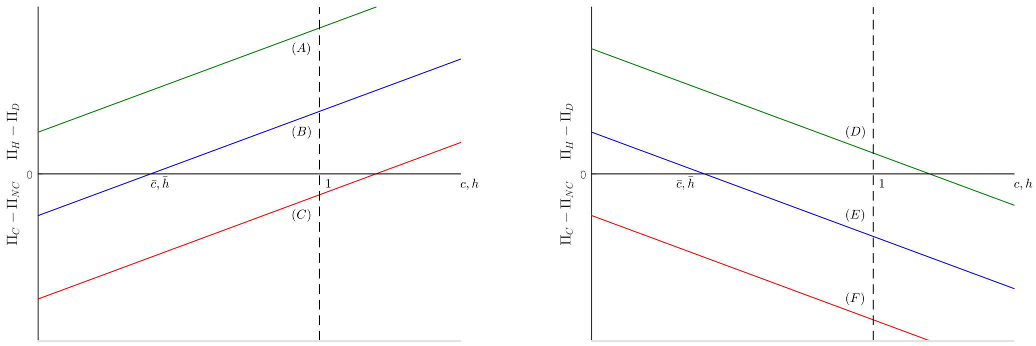
$$b_c - b_e + \theta\ (\sigma_1 - \sigma_2) < 0,\ \textit{that is},\ \sigma_1 < \bar{\sigma}_1 \tag{9}$$

The graph of the payoff differential $\Pi_H(c) - \Pi_D(c)$ is a line with positive slope (i.e., $\Pi_H(c) - \Pi_D(c)$ is an increasing function of c) in Case (c), while it is a line with negative slope (i.e., $\Pi_H(c) - \Pi_D(c)$ is a decreasing function of c) in Case (d). This implies that, in the context of Case (c), the strategy H becomes relatively more remunerative (compared to the strategy D) when the share of compliant firms c increases; the opposite occurs in Case (d).

The four vertices of S, that is $(c, h) = (0, 0),\ (1, 0),\ (0, 1),\ (1, 1)$, are always stationary states of the dynamic system (1). In these stationary states, the populations of firms and bureaucrats play only one strategy. In $(1, 1)$ all firms play C and all bureaucrats play H; in $(0, 0)$ all firms play NC and all bureaucrats play D, and so on.

Another stationary state of the system (1) is the intersection point $(\bar{c}, \bar{h})$ of the straight lines (4) and (7), when it belongs to the interior of the square S, that is when $0 < \bar{c} < 1$ and $0 < \bar{h} < 1$. At the stationary state $(\bar{c}, \bar{h})$ all the strategies C, NC, H and D coexist.

Finally, all the points belonging to the side of S with $h = 0$ (respectively, $h = 1$) are stationary states in the case in which $\bar{h} = 0$ (respectively, $\bar{h} = 1$) holds. Analogously, all the points belonging to the side of S with $c = 0$ (respectively, $c = 1$) are stationary states if $\bar{c} = 0$ (respectively, $\bar{c} = 1$) holds.



(a) Increasing payoff differentials. **(b)** Decreasing payoff differentials.

Fig. 1. Dominance of strategies.
Legend: line (A) dominant strategy C or H, line (B) no dominant strategy, line (C) dominant strategy NC or D; line (D) dominant strategy C or H, line (E) no dominant strategy, line (F) dominant strategy NC or D.

5 Dominance relationship

In this section, we define the conditions under which a given strategy does not dominate the alternative one, in each population of players. Proposition 1 refers to Case (a) and Case (b), while Proposition 2 refers to Case (c) and Case (d).

Proposition 1 *In Case* (a) *(see (5)),* $\Pi_C(h)-\Pi_{NC}(h)$ *is strictly increasing in* h *(see Fig. 1(a)), and there is no dominance of strategies if:*

$$s_2 < \bar{s}_2 := \frac{C_C + b_e - b_c}{\theta} - \eta \quad \textit{and} \quad s_1 > \frac{C_C}{p} \tag{10}$$

In Case (b) *(see (6)),* $\Pi_C(h) - \Pi_{NC}(h)$ *is strictly decreasing in* h *(see Fig. 1(b)), and there is no dominance of strategies if:*

$$s_2 > \bar{s}_2 \quad \textit{and} \quad s_1 < \frac{C_C}{p} \tag{11}$$

Proof. See Appendix. □

In Case (a), if condition (10) holds, then no strategy dominates the other one, and the graph of the payoff differential $\Pi_C(h) - \Pi_{NC}(h)$ intersects the h-axis at $h = \bar{h} \in (0, 1)$. In this case, for $h > \bar{h}$ (respectively, $h < \bar{h}$), it holds $\Pi_C(h) - \Pi_{NC}(h) > 0$ (respectively, $\Pi_C(h) - \Pi_{NC}(h) < 0$) (see (4)).

On the contrary, in Case (b), if condition (11) holds, then no strategy dominates the other one, and the graph of the payoff differential $\Pi_C(h) - \Pi_{NC}(h)$ intersects the h-axis at $h = \bar{h} \in (0, 1)$. If so, for $h > \bar{h}$ (respectively, $h < \bar{h}$), it holds $\Pi_C(h) - \Pi_{NC}(h) < 0$ (respectively, $\Pi_C(h) - \Pi_{NC}(h) > 0$) (see (4)).

Proposition 2 *In Case (c) (see (8)), $\Pi_H(c) - \Pi_D(c)$ is strictly increasing (see Fig. 1(a)), and there is no dominance of strategies if:*

$$\sigma_1 > \frac{b_e}{\theta} \quad \textit{and} \quad \sigma_2 < \frac{b_c}{\theta} \tag{12}$$

In Case (d) (see (9)), $\Pi_H(c) - \Pi_D(c)$ is strictly decreasing (see Fig. 1(b)), and there is no dominance of strategies if:

$$\sigma_1 < \frac{b_e}{\theta} \quad \textit{and} \quad \sigma_2 > \frac{b_c}{\theta} \tag{13}$$

Proof. See Appendix. □

In Case (c) if condition (12) holds, then no strategy dominates the other one, and the graph of the payoff differential $\Pi_H(c) - \Pi_D(c)$ intersects the c-axis at $c = \bar{c} \in (0, 1)$. If this is the case for $c > \bar{c}$ (respectively, $c < \bar{c}$), it holds $\Pi_H(c) - \Pi_D(c) > 0$ (respectively, $\Pi_H(c) - \Pi_D(c) < 0$) (see (7)).

The same result (no dominant strategy) occurs in Case (d) if condition (13) holds, but in this case the graph of the payoff differential $\Pi_H(c) - \Pi_D(c)$ intersects the c-axis at $c = \bar{c} \in (0, 1)$ from above: for $c > \bar{c}$ (respectively, $c < \bar{c}$), it holds $\Pi_H(c) - \Pi_D(c) < 0$ (respectively, $\Pi_H(c) - \Pi_D(c) > 0$) (see (7)).

6 Dynamic regimes

When a dominated strategy exists, the share of agents adopting it decreases monotonically over time and approaches (asymptotically) the value 0; therefore, in such a context, the dynamics is very simple. The most interesting dynamic regimes arise when no strategy dominates the other one, in each population of agents. In such cases, the internal stationary state $(\bar{c}, \bar{h})$ exists. The following subsections illustrate these dynamic regimes. The classification of regimes that will be given below provides an exhaustive description all the possible cases that can occur:[12]

1) the case in which the parameter values satisfy the conditions (5) and (8) characterizing, respectively, Case (a) (relatively to the population of firms) and Case (c) (relatively to the population of bureaucrats);

2) the case in which the parameter values satisfy the conditions (6) and (9) characterizing, respectively, Case (b) and Case (d);

3) the case in which the parameter values satisfy the conditions (6) and (8) characterizing, respectively, Case (b) and Case (c);

4) the case in which the parameter values satisfy the conditions (5) and (9) characterizing, respectively, Case (a) and Case (d).

As it will be shown below, the first two cases are characterized by bi-stable dynamics, while the latter two by oscillatory dynamics.

The proofs of the following propositions are straightforward, since the dynamic regimes that may be observed under replicator equations, in a context with two populations and two strategies, have been completely classified (see Hofbauer and Sigmund, 1988).

[12]For simplicity, we do not consider the non-robust cases with $s_1 = \bar{s}_1$ and/or $\sigma_1 = \bar{\sigma}_1$

6.1 Bi-stable dynamics

6.1.1 Dynamic regime in the context of Cases (a) and (c)

This case is characterized by the conditions (see (5) and (8)):

$$s_1 > \frac{b_c - b_e + \theta\,(\eta + s_2)}{p} \tag{14}$$

$$\sigma_1 > \sigma_2 - \frac{b_c - b_e}{\theta} \tag{15}$$

which, as shown in Section 5, imply that the payoff differentials $\Pi_C(h) - \Pi_{NC}(h)$ and $\Pi_H(c) - \Pi_D(c)$ are strictly increasing in h and c, respectively. Furthermore, in such a context, no dominance relationship (between the two available strategies) exists, in each population, if the following conditions are satisfied (see (10) and (12)):

$$s_2 < \frac{C_C + b_e - b_c}{\theta} - \eta \quad \textit{and} \quad s_1 > \frac{C_C}{p} \tag{16}$$

$$\sigma_1 > \frac{b_e}{\theta} \quad \textit{and} \quad \sigma_2 < \frac{b_c}{\theta} \tag{17}$$

Notice that if condition (17) holds, then also condition (15) holds. If conditions (14), (16) and (17) are satisfied, then a "bi-stable" dynamic regime is observed, described by the following proposition:

Proposition 3 *If conditions (14), (16) and (17) are satisfied, then the stationary states $(c,h) = (0,0)$ and $(c,h) = (1,1)$ are sinks (i.e., locally attractive), the stationary states $(c,h) = (1,0)$ and $(c,h) = (0,1)$ are sources (i.e., repulsive) and the stationary state $(c,h) = (\bar{c},\bar{h})$, in the interior of the square S, is a saddle point. The basins of attraction of $(0,0)$ and $(1,1)$ are separated by the stable branch of $(\bar{c},\bar{h})$ (see Fig. 2(a)).*

In such a context, strategy C is the best reply when the share of honest bureaucrats is high, while strategy NC is the best reply when the share of honest bureaucrats is low.[13] With regard to bureaucrats' behaviour, instead, strategy H is the best reply when the share of compliant firms is high, while strategy D is the best reply when the share of the compliant firms is low. This occurs because:

- If the share of honest bureaucrats is high, for firms is more rewarding to adopt strategy C, since s_1 and p are relatively high, while C_C is relatively low ($s_1 > C_C/p$).
- If the share of honest bureaucrats is low, for firms is more rewarding to adopt strategy NC, since s_2, b_c, θ and η are relatively low, while C_C and b_e are relatively high ($s_2 < (C_C + b_e - b_c)/\theta - \eta$).
- If the share of compliant firms is high, for bureaucrats is more rewarding to adopt strategy H, since σ_1 and θ are relatively high, while b_e is relatively low ($\sigma_1 > b_e/\theta$).
- If the share of compliant firms is low, for bureaucrats is more rewarding to adopt strategy D, since σ_2 and θ are relatively low, while b_c is relatively high ($\sigma_2 < b_c/\theta$).

[13]This can be easily shown by observing line (B) in Fig. 1(a) that describes Case (a): indeed, when h is sufficiently high, $\Pi_C(h) - \Pi_{NC}(h)$ is positive, therefore the strategy C is the best response of firms to the bureaucrats' behaviour as it is more remunerative than strategy NC. Mutatis mutandis, the same reasoning underlies the identification of the best replies in all the other cases that will be described below.

An economy can converge to the “vicious” stationary state $(0,0)$ - in which all firms are non-compliant and all bureaucrats are dishonest - if both initial shares of compliant firms and honest bureaucrats are relatively low. In point $(0,0)$ corruption is the only existing crime. On the contrary, an economy can converge to the “virtuous” stationary state $(1,1)$ - in which all firms are compliant and all bureaucrats are honest - if both initial shares of compliant firms and honest bureaucrats are relatively high. In point $(1,1)$ there are no crimes.

6.1.2 Dynamic regime in the context of Cases (b) and (d)

This case is characterized by the conditions (see (6) and (9)):

$$s_1 < \frac{b_c - b_e + \theta\,(\eta + s_2)}{p} \tag{18}$$

$$\sigma_1 < \sigma_2 - \frac{b_c - b_e}{\theta} \tag{19}$$

which imply that the payoff differentials $\Pi_C(h) - \Pi_{NC}(h)$ and $\Pi_H(c) - \Pi_D(c)$ are strictly decreasing in h and c, respectively. Furthermore, in such a context, no dominance relationship exists, in each population, if the following conditions are satisfied (see (11)) and (13)):

$$s_2 > \frac{C_C + b_e - b_c}{\theta} - \eta \quad \textit{and} \quad s_1 < \frac{C_C}{p} \tag{20}$$

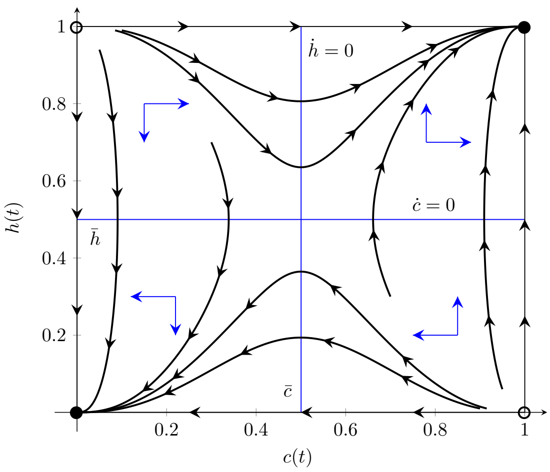
$$\sigma_1 < \frac{b_e}{\theta} \quad \textit{and} \quad \sigma_2 > \frac{b_c}{\theta} \tag{21}$$

Notice that if condition (21) holds, then also condition (19) holds. If conditions (18), (20) and (21) are satisfied, the bi-stable regime described by the following proposition occurs:

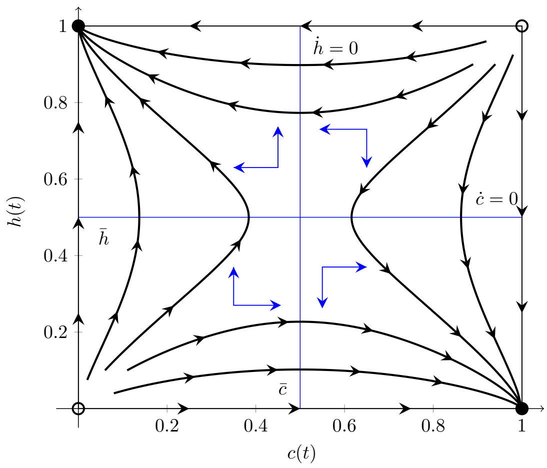
Proposition 4 *If the condition (18), (20) and (21) are satisfied, then the stationary states $(c,h) = (0,1)$ and $(c,h) = (1,0)$ are sinks, the stationary states $(c,h) = (0,0)$ and $(c,h) = (1,1)$ are sources and the stationary state $(c,h) = (\bar{c},\bar{h})$, in the interior of the square S, is a saddle point. The basins of attraction of $(0,1)$ and $(1,0)$ are separated by the stable branch of $(\bar{c},\bar{h})$ (see Fig. 2(b)).*

In such a context, strategy C is the best reply when the share of honest bureaucrats is low, while strategy NC is the best reply when the share of honest bureaucrats is high. With regard to bureaucrats' behaviour, instead, strategy H is the best reply when the share of compliant firms is low, while strategy D is the best reply when the share of the compliant firms is high. This occurs because:

- If the share of honest bureaucrats is high, for firms is more rewarding to adopt strategy NC, since s_1 and p are relatively low, while C_C is relatively high ($s_1 < C_C/p$).
- If the share of honest bureaucrats is low, for firms is more rewarding to adopt strategy C, since s_2, b_c, θ and η are relatively high, while C_C and b_e are relatively low ($s_2 > (C_C + b_e - b_c)/\theta - \eta$).
- If the share of compliant firms is high, for bureaucrats is more rewarding to adopt strategy D, since σ_1 and θ are relatively low, while b_e is relatively high ($\sigma_1 < b_e/\theta$).
- If the share of compliant firms is low, for bureaucrats is more rewarding adopt strategy H, since σ_2 and θ are relatively high, while b_c is relatively low ($\sigma_2 > b_c/\theta$).



(a) Cases (a) and (c). *Parameter values:* $C_C = 129.09$, $b_c = 75$, $b_e = 50$, $p = 0.67$, $\theta = 0.29$, $\eta = 95.76$, $s_1 = 217.110$, $s_2 = 202.583$, $\sigma_1 = 231.191$, $\sigma_2 = 193.019$.



(b) Cases (b) and (d). *Parameter values:* $C_C = 156.808$, $b_c = 75$, $b_e = 50$, $p = 0.63$, $\theta = 0.22$, $\eta = 275.35$, $s_1 = 144.174$, $s_2 = 610.660$, $\sigma_1 = 13.209$, $\sigma_2 = 546.598$.

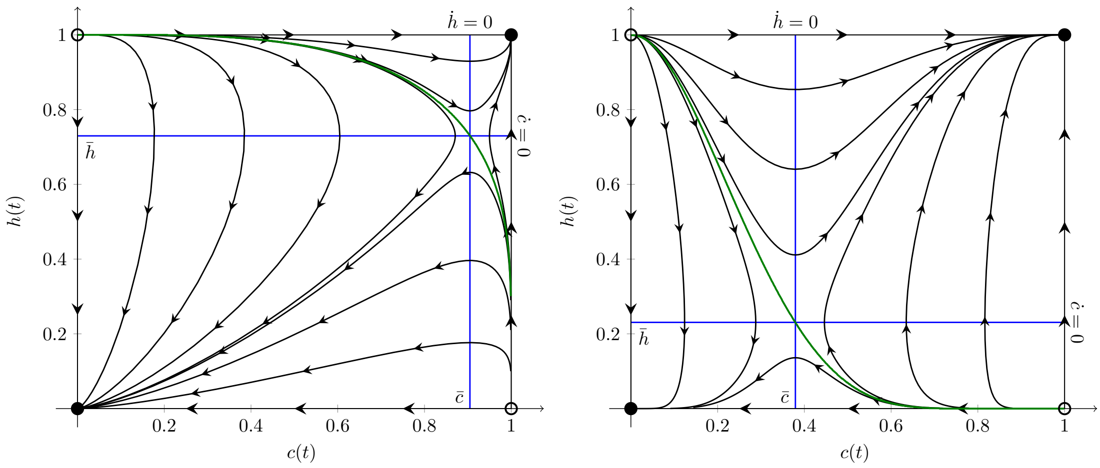
Fig. 2. Path-dependent dynamics.
Legend: • *attractors,* ○ *repellers.*

An economy can converge to the stationary state $(0, 1)$ - in which no firm is compliant but all bureaucrats are honest - if the initial share of compliant firms is relatively low and the initial share of honest bureaucrats is relatively high. In point $(0, 1)$ there are no crimes.[14] On the contrary, an economy can converge to the stationary state $(1, 0)$ - in which all firms are compliant and all bureaucrats are dishonest - if the initial share of compliant firms is relatively high and the initial share of honest bureaucrats is relatively low. In point $(1, 0)$ extortion is the only existing crime.

The states $(c, h) = (0, 0)$, $(0, 1)$, $(1, 0)$, $(1, 1)$, when locally attractive, as in Propositions 3 and 4, are Nash equilibria. This finding follows from standard results in evolutionary game theory (see, e.g., Weibull, 1995). We can interpret Nash equilibria as social conventions, that is, as customary and expected states of things in which no single individual has an incentive to modify her choices if the others do not modify theirs.

Performing numerical simulations in the context of the bi-stable dynamics examined above, it is possible to show the dynamics that may emerge in the model from an increase in the policy parameters, namely, the parameters $(\theta, s_1, s_2, \sigma_1, \sigma_2)$ of the model that the policy-maker can directly modify. Let us first consider the case in which the "virtuous" equilibrium $(1, 1)$ and the "vicious" equilibrium $(0, 0)$ are the two attractors of the system (Cases (a) and (c) above). As Figs. 3(a) and 3(b) show, an increase in the effort of the anti-corruption agency that increases

[14]By this we mean that at this stationary state there is neither corruption nor extortion. There is, however, a widespread violation of the environmental laws since all firms are non-compliant, but this will be properly sanctioned by bureaucrats (that are all honest), provided they manage to discover the violation.



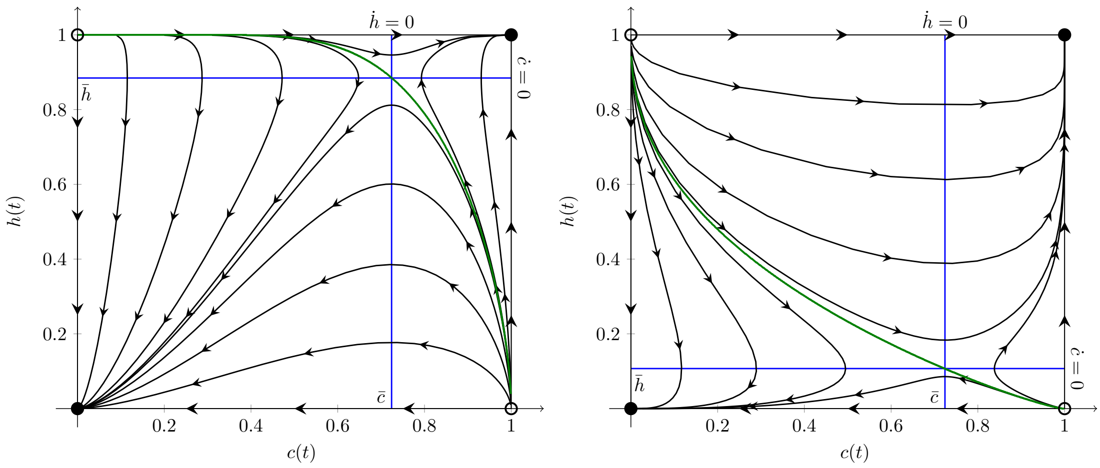
(a) $\theta = 0.55$.

(b) $\theta = 0.95$.

Fig. 3. Basins of attraction of Cases *(a)* and *(c)*: low and high value of θ.
Parameter values: $C_C = 100$, $b_c = 75$, $b_e = 50$, $\eta = 50$, $p = 0.5$, $s_1 = 225$, $s_2 = 25$, $\sigma_1 = 100$, $\sigma_2 = 50$.
Legend: $\bullet$ *attractors,* $\circ$ *repellers.*

the probability θ of discovering crimes will tend to enhance the attraction basin of the virtuous equilibrium $(1, 1)$ and to reduce that of the vicious equilibrium $(0, 0)$. Stated differently, in this case an increase in θ will increase the range of initial values (c, h) that make the system eventually converge towards the "ideal" equilibrium in which all firms are compliant and all bureaucrats are honest. As a consequence, this will automatically also decrease the range of initial values (c, h) that lead to the opposite undesirable outcome in which all firms are non-compliant and all bureaucrats dishonest. Figs. 4(a) and 4(b) show the effects of an increase in the sanctions s_1 and s_2 levied by the Public Administration on non-compliant firms. Even in this case, an increase in s_1 and s_2 tends to enlarge the attraction basin of $(1, 1)$ and conversely to reduce that of $(0, 0)$, increasing the range of values (c, h) that lead at the end of the day to the desirable situation in which none violates the laws. Notice that, as Figs. 4(a) and 4(b) shows, an increase in the sanctions level does not modify the share of compliant firms $\bar{c}$ at the (unstable) inner equilibrium $(\bar{c}, \bar{h})$.

Let us now focus attention on the basins of attraction of Cases (b) and (d) above (cf. Figs. 5(a) and 5(b) and Figs. 6(a) and 6(b)). In this case, the extreme equilibria $(1, 1)$ and $(0, 0)$ are repellors and cannot be achieved, while the two attractors are now $(1, 0)$ and $(0, 1)$ in which one entire population respects the law whereas the others violate it. In this case, an increase in the probability θ that the anti-corruption agency may discover the crime increases the share of compliant firms $\bar{c}$ and of honest bureaucrats $\bar{h}$ at the inner equilibrium (Figs. 5(a) and 5(b)). Instead, an increase in the sanctions σ_1 and σ_2 (imposed on the bureaucrats for the extortion and corruption crimes, respectively) increases the share of compliant firms $\bar{c}$ but it does not affect that of honest bureaucrats $\bar{h}$ at the inner equilibrium (Figs. 6(a) and 6(b)). Moreover, an increase in σ_1 and σ_2 augments the attraction basin of $(0, 1)$ in which all firms are non-compliant but all bureaucrats are honest; vice versa it shrinks the attraction basin of $(1, 0)$ in which all firms are compliant while all bureaucrats are dishonest. This implies that higher sanctions on the bureaucrats tend to increase the probability that the system may eventually end up in the equilibrium $(0, 1)$ in which no extortion and/or corruption takes place (since all bureaucrats



(a) $s_1 = 207$, $s_2 = 23$.

(b) $s_1 = 405$, $s_2 = 45$.

Fig. 4. Basins of attraction of Cases *(a)* and *(c)*: low and high values of sanctions s_1 and s_2. *Parameter values:* $C_C = 100$, $b_c = 75$, $b_e = 50$, $\eta = 50$, $p = 0.5$, $\theta = 0.66$, $\sigma_1 = 100$, $\sigma_2 = 50$. *Legend:* $\bullet$ *attractors,* $\circ$ *repellers.*

are honest), while they tend to decrease the likelihood of ending up in the equilibrium $(1, 0)$ characterized by the maximum number of extortion crimes (since all bureaucrats are dishonest while no firm tries to corrupt them).

6.2 Oscillatory dynamics

6.2.1 Dynamic regime in the context of Cases *(b)* and *(c)*

This context is characterized by the following conditions (see (6) and (8)):

$$s_1 < \frac{b_c - b_e + \theta\,(\eta + s_2)}{p} \tag{22}$$

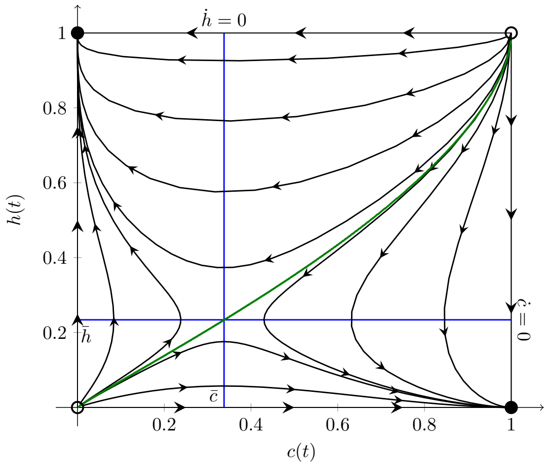
$$\sigma_1 > \sigma_2 - \frac{b_c - b_e}{\theta} \tag{23}$$

which imply that the payoff differentials $\Pi_C(h) - \Pi_{NC}(h)$ and $\Pi_H(c) - \Pi_D(c)$ are, respectively, strictly decreasing in h and strictly increasing in c. In such a context, no dominance relationship exists, in each population, if the following conditions are satisfied (see (11) and (12)):

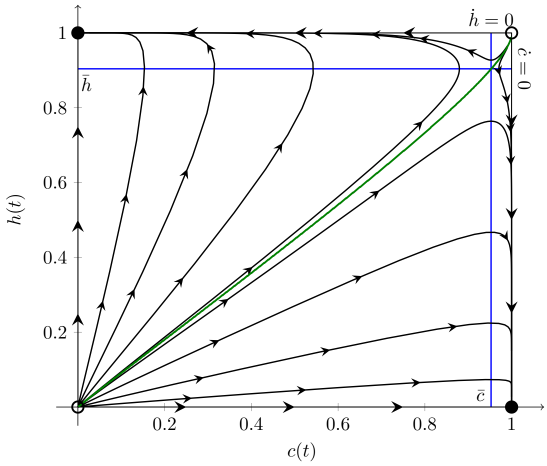
$$s_2 > \frac{C_C + b_e - b_c}{\theta} - \eta \quad \text{and} \quad s_1 < \frac{C_C}{p} \tag{24}$$

$$\sigma_1 > \frac{b_e}{\theta} \quad \text{and} \quad \sigma_2 < \frac{b_c}{\theta} \tag{25}$$

Notice that if condition (25) holds, then also condition (23) holds. The following proposition illustrates the basic properties of the dynamic regime observed if conditions (22), (24) and (25) are satisfied:



(a) $\theta = 0.05$.



(b) $\theta = 0.45$.

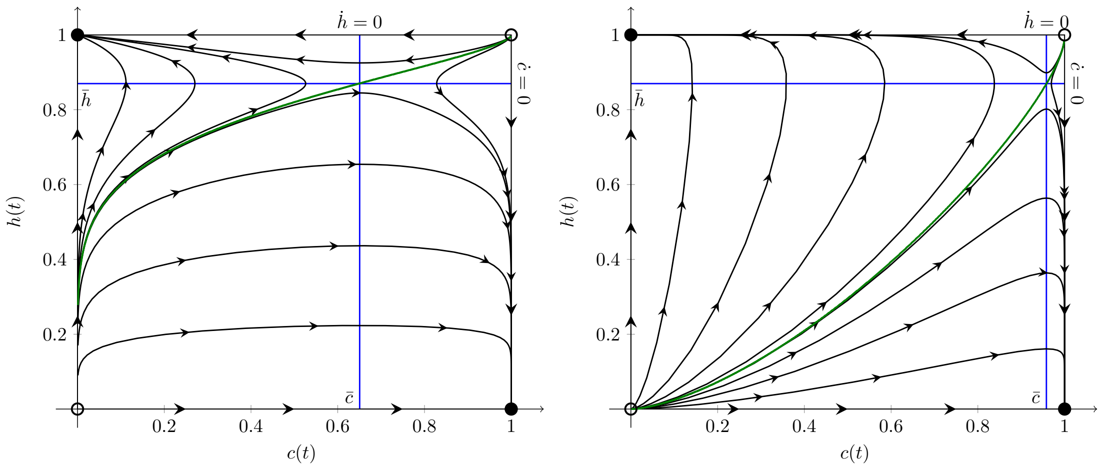
Fig. 5. Basins of attraction of Cases *(b)* and *(d)*. *Parameter values:* $C_C = 100$, $b_c = 75$, $b_e = 50$, $\eta = 50$, $p = 0.5$, $s_1 = 20$, $s_2 = 2000$, $\sigma_1 = 20$, $\sigma_2 = 2000$.
Legend: $\bullet$ *attractors,* $\circ$ *repellers.*

Proposition 5 *If conditions (22), (24) and (25) are satisfied, then the stationary states* $(c, h) = (0, 1), (1, 0), (0, 0)$ *and* $(1, 1)$ *are saddle points, while the internal stationary state* $(c, h) = (\bar{c}, \bar{h})$ *is a (Lyapunov) stable stationary state surrounded by closed trajectories turning counter-clockwise (see Fig. 7(a)).*

In such a context, strategy C is the best reply when the share of honest bureaucrats is low, while strategy NC is the best reply when the share of honest bureaucrats is high. With regard to bureaucrats' behaviour, instead, strategy H is the best reply when the share of compliant firms is high, while strategy D is the best reply when the share of the compliant firms is low. This occurs because:

- If the share of honest bureaucrats is high, for firms is more rewarding to adopt strategy NC, since s_1 and p are relatively low, while C_C is relatively high ($s_1 < C_C/p$).
- If the share of honest bureaucrats is low, for firms is more rewarding to adopt strategy C, since s_2, b_c, θ and η are relatively high, while C_C and b_e are relatively low ($s_2 > (C_C + b_e - b_c)/\theta - \eta$).
- If the share of compliant firms is high, for bureaucrats is more rewarding to adopt strategy H, since σ_1 and θ are relatively high, while b_e is relatively low ($\sigma_1 > b_e/\theta$).
- If the share of compliant firms is low, for bureaucrats is more rewarding to adopt strategy D, since σ_2 and θ are relatively low, while b_c is relatively high ($\sigma_2 < b_c/\theta$).

This oscillatory dynamics could be explained using the *prey-predator* conceptual framework à la Lotka-Volterra that is commonly used in evolutionary biology and is largely adopted also in the environmental economics literature (e.g. Brander and Taylor, 1998; Rosser, 2011; Antoci et al., 2005, 2016). In the present context, dishonest bureaucrats play the role of the predators and non-compliant firms are the preys. In fact, a high share of non-compliant firm "attracts" dishonest bureaucrats (just like preys attract predators) for the possibility that the latter may



(a) $\sigma_1 = 5$, $\sigma_2 = 500$.

(b) $\sigma_1 = 30$, $\sigma_2 = 3000$.

Fig. 6. Basins of attraction of Cases *(b)* and *(d)*. *Parameter values:* $C_C = 100$, $b_c = 75$, $b_e = 50$, $\eta = 50$, $p = 0.5$, $\theta = 0.33$, $s_1 = 20$, $s_2 = 2000$.
Legend: $\bullet$ *attractors,* $\circ$ *repellers.*

obtain a corruption bribe from the former. Starting from an initial condition in which the share of Not Complaint firms is high (many preys), for bureaucrats is more rewarding to adopt strategy D, therefore the share of predators increases. However, the increase of dishonest bureaucrats decreases the share of preys since the firms' best reply is to adopt strategy C. A reduction in the number of preys decreases the share of predators, since the bureaucrats' best reply is to adopt strategy H when the share of compliant firms is high. A lower share of predators allows the proliferation of the preys: for firms it becomes more rewarding to adopt strategy NC if the share of honest bureaucrats is high. And so on, leading to the oscillatory dynamics described above.

6.2.2 Dynamic regime in the context of Cases (a) and (d)

This context is characterized by the following conditions (see (5) and (9)):

$$s_1 > \frac{b_c - b_e + \theta\,(\eta + s_2)}{p} \tag{26}$$

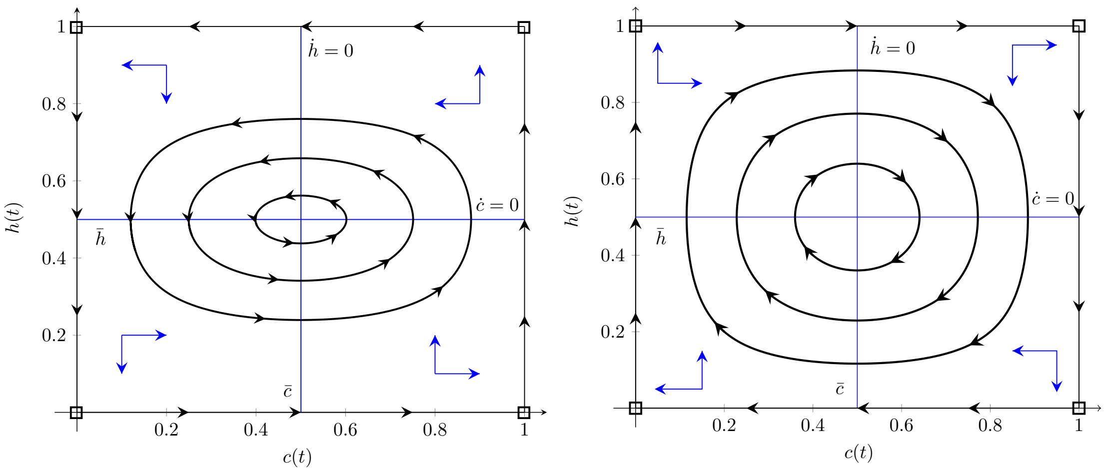
$$\sigma_1 < \sigma_2 - \frac{b_c - b_e}{\theta} \tag{27}$$

which imply that the payoff differentials $\Pi_C(h) - \Pi_{NC}(h)$ and $\Pi_H(c) - \Pi_D(c)$ are, respectively, strictly increasing in h and strictly decreasing in c. Furthermore, in such a context, no dominance relationship exists, in each population, if the following conditions are satified (see (10) and (13)):

$$s_2 < \frac{C_C + b_e - b_c}{\theta} - \eta \quad \textit{and} \quad s_1 > \frac{C_C}{p} \tag{28}$$

$$\sigma_1 < \frac{b_e}{\theta} \quad \textit{and} \quad \sigma_2 > \frac{b_c}{\theta} \tag{29}$$

Notice that if condition (29) holds, then also condition (27) holds. The following proposition illustrates the basic properties of the dynamic regime observed if conditions (26), (28) and (29) are satisfied:



(a) Cases (b) and (c). *Parameter values:* $C_C = 129.069$, $b_c = 75$, $b_e = 50$, $p = 0.67$, $\theta = 0.29$, $\eta = 95.76$, $s_1 = 72.248$, $s_2 = 531.428$, $\sigma_1 = 72.248$, $\sigma_2 = 182.513$.

(b) Cases (a) and (d). *Parameter values:* $C_C = 111.367$, $b_c = 75$, $b_e = 50$, $p = 0.78$, $\theta = 0.09$, $\eta = 123.47$, $s_1 = 205.290$, $s_2 = 252.576$, $\sigma_1 = 8.847$, $\sigma_2 = 1272.762$.

Fig. 7. Dynamics with a stable internal equilibrium.
Legend: □ *saddle points.*

Proposition 6 *If conditions (26), (28) and (29) are satisfied, then the stationary states* $(c,h) = (0,1),(1,0),(0,0)$ *and* $(1,1)$ *are saddle points, while the internal stationary state* $(c,h) = (\bar{c},\bar{h})$ *is a (Lyapunov) stable stationary state surrounded by closed trajectories turning clockwise (see Fig. 7(b)).*

In such a context, strategy C is the best reply when the share of honest bureaucrats is high, while strategy NC is the best reply when the share of honest bureaucrats is low. With regard to bureaucrats' behaviour, instead, strategy H is the best reply when the share of compliant firms is low, while strategy D is the best reply when the share of the compliant firms is high. This occurs because:

- If the share of honest bureaucrats is high, for firms is more rewarding to adopt strategy C, since s_1 and p are relatively high, while C_C is relatively low ($s_1 > C_C/p$).
- If the share of honest bureaucrats is low, for firms is more rewarding to adopt strategy NC, since s_2, b_c, θ and η are relatively low, while C_C and b_e are relatively high ($s_2 < (C_C + b_e - b_c)/\theta - \eta$).
- If the share of compliant firms is high, for bureaucrats is more rewarding to adopt strategy D, since σ_1 and θ are relatively low, while b_e is relatively high ($\sigma_1 < b_e/\theta$).
- If the share of compliant firms is low, for bureaucrats is more rewarding to adopt strategy H, since σ_2 and θ are relatively high , while b_c is relatively low ($\sigma_2 > b_c/\theta$).

Analogously to what has been done before, the *prey-predator* conceptual framework can be used also in the present context to explain the oscillatory dynamics observed here. For this purpose, the dishonest bureaucrats can still be interpreted as the predators, whereas the role of the preys is now played by the compliant firms. In fact, if bureaucrats expect that the probability of being discovered (and sanctioned) by the anti-corruption agency is relatively low, a high share of compliant firms will attract a high share of dishonest bureaucrats. Starting from an initial condition in which the share of compliant firms is high (many preys), therefore, the share of predators increases since bureaucrats find more rewarding to adopt strategy D. However, the increase of dishonest bureaucrats reduces the share of preys: the best reply for the firms is to adopt strategy NC. A lower number of preys decreases the share of predators, since the best reply for bureaucrats is to adopt strategy H if the share of non-compliant firms is high. A lower share of predators allows the proliferation of the preys: for firms is more rewarding to adopt strategy C if the share of honest bureaucrats is high. And so on.

The state $(c, h) = (\bar{c}, \bar{h})$, in Propositions 5 and 6, corresponds to the mixed-strategy Nash equilibrium of the one shot (static) game defined by the payoff matrices shown in Tables 1 and 2. Accordingly, the firm chooses the strategy C with probability $\bar{c}$ and the bureaucrat chooses the strategy H with probability $\bar{h}$; therefore $(\bar{c}, \bar{h})$ can be interpreted as the equilibrium that would be achieved if all agents were perfectly rational. Given that individuals are assumed here to be boundedly rational, in the present context the system oscillates around the equilibrium $(\bar{c}, \bar{h})$. The latter, therefore, can be interpreted as the time-average values of the shares of compliant firms and honest bureaucrats, evaluated over the closed trajectories in Figs. 7(a) and 7(b). In this sense $(\bar{c}, \bar{h})$ can estimate the behaviour of economic agents in random observations over long time periods (see Weibull, 1995).

7 Comparative statics

This section studies the effects that variations in the parameter values can have on the coordinates of the internal equilibrium $(\bar{c}, \bar{h})$. We focus our analysis on the two dynamic regimes in which the internal equilibrium $(\bar{c}, \bar{h})$ is stable, therefore, the values of c and h represent also the average values along the closed trajectories (i.e., the context of Cases (b) and (c), and that of Cases (a) and (d)). In the other cases, the internal equilibrium is a saddle point, therefore, it is not stable. The following Proposition 7 provides the general comparative statics results concerning variations in the parameters of the model whose values can be influenced by the Public Administration's choices:

- p: probability for a non-compliant firm to be discovered by a honest bureaucrat;
- θ: probability for a non-compliant firm (that has encountered a dishonest bureaucrat who did not sanction it) to be discovered by the anti-corruption agency;
- s_1: sanction incurred by the firm for not being compliant;
- s_2: sanction incurred by the firm for its corruption crime and for not being compliant;
- σ_1: sanction incurred by the bureaucrat for the extortion crime;
- σ_2: sanction incurred by the bureaucrat for the corruption crime.

The symbols $x \uparrow$ and $x \downarrow$ indicate, respectively, that the value of x increases or decreases, where x may represent $\bar{c}$, $\bar{h}$, or a parameter of the model.

Proposition 7

1) If $p \uparrow$, then $\bar{c}$ remains always constant, while $\bar{h} \uparrow$ if and only if (iff) $s_2 > (C_C + b_e - b_c)/\theta - \eta$.

2) If $\theta \uparrow$, then $\bar{c} \uparrow$ iff $\sigma_2 b_e > \sigma_1 b_c$, while $\bar{h} \uparrow$ iff $s_1 < C_C/p$.

3) If $s_1 \uparrow$, then $\bar{c}$ remains always constant, while $\bar{h} \uparrow$ iff $s_2 > (C_C + b_e - b_c)/\theta - \eta$.

4) If $s_2 \uparrow$, then $\bar{c}$ remains always constant, while $\bar{h} \uparrow$ iff $s_1 < C_C/p$.

5) If $\sigma_1 \uparrow$, then $\bar{c} \uparrow$ iff $\sigma_2 > b_c/\theta$, while $\bar{h}$ remains always constant.

6) If $\sigma_2 \uparrow$, then $\bar{c} \uparrow$ iff $\sigma_1 < b_e/\theta$, while $\bar{h}$ remains always constant.

Proof. This can be easily proved by looking at the signs of the partial derivatives of functions (4) and (7). □

7.1 Comparative statics in the context of Cases *(b)* and *(c)*

When Cases *(b)* and *(c)*occur, it is important to recall that the following properties hold:

- The payoff differential $\Pi_C(h) - \Pi_{NC}(h)$ is a decreasing function of h, therefore, the higher is the share of honest bureaucrats h, the lower is the payoff of strategy C relative to strategy NC. This implies that, for sufficiently low values of h, it holds $\Pi_C(h) - \Pi_{NC}(h) > 0$ (therefore, $\dot{c} > 0$), while the opposite occurs for sufficiently high values of h.
- The payoff differential $\Pi_H(c) - \Pi_D(c)$ is an increasing function of c, therefore, the higher is the share of compliant firms c, the higher is the payoff of strategy H relative to strategy D. It follows that, when c is sufficiently low, it holds $\Pi_H(c) - \Pi_D(c) < 0$ (therefore, $\dot{h} < 0$), while the opposite occurs when c is sufficiently high.

In such a context, as described in Section 6, in an *environment* characterized by a low share of honest bureaucrats and of compliant firms, C is the best reply of the firms, while D is the best reply of the bureaucrats. In other words, from conditions (24) and (25) it follows that firms adopting strategy C show an *evolutionary advantage* over firms adopting the alternative strategy NC. The same applies to bureaucrats that adopt strategy D over those adopting strategy H. If the Public Administration increases the sanctions (s_1, s_2, σ_1, and σ_2) and its monitoring effort so as to increase the probabilities of discovering non-compliant firms (p and θ), the effects will be mixed (see Table 3). In fact, an increase in the policy parameters (p, θ, s_1, s_2, σ_1, σ_2) has the effect of increasing (or at least not decreasing) the share of honest bureaucrats (i.e., $\bar{h}$), but decreasing (or at least not increasing) the share of compliant firms (i.e., $\bar{c}$).

7.2 Comparative statics in the context of Cases *(a)* and *(d)*

When Cases *(a)* and *(d)* occur, the following properties hold:

- The payoff differential $\Pi_C(h) - \Pi_{NC}(h)$ is an increasing function of h, so that strategy C becomes more and more rewarding with respect to strategy NC as the share of honest bureaucrats h increases. It follows that $\Pi_C(h) - \Pi_{NC}(h) < 0$ (therefore, $\dot{c} < 0$) when h is low enough, while the opposite occurs when h is high enough.
- The payoff differential $\Pi_H(c) - \Pi_D(c)$ is a decreasing function of c, therefore, the higher is the share of compliant firms c, the lower is the payoff of strategy H with respect to strategy D. As a consequence, it holds $\Pi_H(c) - \Pi_D(c) > 0$ (therefore, $\dot{h} > 0$) for relatively low values of c (when $c < \bar{c}$), while the opposite occurs for relatively high values of c (when $c > \bar{c}$).

Table 3
Cases (b) and (c): monotonic relations between equilibrium shares ($\bar{c}$, $\bar{h}$) and their parameters

	$\bar{c}$	$\bar{h}$
p	$-$	$\uparrow$
θ	$\downarrow$	$\uparrow$
s_1	$-$	$\uparrow$
s_2	$-$	$\uparrow$
σ_1	$\downarrow$	$-$
σ_2	$\downarrow$	$-$

Legend: $\uparrow$ Increasing, $\downarrow$ Decreasing, $-$ Independent.

Table 4
Cases (a) and (d): monotonic relations between equilibrium shares ($\bar{c}$, $\bar{h}$) and their parameters

	$\bar{c}$	$\bar{h}$
p	$-$	$\downarrow$
θ	$\uparrow$	$\downarrow$
s_1	$-$	$\downarrow$
s_2	$-$	$\downarrow$
σ_1	$\uparrow$	$-$
σ_2	$\uparrow$	$-$

Legend: $\uparrow$ Increasing, $\downarrow$ Decreasing, $-$ Independent.

In such a context, as described in Section 6, in an *environment* characterized by a low share of honest bureaucrats and a low share of compliant firms, then NC turns out to be the best reply of the firms, while H is the best reply of the bureaucrats. From conditions (28) and (29), we have that firms adopting strategy NC and bureaucrats adopting strategy H show an *evolutionary advantage* over the member of the two populations who adopted the alternative strategies (C and D, respectively). If there exist high shares of non-compliant firms and dishonest bureaucrats, and the Public Administration tries to address the problem by increasing sanctions (s_1, s_2, σ_1, and σ_2) and the monitoring effort so as to enhance the probabilities p and θ, comparative static analysis shows that the effects will be mixed (see Table 4). In fact, an increase in the policy parameters (p, θ, s_1, s_2, σ_1, σ_2) increases (or at least it does not decrease) the share of compliant firms (i.e., $\bar{c}$), but, at same time, it tends to reduce (or at least it does not increase) the share of honest bureaucrats (i.e., $\bar{h}$).

8 Conclusions

Environmental corruption has recently attracted particular attention among the media and policy-makers due to the discovery of a few important frauds and scandals that may have large implications on the credibility of environmental data and policies. To contribute to the current debate on environmental corruption, this paper investigates it from a novel perspective, adopting a theoretical framework (i.e. the random matching models) that has been used in other contexts of economic theory (e.g. labour economics) but has found little or no application among the studies on environmental corruption so far. For this purpose, this paper proposes a random matching evolutionary game between a population of firms and a population of bureaucrats. In each encounter a bureaucrat checks the firm's compliance with environmental regulations. When the firm respect the environmental laws, it obtains a "green" license; otherwise, it receives a penalty. We assume the existence of two types of firms, compliant and non-compliant, two types of bureaucrats, honest and dishonest, and also two types of crimes, corruption (when a dishonest bureaucrat accepts a bribe from a non-compliant firm), and extortion (when a dishonest bureaucrat extorts a bribe from a compliant firm).

Four possible dynamic regimes emerge from the analysis of the model: two of them are bistable, while the other two have an internal stable equilibrium, which corresponds to the mixed-strategy Nash equilibrium of the one-shot static game, surrounded by closed trajectories. In the two bistable regimes, the dynamics is path-dependent and the outcome depends on the initial conditions, i.e., the share of compliant firms and of honest bureaucrats that characterize the economy at the beginning. In the two bistable regimes, moreover, all agents within each population end up adopting the same strategy at the equilibrium. In the first regime one equilibrium is "virtuous", all firms are compliant and all bureaucrats are honest, while the other is "vicious", all firms are non-compliant and all bureaucrats are dishonest. In the second regime, instead, one of the two population behaves in a virtuous way while the other does not: in one equilibrium all firms are compliant but all bureaucrats are dishonest, while in the other all bureaucrats are honest but all firms are non-compliant.

While in the bistable regimes only one strategy prevails within each population (i.e. all agents behaves the same way), in the two regimes with an internal stable equilibrium different strategies can coexist in each population. Such an internal stable equilibrium is surrounded by closed trajectories that turn in opposite directions in the two possible regimes: clockwise in one case, counter-clockwise in the other. As explained in the paper, these oscillatory dynamics can be explained using the *prey-predator* conceptual framework. When the trajectories oscillate counter-clockwise, honest bureaucrats can be seen as the predators, while non-compliant firms play the role of the preys. On the contrary, when the trajectories oscillate clockwise, dishonest bureaucrats are the predators and compliant firms are the preys. From comparative static analysis of these two dynamic regimes emerges that policy instruments can help the Public Administration reduce both corruption and extortion. However, in an environment characterized by high shares of non-compliant firms and dishonest bureaucrats, an increase in the policy parameters (larger sanctions and higher effort to discover corruption/extortion crimes) has mixed effects on crime deterrence: in the regime with trajectories that turn counter-clockwise, a more stringent policy (higher policy parameters) increases the share of honest bureaucrats, but decreases that of compliant firms, whereas if trajectories turn clockwise, the opposite occurs.

Although the present model is rather simple, in our opinion it manages to provide some interesting and novel insights on the possible dynamics and outcomes that may emerge from the interaction between firms that should comply with the environmental laws and bureaucrats who should verify that this is the case. Moreover, the model provides a general framework that can be easily extended in several directions. To provide an example, further research should be devoted to account for the possibility that the compliant firm may denounce the dishonest bureaucrat who claims a bribe. This possibility would certainly enrich the analysis but it would also further complicate the complex dynamics characterizing the model, therefore it is left for future research.

Appendix

Proof of Proposition 1

1) In Case (a) (see (5)), $\Pi_C(h) - \Pi_{NC}(h)$ is strictly increasing in h (see Fig. 1(a)) and the following sub-cases can occur:

   i) If:
   $$\Pi_C(0) - \Pi_{NC}(0) = b_c - b_e + \theta\,(\eta + s_2) - C_C \geq 0$$
   that is, if:
   $$s_2 \geq \bar{s}_2 := \frac{C_c + b_e - b_c}{\theta} - \eta \tag{30}$$
   then $\Pi_C(h) - \Pi_{NC}(h) > 0$ holds for every $h \in (0,1)$ and, consequently, the strategy C dominates the strategy NC.

   ii) If:
   $$\Pi_C(1) - \Pi_{NC}(1) = ps_1 - C_C \leq 0$$
   that is, if:
   $$s_1 \leq \frac{C_C}{p} \tag{31}$$
   then $\Pi_C(h) - \Pi_{NC}(h) < 0$ holds for every $h \in (0,1)$ and, consequently, the strategy NC dominates the strategy C.

   iii) If neither condition (30) nor (31) hold, that is if:
   $$s_2 < \bar{s}_2 \quad \textit{and} \quad s_1 > \frac{C_C}{p} \tag{32}$$
   then no strategy dominates the other one, and the graph of the payoff differential $\Pi_C(h) - \Pi_{NC}(h)$ intersects the h-axis at $h = \bar{h} \in (0,1)$ (see (4)): for $h > \bar{h}$ (respectively, $h < \bar{h}$), it holds $\Pi_C(h) - \Pi_{NC}(h) > 0$ (respectively, $\Pi_C(h) - \Pi_{NC}(h) < 0$).

2) In Case (b) (see (6)), $\Pi_C(h) - \Pi_{NC}(h)$ is strictly decreasing in h (see Fig. 1(b)) and the following sub-cases can be observed:

   i) If:
   $$\Pi_C(0) - \Pi_{NC}(0) = b_c - b_e + \theta\,(\eta + s_2) - C_C \leq 0$$
   that is, if:
   $$s_2 \leq \bar{s}_2 \tag{33}$$
   then $\Pi_C(h) - \Pi_{NC}(h) < 0$ holds for every $h \in (0,1)$ and, therefore, the strategy NC dominates the strategy C.

   ii) If:
   $$\Pi_C(1) - \Pi_{NC}(1) = ps_1 - C_C \geq 0$$
   that is, if:
   $$s_1 \geq \frac{C_C}{p} \tag{34}$$
   then $\Pi_C(h) - \Pi_{NC}(h) > 0$ holds for every $h \in (0,1)$ and, therefore, the strategy C dominates the strategy NC.

iii) If neither condition (33) nor condition (34) hold, that is, if:

$$s_2 > \bar{s}_2 \quad \textit{and} \quad s_1 < \frac{C_C}{p} \tag{35}$$

then no strategy dominates the other one, and the graph of the payoff differential $\Pi_C(h) - \Pi_{NC}(h)$ intersects the h-axis at $h = \bar{h} \in (0,1)$ (see (4)): for $h > \bar{h}$ (respectively, $h < \bar{h}$), it holds $\Pi_C(h) - \Pi_{NC}(h) < 0$ (respectively, $\Pi_C(h) - \Pi_{NC}(h) > 0$).

Proof of Proposition 2

1) In Case (c) (see (8)), $\Pi_H(c) - \Pi_D(c)$ is strictly increasing (see Fig. 1(a)) and the following sub-cases can occur:

   i) If:

   $$\Pi_H(0) - \Pi_D(0) = \theta\sigma_2 - b_c \geq 0$$

   that is, if:

   $$\sigma_2 \geq \frac{b_c}{\theta} \tag{36}$$

   then $\Pi_H(c) - \Pi_D(c) > 0$ holds for every $c \in (0,1)$ and, consequently, the strategy H dominates the strategy D.

   ii) If:

   $$\Pi_H(1) - \Pi_D(1) = -b_e + \theta\sigma_1 \leq 0$$

   that is, if:

   $$\sigma_1 \leq \frac{b_e}{\theta} \tag{37}$$

   then $\Pi_H(c) - \Pi_D(c) < 0$ holds for every $c \in (0,1)$ and, consequently, the strategy D dominates the strategy H.

   iii) If neither condition (36) nor condition (37) hold, that is if:

   $$\sigma_1 > \frac{b_e}{\theta} \quad \textit{and} \quad \sigma_2 < \frac{b_c}{\theta} \tag{38}$$

   then no strategy dominates the other one, and the graph of the payoff differential $\Pi_H(c) - \Pi_D(c)$ intersects the c-axis at $c = \bar{c} \in (0,1)$ (see (7)): for $c > \bar{c}$ (respectively, $c < \bar{c}$), it holds $\Pi_H(c) - \Pi_D(c) > 0$ (respectively, $\Pi_H(c) - \Pi_D(c) < 0$).

2) In Case (d) (see (9)), $\Pi_H(c) - \Pi_D(c)$ is strictly decreasing (see Fig. 1(b)) and the following sub-cases can be observed:

   i) If:

   $$\Pi_H(0) - \Pi_D(0) = \theta\sigma_2 - b_c \leq 0$$

   that is, if:

   $$\sigma_2 \leq \frac{b_c}{\theta} \tag{39}$$

   then $\Pi_H(c) - \Pi_D(c) < 0$ holds for every $c \in (0,1)$ and, therefore, the strategy D dominates the strategy H.

ii) If:

$$\Pi_H(1) - \Pi_D(1) = -b_e + \theta\sigma_1 \geq 0$$

that is, if:

$$\sigma_1 \geq \frac{b_e}{\theta} \tag{40}$$

then $\Pi_H(c) - \Pi_D(c) > 0$ holds for every $c \in (0,1)$ and, therefore, the strategy H dominates the strategy D.

iii) If neither condition (39) nor condition (40) hold, that is, if:

$$\sigma_1 < \frac{b_e}{\theta} \quad \textit{and} \quad \sigma_2 > \frac{b_c}{\theta} \tag{41}$$

then no strategy dominates the other one, and the graph of the payoff differential $\Pi_H(c) - \Pi_D(c)$ intersects the c-axis at $c = \bar{c} \in (0,1)$ (see (7)): for $c > \bar{c}$ (respectively, $c < \bar{c}$), it holds $\Pi_H(c) - \Pi_D(c) < 0$ (respectively, $\Pi_H(c) - \Pi_D(c) > 0$).

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