Cascading Defections from Cooperation Triggered by Present-Biased Behaviors in the Commons

Persichina, Marco

Department of Forest Economics - SLU - Sweden, CERE - Centre for Environmental and Resource Economics - Umeå, Department of Economics - Umeå University

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Abstract:

This work shows that defective behaviors from the cooperative equilibrium in the management of common resources can be fueled and triggered by the presence of agents with myopic behaviors. The behavior implemented by naïve agents, even if performed with cooperative intent, can activate a dynamic of cascading defections from the cooperative strategy within the harvesters' group.

This paper demonstrates and discusses that the apparent and detectable decay of the cooperative choices in the dilemmas of common resources is not an exclusive and indisputable signal of an escalation in free-riding intentions but also an outcome of the present-biased preferences and myopic behaviors of the cooperative agents. Notably, within the context populated by conditional cooperators with a heterogeneous myopic discount factor, in the absence of information on agents' intentions, the present-biased preferences can trigger a strategy that directs the community to excessively increase its harvesting level, even in presence of the other-regarding motives. Therefore, lowering cooperative behaviors can also be the effect of the absence of coordination instruments in response to the cognitive bias that influences human behaviors.

Keywords: Present bias, Commons, Cooperation, Cascading Defections, Naïve Agent.

JEL Classification : C71, C73, D01, D90, D91, Q20, Q29.

Contents

1. Introduction

In the task of managing common resources, one of the main issues that a community faces is avoiding the trigger of the tragedy of the commons. Non-collapsing management of the commons largely depends on the cooperative capabilities of communities and their ability to maintain the cooperation inside groups over time. This study shows when and in what manner there is involvement of present-biased preferences in the triggering of strategies that contribute to non-cooperative behaviors in common harvesting.

Cooperative behaviors have been largely investigated in behavioral economics (Ernst Fehr and Gächter 2000; Gächter 2007; Sally 1995), and other-regarding and social preferences are found in everyday life (Gintis 2000) and in a wide range of situations and cultures (Alpizar et al. 2008; Frey and Meier 2004; Meier and Stutzer 2008; Henrich et al. 2005). Nevertheless, in presence of social preferences, when individuals participate in common pool resources or public good games, in the absence of coordination and enforcement instruments or institutions, cooperative behaviors frequently decay (Andreoni 1988; Dawes and Thaler 1988; E. Fehr and Schmidt 1999; Gintis 2000; Gintis et al. 2003; Isaac et al. 1994; Ledyard 1994). When individuals cooperate only when others also cooperate (conditional cooperators), the presence of free riders, or individuals without full cooperative behaviors, can trigger a dynamic of defection by cooperation (Fischbacher et al. 2001; Fischbacher and Gächter 2010).

When resource management includes specific intertemporal peculiarities with relevant externalities, resource harvesting is vulnerable to the risks of inefficient intertemporal management. This phenomenon is evident when observing the difficulties that individuals often encounter in defining intertemporal choices and allocating consumption in a consistent manner. This phenomenon refers to the existence of present-biased preferences. Notably, individuals, because of their impulsivity, follow short-term benefits without adequately considering long-term consequences, particularly in situations where individuals systematically behave by discounting the near future more than the distant future (G. Loewenstein and Prelec 1992). These behaviors reveal a lack of self-control when individuals feel pressured by the present (D. Laibson 1997; T. O'Donoghue and Rabin 1999). This situation occurs when because of present-biased preferences, the immediate benefit directs the choices despite the long-run interest, which is true also in social dilemmas. In Herr et al. (1997), for example, participants interact in a common pool resource experiment that reveals lower efficiency when the experimental design provides intertemporal externalities, showing substantially shortsighted behaviors. The participants, notably, do not adequately consider the future consequences of their decisions, and they show shortsighted behaviors in dynamic games (Pevnitskaya and Ryvkin 2013).

Myopic behavioral patterns are particularly dangerous in the context of common resources because they can generate rapid resource depletion. Generally, common resource dilemmas are defined within a context in which the long-run choices and short-run choices can conflict, exposing the resources to the risks derived from present bias. Thus, the role played by present bias in the decay dynamics of cooperation in the commons could be consistent with the systematic decline of the cooperative propensity with the passage of time. Notably, one of the salient elements present in common resource experiments is the progressive decay of the cooperative behaviors with the advancement of the interactions (Ostrom 2000).

When resources are commons with intertemporal harvesting peculiarities, the decay of cooperation intentions can be the main obstacle to the preservation of a given stock of resources. Hence, the reason why the decay of cooperation in the commons has so much relevance is clear. However, in this context, the role of the cognitive biases is not adequately investigated, namely, if and in what manner can present bias affect the dynamics of the cooperation inside the group. Notably, although cooperation capability as part of human evolutionary success was confirmed (Gintis 2009), why societies sometimes do not achieve the level of fairness and cooperation that they desire has not been investigated. Therefore, this work presents a representation of human behaviors that do not exclude these cognitive foundations of the process of decision-making in the intertemporal context. Without the necessary inclusion of the intertemporal cognitive features of human behavior, the models used to describe the human phenomena in resource harvesting are unable to include some of the real issues that can trigger the defective strategies from cooperation in the management of the common resources that generate the overexploitation.

2. Present bias and why take care of it in the commons

Present bias refers to behaviors derived from the duality of the discount rate in short-term and long-term periods that determine a non-consistent time behavior in tasks that require intertemporal planning. Time inconsistency implies that an optimal choice defined in the present could be revisited in the future (Strotz 1955). The present bias thus determines the emergence of preference reversals that generate a conflict between long-run preferences and immediate choices, resulting in a conflict between the early intention of the agent and the choice made at the moment. The genesis of these phenomena has a solid cognitive foundation.

Notably, researchers of cognitive neuroscience have supported a non-constant discount rate, namely, two ways to process the discounting: for immediate rewards and for delayed rewards.[1] Experiments have revealed the activation of the limbic circuit just prior to choices that provide an immediate reward (Samuel M McClure et al. 2004). Similar conclusions have also been drawn by Hariri et al. (2006) and McClure et al.

[1] Two distinct brain areas are involved in the definition of intertemporal choices. The first area, the limbic and paralimbic, is a brain region heavily innervated by the dopaminergic system and connected to rewards expectation (Breiter and Rosen 1999; Knutson et al. 2001; Samuel M. McClure et al. 2003), whereas the other area belongs to the front-parietal region, an area that supports higher cognitive functions (G. F. Loewenstein et al. 2008).

(2007).[2] The joint involvement of two systems in decision-making processes is further supported by Bechara (2005), Bechara et al. (1999), Damasio (1994), and LeDoux (1996). Therefore, for choices defined in an intertemporal context, the dualism between the limbic system and the deliberative-cognitive system of the neocortex highlights a distinction between the reactions in responses to short-term and long-term stimuli.

Information related to immediate rewards is mostly subjected to processing by the impulsive system, and a more appropriate reflective system refers to decisions regarding long-run rewards. A possible assertion is that the present bias is an element of decision-making processes deeply rooted in human nature, in several areas of an individual's life. Notably, present-biased behaviors are also clearly evident in several situations (Della Vigna 2009; Frederick et al. 2002; Thaler 1981) and different contexts, such as the low saving rate (Ashraf et al. 2006; Harris and Laibson 2001; D. Laibson 1997; D. I. Laibson et al. 1998); health choices (van der Pol and Cairns 2002); addiction to drugs, tobacco smoking, or shopping (Frederick et al. 2002; Gruber and Koszegi 2001; Thaler and Shefrin 1981; Wertenbroch 1998); and procrastination behaviors (Benabou and Tirole 2003; T. O'Donoghue and Rabin 1999).

The unifying factor in all these fields is the contrasting dichotomy between long-term well-being and immediate enjoyment. This dichotomy characterizes the emergence of present-biased behaviors. Present bias seems, therefore, to be a specific peculiarity of decision heuristics on intertemporal choices in frameworks where long-term plans can

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[2] The limbic circuit is the seat of the emotional reaction processes (A R Hariri et al. 2000) and impulsive behaviors (Pattij and Vanderschuren 2008); in fact the limbic system - the most ancient part of a human's brain – also includes the amygdala (Isaacson 1974), whose functions are closely related to emotional activities (Cardinal et al. 2002; Ahmad R. Hariri et al. 2002). Vice versa, a second area that it is afferent to the neocortex, the most recently formed brain area from an evolutionary perspective, shows prevalent activation in correspondence of actions that are the outcome of choices that take future gains into consideration best. This second area, exclusive to mammals and distinctly developed in humans (Rachlin 1989), plays a key role in appropriate deliberative-cognitive activities.

be subject to revision and where the long-term outcomes depend on a continuum of instantaneous or short-term choices. These peculiarities also define the framework of common resource dilemmas. Notably, the intertemporal management of the commons has the characteristics of the framework in which the long-term and short-term choices can conflict, consequently exposing the resources to the risks that can derive from behaviors strongly oriented to the present. In resource exploitation, the present bias and naïve behaviors could prove dangerous to the sustainability of the resources; notably, in the absence of time consistency, an undesired collapse of natural resources could occur (Hepburn et al. 2010). Hence, when conflict arises between short-term and long-term interests, such as in the management of common resources, present-biased preferences are likely to play a critical role.[3]

The commons is a field in which the relevant elements of human choosing are not limited to the area of intertemporal resources management and in which human sociality plays a diriment role. On the one hand, the adoption of sustainable and cooperative behaviors in relevant social dilemmas depends on the degree of consciousness of the effect of their behaviors on others, and on the common resources; this inclination finds form in cooperative and other-regarding motives. On the other hand, the choices made reflect the capability of correctly reading and weighing costs and benefits that result from an individual's choices. The intertemporal decision-making processes that involve the present-biased preferences directing these choices are also the paths by which individuals solve social dilemmas. Within this process, cooperation is also realized. For these reasons, cooperative behaviors and intertemporal dynamics must be analyzed together.

[3] In renewable resources management, the literature has already shown that present biased-preferences can reduce the agent's welfare (Persichina, 2019 b) and that in the context of the intergenerational transfer of resources, the present bias can generate intergenerational inequality even in presence of other-regarding preferences (Persichina, 2019 a).

The contributions to understanding the role of other-regarding preferences in social dilemmas are abundant in the literature and reveal that the cooperation and fairness principle contributes to the formulation of the agent's choices (Ernst Fehr and Gächter 2000; Gächter 2007; Ostrom et al. 1994). Several works have investigated the true foundations of economics when individuals make decisions within a social context, showing with undisputed clarity that an individual's decisions are mediated by other-regarding motives and by prosocial concepts such as fairness, cooperation, and reciprocity (Andreoni 1990; Bolton and Ockenfels 2000; G. Charness and Rabin 2002; Falk and Fischbacher 2006; E. Fehr and Schmidt 1999; Rabin 1993). Furthermore, the consequences of the introduction of the other-regarding preferences in the theoretical framework on the management of the commons draw great attention and offer additional elements of analysis for applications in environmental and resources issues (Brekke and Johansson-Stenman 2008; Carlsson and Johansson-Stenman 2012; Gowdy 2008; Gsottbauer and van den Bergh 2011; S. Frey and Stutzer 2006). Additionally, in the field of the commons, several studies have confirmed the ability of individuals to voluntarily sustain cooperation in resource dilemmas (Casari and Plott 2003; Gary Charness and Villeval 2009; Chaudhuri 2011; Ernst Fehr and Leibbrandt 2011; Ledyard 1994; Ostrom et al. 1992).

However, merely emphasizing the presence of the cooperative will of individuals is not possible because of the necessity to truly comment on the frequent observations, especially in controlled experiments, of the systematic decay of cooperative behaviors over time in repeated interactions (Ostrom 2000). The reasons for the decay of the cooperation propensity over time is an argument of great relevance, not merely theoretically but also from the applied perspective: when confronted with resources, which are intrinsically commons and have an intertemporal harvesting peculiarity, the decay of the cooperation instances can become the main obstacle to the preservation of a given stock of common resources over time and generations. However, in this context, the role of cognitive biases has not been adequately explored. If and in which manner phenomena such as present bias can affect the dynamics of cooperation and its decay remains to be defined.

But, as has been discussed here, the dynamics of harvesting in the commons has a double determination that involves both the cognitive sphere (i.e., intertemporal decision-making processes) and the social sphere (i.e., cooperative attitudes). Thus, the role of present-biased preferences in the decay of cooperation must be clarified to demonstrate that shortsighted behaviors derived from present bias can be involved in the decay of cooperative interactions over time and within a framework that includes common resources, even when agents have preferences for cooperation. Therefore, the following sections demonstrate the involvement of present bias in triggering strategies that contribute to non-cooperative behavior in common harvesting, determining cascading defections.

3. Harvesting model and baseline emerged behaviors

The model concerns the activity of harvesting from a stock of non-perishable resources, and a discrete time framework is considered. The stock of resources at time t is $R(t)$, with $t \in [0, T]$ and $T \neq \infty$. The harvested amount at time t is expressed as $h(t)$. The fundamental equation of the dynamics of the growth of the resources is as follows:

$$R(t+1) - R(t) = f\big(g, R(t)\big)R(t) - h(t), \tag{1}$$

where the growth rate, $f\big(g, R(t)\big)$, is not negative.[4] In a case in which the stock size does not affect the growth rate, the resource stock grows at a constant and strictly positive exponential rate equal to g, such that

$$f\big(g, R(t)\big) \geq 0 \text{ and } g > 0, \tag{2}$$

and

[4] The non-negative growth rate is derived from the non-perishability of the resources.

$$\text{if } \frac{\partial f(g, R(t))}{\partial R(t)} = 0 \; \rightarrow R(t+1) - R(t) = (g - \hat{h})R(t) \text{ with } \hat{h} = \frac{h(t)}{R(t)}. \tag{3}$$

The time interval from 0 to T is the finite lifetime of a single agent. Moreover, the initial stock of resources and the growth rate are known by all the agents.

The initial stock at time zero is strictly positive. An assumption is that resources are material; therefore, a negative stock is not possible:

$$R(t) \geq 0 \text{ with } R(0) = R_0 \wedge R_0 > 0 \quad \forall\, t \in [0, T]. \tag{4}$$

The amount harvested at time t by the agent, $h(t)$, is not restorable; therefore,

$$h(t) \geq 0 \;\; \forall\, t \in [0, T]. \tag{5}$$

The agent faces a capacity constraint: in each period, she cannot harvest more than h_{max}, a value that is strictly positive and finite; thus, together with the non-negativity constraint,

$$0 \leq h(t) \leq h_{max} \quad \forall\; t \in [0, T] \quad \text{with} \quad h_{max} > 0 \text{ and } h_{max} \neq \infty. \tag{6}$$

Furthermore, each agent also faces a resources constraint such that she cannot harvest at time t more than the stock of resources available in that moment:

$$h(t) \leq R(t) \quad \forall\, t \in [0, T]. \tag{7}$$

Both the capacity and resource constraints are assumed exogenous and equal for all the agents.

The model assumes only material resources and no exchange market; hence, the welfare of the agents depends only on the amount of resources harvested and enjoyed at each time; thus, the lifetime utility of the agent evaluated at time 0 is

$$U = \sum_{t=0}^{T} \delta(t)\, u(h(t)). \tag{8}$$

The monotonicity and strict concavity of the utility function is assumed:[5]

$$u'(h_t) > 0 \quad u''(h_t) < 0 \quad \forall\, h_t \in \mathcal{R}^+. \tag{9}$$

The discount factor $\delta(t)$ represents the degree of impatience with harvesting. Agents exhibit impatience with the harvesting time, such that $\delta' < 0$;[6] thus, the discount factor is monotonic and decreasing over time with

$$\delta(t) > \delta(t+1) \;\; \forall t \in [0, T]. \tag{10}$$

The problem of the optimal harvesting path can be summarized as the maximization of the agent's utility function (8) under the constraints expressed in (4), (6) and (7) when the initial condition and the natural growth rate respect the non-negative constraints and the dynamic of resource growth is defined by (1).

Thus, assuming continuity for the harvesting amount on the interval $[0, h_{max}]$, given the discount factors $D = \{\delta(0), \dots, \delta(t), \dots, \delta(T)\}$ that respect the peculiarity just enounced, at any time $t \in [0, T]$, there is just one optimal solution for the problem of maximization that the agent must face.

Of course, the intertemporal harvesting plan depends on the form of the discount factor, in particular, if it is expressed in an exponential manner that guarantees time consistency, or if the agent has another form of discount that generates time inconsistency such as in the case of present-biased preferences.

Hence, two possible and alternative outcomes from the process of optimization are considered. The first is the no-bias optimal harvesting strategy expressed as follows:

$$H_{opt} = \{h_{opt}(0), \dots, h_{opt}(t), \dots, h_{opt}(T)\}. \tag{11}$$

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[5] This guarantees the existence of a unique optimal solution.

[6] With this assumption, the case of pleasure in procrastination, $\delta'(t) > 0$, is excluded.

The no-bias optimal harvesting strategy, H_{opt}, is the strategy defined when the discount factor of the agent is expressed in an exponential manner that guarantees time consistency. [7] H_{opt} also corresponds to the long-run optimal harvesting plan for the agent (Ted O'Donoghue and Rabin 2002). Clearly, in the presence of time consistency, the agent does not vary her optimal strategy with the passage of time.

The second possible outcome of the process of optimization, the biased harvesting strategy, defined as H_{bias} , occurs when time inconsistency is assumed. Time inconsistency implies that the discount factor of the agent is not constant over time; thus, an assumption is that

$$\begin{cases} \dfrac{\delta_t}{\delta_{t+1}} > \dfrac{\delta_s}{\delta_{s+1}} \quad \text{with } t < s \text{ and } s \in [0, T] \text{ for } t = 0, \\ \dfrac{\delta_t}{\delta_{t+1}} \geq \dfrac{\delta_s}{\delta_{s+1}} \quad \text{with } t < s \text{ and } t, s \in [0, T] \text{ for } t > 0. \end{cases} \tag{12}$$

The consequences of a no constant discount factor can be defined in Postulate 1.

Postulate 1: If it is solved at time t, $t < s$, with $\frac{\delta_s}{\delta_{s+1}} = \frac{\delta_{s+1}}{\delta_{s+2}}$, the problem of intertemporal optimization in the interval $[s, T]$, with an existent unique optimal solution :

$H_t = \{E[h(s)]_t, \ldots, E[h(s+1)]_t, \ldots, E[h(T)]_t\}$, where $E[h(s)]_t$ is the expected harvesting amount for time s, and at time s, the same optimization problem is solved in the interval $[s, T]$ with the following optimal solution:

$H_s = \{h(s), \ldots, E[h(s+1)]_s, \ldots, E[h(T)]_s\}$; when $E[h(s)]_t < R(s)$ and $E[h(s)]_t < h_{max}$ and time s $\frac{\delta_s}{\delta_{s+1}} > \frac{\delta_{s+1}}{\delta_{s+2}}$ with $\frac{\partial \delta}{\partial t} < 0$; then, $h(s) > E[h(s)]_t$.

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[7] Agent has no biased preferences when $\frac{\delta_t}{\delta_{t+n}} = \frac{\delta_s}{\delta_{s+n}}$ $\forall\, t \in [0, T]$ and $\forall\, s \in [0, T]$. Only when the discounting respects this condition will the agent's evaluation of the optimal strategy in every period s between 0 and T conduct to the same optimal harvesting strategy evaluated in any period t in [0, T].

Thus, as anticipated, the agent can be present-biased and, in this case, the biased harvesting strategy can be expressed as follows:

$$H_{bias} = \{h_{bias}(0), \dots, h_{bias}(t_b), \dots, h_{bias}(T)\}. \quad (13)$$

H_{bias} is derived from the instantaneous maximization at each time of the utility of the agent as well the H_{opt}, but contrary to the case of no-bias optimal harvesting strategy, the discount factor incorporates the present-bias peculiarities expressed in (12) under the constraints expressed earlier.[8] The consequences can be synthesized in the following:

Lemma 1: Given an expected harvesting amount formulated at time t, $h_{opt}(s) > 0$, with $t < s$, t and s in $[0,T]$ and $h_{opt}(s) < h_{max}$, under the assumption of present bias defined in (12), if $R(s) > h_{opt}(s)$ and $R(s) = E[R(s)]_t$, where $R(s)$ is the resources stock at time s and $E[R(s)]_t$ is the expected stock estimated at time t, at time s, the agent harvests an amount greater than the amount predicted for the same period in the optimal strategy formulated at time t, $h_{opt}(s)$, which could be harvested in absence of bias, such that

$$h_{bias}(s) > h_{opt}(s) \text{ with } h_{opt}(s) \in H_{opt} \text{ and } h_{bias}(s) \in H_{bias}. \quad (14)$$

Notably, when $R(s) = E[R(s)]_t$, in the interval $[s, T]$, at time t in the no-bias condition the agent will face the same situation faced at time s, but under the bias condition. Thus, $H_{opt} \succ H_i$ at time t, where H_{opt} is the optimal harvesting plan evaluated at time t and H_i is any other harvesting plan different from H_{opt} in the set of all possible plans, and H_{opt}

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[8] Notably that both the hyperbolic that quasi-hyperbolic discounts respond to the property defined.

is defined under the hypothesis of an exponential discount such that $\frac{\delta_s}{\delta_{s+1}} = \frac{\delta_{s+1}}{\delta_{s+2}}$ with $\frac{\partial\delta}{\partial t} < 0$ and, $h_{opt}(s) \in H_{opt}$. However, at time s with $\frac{\delta_s}{\delta_{s+1}} > \frac{\delta_{s+1}}{\delta_{s+2}}$ and $\frac{\partial\delta}{\partial t} < 0$, $H_{bias} \succ H_{opt}$; hence, at time s, the situation expressed in Postulate 1 occurs. Thus, because $h_{opt}(s) < h_{max} \wedge h_{opt}(s) < R(s)$ it will be

$h_{bias}(s) > h_{opt}(s)$.

Hence given a context in which it is effectively possible to assist in a reduction of the stock of resources, the existence of present-biased preferences could move out the harvesting path. This context is characterized by a situation where the agents cannot avoid total exploitation of the resources before the end of the periods if they harvest the amount h_{max} continuously in the interval $[0,T]$. Obviously, in this context, the agent is called to determine a harvesting plan that contains the following condition:

$$R_0 + \sum_{t=0}^{T-1} \left[[R(t) - h(t)] \cdot f\big(g, R(t)\big) \right] - \sum_{n=1}^{N} \sum_{t=0}^{T-1} \left[h_{max} \cdot \Big(1 + f\big(g, R(t)\big)\Big)^t \right] \leq 0, \tag{15}$$

where N is the number of agents that harvest from the stock.

The (15) implies that there is at least one period in which $h(t) < \mathrm{h_{max}}$. Then, considering that the agent tends distribute her consumption over time, the assumption is that the agent's intertemporal preferences are given such that

$$H_{opt} = \left\{ h_{opt}(0), \ldots, h_{opt}(t_b), \ldots, h_{opt}(s) \ldots, h_{opt}(T) \,\middle|\, \begin{matrix} 0 < h_{opt}(t_b) < h_{max} \\ \wedge \\ 0 < h_{opt}(s) < h_{max} \end{matrix} \right\}. \tag{16}$$

This implies that if $h_{opt}(t) = h_{max} \; \forall \; t \in [0, t_b - 1]$, then $h_{opt}(t_b) < R(t_b)$ must be true to have $0 < h_{opt}(s) < h_{max}$. Thus, considering the implications of (15) and (16) and Lemma 1, the following assertion is possible:

Lemma 2: Given conditions (15) and (16), and given two possible strategies that can be derived by the decision-making process of the agent, the first one,

$H_{opt} = \{h_{opt}(0), \ldots, h_{opt}(t_b), \ldots, h_{opt}(T)\}$, in which, at time t_b, $\frac{\delta_{t_b}}{\delta_{t_b+1}} = \frac{\delta_{t_b+1}}{\delta_{t_b+2}}$, and the second one, $H_{bias} = \{h_{bias}(0), \ldots, h_{bias}(t_b), \ldots, h_{bias}(T)\}$, in which, at time t_b, $\frac{\delta_{t_b}}{\delta_{t_b+1}} > \frac{\delta_{t_b+1}}{\delta_{t_b+2}}$, in the time interval [0,*T*], there is at least one period, t_b, such that $h_{bias}(t_b) > h_{opt}(t_b)$.

Notably, R_0 is unique and invariable with respect to the strategy implemented, and (15) implies that there is at least one period where $h_{bias}(t) < h_{max}$ and at least one period where $h_{opt}(t) < h_{max}$. Given the existence of a first period in which $h_{opt}(t)$ is lower than h_{max}, t_b, if $h_{opt}(t_b) < h_{max}$ and $h_{bias}(t_b) = h_{max}$, clearly, $h_{bias}(t_b) > h_{opt}(t_b)$. Additionally, when $h_{opt}(t_b) < h_{max}$ and $h_{bias}(t_b) < h_{max}$, because in this first period, $R(t_b)$ clearly has the same value in both strategies, and because $R(t_b)$ must be greater than $h_{opt}(t_b)$ as consequence of (16), taking care of Lemma 1, the present bias as expressed in (12) determines that $h_{bias}(t_b) > h_{opt}(t_b)$.

The lemmas just enounced have deep consequences in relation to the outcome of the cooperative behavior implemented by an agent inside a group of harvesters managing a common stock of resources. Notably, the same relationship expressed in these propositions also exists when an agent inside a group has cooperative behavior.

Notably, two possible outcomes of the process of maximization also exist in the case of cooperative intentions of the agent: one in the case of the exponential discount rate and the other derived by present-biased preferences. Both outcomes correspond to a cooperative strategy: in the first case, it is a no-bias cooperative strategy (called the "optimal strategy"), and in the second case it is a biased cooperative strategy (hereafter the "biased strategy").

The context in which the agents cooperate in the management of the commons are so defined: the number of the harvester, *N*, is common knowledge, and homogeneity is assumed between the *N* agents in the instantaneous harvesting utilities $u_n(h_t)$ with $0 \leq h_t \leq h_{max}, \forall\, n \in N$.[9] Recall that the agent does not exercise a deliberative choice of one or the other strategies, but can choose between cooperating and being a free rider (or stop cooperating). Implementation of the optimal strategy by a biased agent is not possible because of the naïve nature of a biased agent who is not conscious of the implementation of a biased strategy.[10]

Therefore, for the single cooperative agent, when she choices to cooperate, the optimal solution is given by the maximization of the sum of the utility of the *N* agents:[11]

$$\max_{h_i} \sum_{i=1}^{N} U_i \ \text{ where } \ U_i = \sum_{t=0}^{T} \delta_i(t)\, u\big(h_i(t)\big), \tag{17}$$

under the constraints and conditions expressed earlier.

Under the hypothesis of the absence of present bias,[12] the cooperative harvesting plan is the optimal cooperative strategy:

$$H_{opt}^{c} = \{h_{opt}^{c}(0), \dots, h_{opt}^{c}(t), \dots, h_{opt}^{c}(T)\}. \tag{18}$$

The following is easy to understand: that a lower amount left unharvested, with respect to the prediction of the optimal cooperative strategy, is also the observable effect of a potential act of free riding. In particular, free-riding behavior at a given time *t* could emerge when the agent harvests an amount greater than the optimal cooperative amount:

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[9] In the following, heterogeneity is assumed in the bias factor.

[10] In this model naïveté of the biased agents is assumed such that naïve agents are fully unaware of their intertemporal inconsistency and of their future re-evaluation of the harvesting amounts.

[11] The assumption is that there is homogeneity in the utility function, and consequently, the cooperative agent maximizes the sum of the utilities.

[12]The hypothesis is satisfied when $\frac{\delta_t}{\delta_{t+n}} = \frac{\delta_s}{\delta_{s+n}}\ \forall\, t \in [0,T]\ \wedge\ \forall\, s \in [0,T]$.

$$h_f(t) > h^c_{opt}(t). \tag{19}$$

Proceeding with the no-biased behavior, a biased cooperative agent maximizes the total amount harvested by the group of *N* agents as expressed in (17) when her utility function is

$$U_i = \sum_{t=0}^{T} \delta_{bias}(t)\, u(h_i(t)), \tag{20}$$

where δ_{bias} has the properties expressed in (12). In this case, the agent adopts the biased cooperative strategy:

$$H^c_{bias} = \{h^c_{bias}(0), \dots, h^c_{bias}(t_b), \dots, h^c_{bias}(T)\}. \tag{21}$$

Now, considering the results described in Lemmas 1 and 2, given that (15) and (16) hold, it is possible to assert Proposition 1.

Proposition 1: Given two possible outcomes of the optimal solution in the presence of cooperative intentions of the agent, the optimal no-biased strategy is

$H^c_{opt} = \{h^c_{opt}(0), \dots, h^c_{opt}(t), \dots, h^c_{opt}(T)\}$, in which $\frac{\delta_t}{\delta_{t+1}} = \frac{\delta_s}{\delta_{s+1}}\ \forall\, t$, and the biased strategy $H^c_{bias} = \{h^c_{bias}(0), \dots, h^c_{bias}(t_b), \dots, h^c_{bias}(T)\}$, in which

$\frac{\delta_t}{\delta_{t+1}} > \frac{\delta_s}{\delta_{s+1}}$ for $t = 0$ and $\frac{\delta_t}{\delta_{t+1}} \geq \frac{\delta_s}{\delta_{s+1}}$ for $t > 0$, with $t < s$ and $t, s \in [0, T]$.

Then, interval (0, *T*] has least one period, denoted with t_b, such that

$$h^c_{bias}(t_b) > h^c_{opt}(t_b). \tag{22}$$

Thus, if several reasons could lead the agents to defect by a perfect cooperative strategy, a pure cooperative agent could also implement a strategy that does not coincide with H^c_{opt} even when her aim is "cooperate" because her choices can be affected by limited capabilities in using a constant discount rate, as in the case of present bias. In what follows, the manner in which the effect of the present bias, also in the presence of cooperative intentions, can trigger the dynamics of defections is exposed.

4. Cooperation failure because of the present bias

In a situation in which (22) holds, if the agents cannot be sure of the biased nature of the choices of others, it is not possible for a member of the group to distinguish if another member of the group harvests an amount greater than the optimal cooperative because she has free-riding intentions or because it is a cooperative biased action. Therefore, excessive harvesting of some present-biased agent can be erroneously interpreted as an act of free riding and in a tit-for-tat strategy, can trigger a round of defections.

To demonstrate this assertion, a situation with only two harvesters is considered. They are conditional cooperators that play a tit-for-tat strategy, harvesting simultaneously from the same stock of resources. It is possible to assign to one agent the capability to suppose that the other agent can be biased, but she has no information on the cooperative intentions of the other or on the biased discount factor; thus, the agent lacks any ability to distinguish the biased agents from the free riders.[13] The agents are homogeneous in the instantaneous harvesting utilities, $u_i(h_t) = u_j(h_t)$, but heterogeneity is assumed in the myopic discount factor $\delta_b(t)$ as defined in (12), denoting i and j as the agents, where the agent i has stronger present-biased preferences, then:

[13] Here, the possibility that one of the two agents can be not biased is assumed.

$$\frac{\delta_i^b(t)}{\delta_i^b(t+1)} \Bigg/ \frac{\delta_i^b(s)}{\delta_i^b(s+1)} > \frac{\delta_j^b(t)}{\delta_j^b(t+1)} \Bigg/ \frac{\delta_j^b(s)}{\delta_j^b(s+1)} \quad \text{with } s > t \; at\; least\; for\; t = 0, \tag{23}$$

where the hypothetical case of no bias is $\frac{\delta_i^{opt}(t)}{\delta_i^{opt}(t+1)} = \frac{\delta_j^{opt}(t)}{\delta_j^{opt}(t+1)}$. Now, considering (23), because the instantaneous harvesting utilities are $u_i(h_t) = u_j(h_t)$, with $0 \leq h_t < h_{max}$, (15) guarantees the existence of a period t_b such that $h_j(t_b) < h_{max}$; additionally, considering the results exposed in Proposition 1,

$$h_i^b(t_b) > h_j(t_b), \tag{24}$$

where $h_i^b(t_b)$ and $h_j(t_b)$ are the amounts effectively harvested by the agents, given the management strategies when behaviors are biased, at least for the agent *i*, and coincide with the cooperative amounts $h_i^c(t_b)$ and $h_j^c(t_b)$ as expressed in (21); then,

$$h_{opt}^c(t_b) \leq h_j(t_b) < h_i^b(t_b). \tag{25}$$

Because the agent *j* does not have instruments to distinguish if the higher harvesting of the other agent responds to a cooperative biased strategy or to free-riding intentions as expressed in (19), the agent can be induced to opt for a trigger strategy in the presence of $h_i(t_b) > h_j^c(t_b)$, even if $h_i(t_b)$ responds to the cooperative strategy in which $h_i(t_b) = h_i^c(t_b)$. If agent *j* interprets $h_i(t_b)$ as a free-rider attempt, the trigger strategy of agent *j* may involve an increase in the next harvesting amount until the Nash dominant non-cooperative amount, such that $h_j(t_b + 1) = h_{max}$; however, agent *i* still harvests her own cooperative amount. Thus, if $h_i(t_b + 1) < h_{max}$, at time $t_b + 1$ is

$$h_i^b(t_b + 1) < h_j(t_b + 1) \text{ with } h_j(t_b + 1) = h_{max}. \tag{26}$$

The increase in the harvesting level of agent *j* cannot be interpreted by agent *i* as an answer to her biased behavior because—as this model assumes—naïve agents are not conscious of their bias and are unable to recognize the appearance of their behavior as potential free-rider behavior. Notably, naïve agents have incomplete self-knowledge regarding the biased nature of their behaviors.

Hence, observing an amount harvested by agent j greater than the cooperative amount, agent i can interpret the harvesting amount of the j agent as a free-riding behavior attempt because from the viewpoint of agent i, she has cooperated until time $t+1$; consequently, she also can choose to start trigger-strategy harvesting at time $t+2$, an amount equal to h_{max}. At this time, a non-cooperant Nash equilibrium is reached in which

$$h_i(t+2) = h_j(t+2) = h_{max}. \tag{27}$$

Similar dynamics can also be triggered by a large number of harvesters. Thus, the question raised next is how the implication of present bias in these defective behaviors from the cooperative equilibrium can explicate a dynamic of cascading defections.

5. A restrictive case of cascading defections

Because the issue is how the present bias leads to defective strategies that in the absence of which such strategies will not occur, analysis of the behavior of the agents that deliberately choose to be free riders from the beginning is unnecessary. In this case, any effect of present bias is not relevant to adopting defective strategies, for the obvious reason that in presence of free-rider intentions, the defective strategies from the cooperative equilibrium are a consequence of free riding *a priori* and independent from the intertemporal bias. Hence, to show the effect of the present bias in the trigger, a defective strategy, the case in which all the *N* agents are cooperative, is considered.

The agents simultaneously harvest from the same stock of resources for *T* periods, the features regarding the stock of resources, growth rate, constraints, and utility function are those already presented in the model. Agents follow a tit-for-tat strategy, implying that they choose the cooperative strategy in the first round, but their cooperative intentions are not common knowledge. Agents are heterogeneous in their bias discount factors, and each agent makes her choice to harvest for a given period after having observed the amount harvested by the other agents in the previous period, which is the only information on others made available.

In every period *t*, each agent performs a cardinal order of all the amounts harvested, such that it is identified with $h_1(t)$, the amount harvested by the agent that harvests less, and in an increasing order $\mathrm{A_h}$ until $h_N(t)$, where agent *N* is that agent who harvests more:

$$A_h = \{h_1(t), \ldots, h_n(t), \ldots, h_N(t)\}, \tag{28}$$

where each *n* agent can distinguish the *n*-1 agents that have harvested less than her from the *N*-*n* agents that have harvested more.

In every round, each agent decides whether to implement the cooperative or defective strategy. In the first case, the cooperative amount harvested will be given by the maximization at time *t* of (17), under the usual constraints, for the periods of the residual periods of interaction $[t\,, T]$. Otherwise, the defection strategy comprises the adoption of the dominant Nash strategy that implies harvesting h_{max} until the end of the interactions.

Each agent assigns a given probability, $p_n(f)$, that other agents are free riders; $p_n(f)$ is based only on the agent's personal belief. The same probability to be a free rider is assigned to each other agent; thus,

$$p_n(f) = \frac{F_n}{N-1}, \tag{29}$$

where F_n is the number of free riders present in the group estimated by agent *n*.

The estimation is only subjective and is formulated by the agent in a condition of lack of information; thus, it is not assumed that this estimation is equal for all agents.[14] The agent constructs her personal beliefs with an action of mental accounting where she infers the probability used in the actual context from her experiences in other contexts (Gigerenzer et al. 1991). The logical induction derived from the representative agent's subjective long-term memory suggests that because she experienced acts of free riding in similar contexts, she should use her experiences in the present context, assuming a strictly positive probability that other agents could be free riders. Hence,

$$p_n(f) > 0 \;\; \forall \, n \in N. \tag{30}$$

The representative agent starts harvesting a cooperative amount, $h_n^c(t)$, and continues to cooperate as long as she believes that the other agents are also cooperating. The strategy instead prescribes the defection when the agent's belief leads her to estimate that at least one agent with free-rider intentions has caused her damage with an amount harvested that is greater than the cooperative amount $h_n^c(t)$. Hence, the condition of damaging harvesting occurs at time *s* when a member of the group takes an amount greater than the cooperative amount of the agent *n*:

$$h_j(s) > h_n^c(s) \;\; \text{with} \;\; j \in N. \tag{31}$$

In the case when damage occurs because of free riding, the agent defects. Thus, at each period *t*, the agent *n* observes the harvesting order, and at time *t*+1, she will select the defective strategy when she observes the damage occurs, and there is a given probability that among the agents that create the damage, there is at least one free rider. This probability, $P_n(F \geq 1)$, to determine a defective choice must be a value at least sufficiently large for the agent to evaluate it as sufficient for the defect: $P_n^d(F \geq 1)$.

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[14] The estimation occurs in a context where each agent is subjected to the absence of information regarding the real intentions of others; hence, the estimated presence of a free rider is not related to the real presence.

Therefore, assuming that s is a period within $[0, T]$ in which (31) holds, the agent defects after time s when the following occurs:

$$P_n(F \geq 1)_s \geq P_n^d(F \geq 1), \tag{32}$$

where $P_n(F \geq 1)_s$ is the probability condition estimated at time s. Then, the harvesting strategy of the agent n is as follows:

$$h_n(t) = \begin{cases} h_{max}, & t > s \text{ if } P_n(F \geq 1)_s \geq P_n^d(F \geq 1) \wedge h_j(s) > h_n^c(s), \\ h_n^c(t), & \text{otherwise.} \end{cases} \tag{33}$$

The result of the first proposition expressed in (22) and condition (24) determined by the heterogeneity in the bias factor imply a first period in $[0, T]$ in which (31) holds such that the agent n is posed in a condition of damage. The observations of the amounts harvested enable the agent to circumscribe the *N-n* agents that determine damage. Among these, the agent n evaluates the presence of the free riders to verify the realization of condition (32). Therefore, defining

$$\Omega = \{1, \dots, n, \dots, N | 1, \dots, N = f, c\} \tag{34}$$

as the set of all possible compositions of the group on N agents where each agent can be a free rider, f, or a cooperant, c. The number of possible cases can be given by the ordered selections of *N-n* subjects in Ω, with the exclusion of the agent, $\binom{N-1}{N-n}$.

The probability of a situation where among the *N-n* agents there is at least one free-rider is given by the ratio between the favorable cases and the possible cases. The favorable cases are those where the *N-n* agents of the upper subgroup, the number of potential free riders are between 1 and F_n. The probability of the presence of a given number of free riders, q, inside subgroup *N-n* is defined as follows:

$$P(F = q) = \frac{\dfrac{F_n!}{q!\,(F_n - q)!} \dfrac{(N - 1 - F_n)!}{(N - n - q)!\,(n + q - 1 - F_n)!}}{\dfrac{(N - 1)!}{(N - n)!\,(n - 1)!}}, \tag{35}$$

where the probability for each agent that *f* is true, regarding event (*f,c*), is given by the subjective estimation of the agent n, $p_n(f)$, as derived by (29).

Therefore,

$$P_n(F \geq 1) = \sum_{q=1}^{F_n} P(F = q), \tag{36}$$

where *F* is the number of free riders.

The defection choice derived from (33), given a period *s* in $[0, T]$ in which the condition (31) is verified a first time, occurs if the probability of the presence of at least one free rider $P_n^d(F \geq 1)$ is greater than or equal to $P_n^d(F \geq 1)$. Now, considering the value of $P_n^d(F \geq 1)$, an assumption is that for a probability of the presence of at least one free rider between the *N-n* agent that harvests more, close to the certitude that is $P_n(F \geq 1) \approx 1$, each agent n chooses non-cooperative harvesting; hence, with $P_n^d(F \geq 1) \leq 1 \;\; \forall \;\; n \in N$, it will be

$$h_n(t) = h_{max} \text{ when } P_n(F \geq 1) \approx 1 \;\; \forall \;\; n \in N \tag{37}$$

Now, an order is considered that includes all *N* agents, where each *n* agent has the position equal to the position that her harvesting h_n has in the order defined in (28). This gives a cardinal order that identifies with *n*=1 the agent who has harvested less and, therefore, increasingly until the agent *N* who has harvested more than all the others; hence,

$$A = \{1, \ldots, n, \ldots, N\}. \tag{38}$$

Each agent estimates a probability of the presence of a free rider among the *N-n* agents that have harvested more than him, $P_n(F \geq 1)$, as defined in (36).

Thus, it becomes easy to understand that for an *n* that approaches 1 in the order defined in (38), remembering that $P_n(F = q) = 0$ when $n \; < \; F_n + 1 - \; q$, $P_n(F \geq 1) \approx 1$. This implies that at least the agent that has the first place, *n*=1, in the order *A* at time *s*, will decide to defect starting in period s+1. In this manner, a new order A is generated at time s+1 in which a new agent takes the first position.

Considering (37), at each period t, $t > s$, after that, for the first time, the condition in (31) is verified, and at least one agent chooses a defective harvesting amount equal to h_{max} from t+1 until T. Notably, at every time t+1, the defection of an agent that at time t was in the condition $P_n(F \geq 1)_t \geq P_n^d(F \geq 1)$, determines a new order where at least one agent, that at time t+1 had harvested the cooperative amount $h_c(t+1)$, evaluates a $P_n(F \geq 1)_{t+1}$ sufficient for the defection at time t+2. This occurs because in every period, there is a new agent n in the first place in the order A such that $P_n(F \geq 1) \approx 1$; hence, (32) holds true. Therefore, in the following period, a new agent will switch from the cooperative strategy to the defective strategy. Thus, Proposition 2 is possible:

Proposition 2: When agents adopt the strategy defined in (33), with heterogeneity in the present-bias factor as defined in (12), and they assign a positive probability of the presence of free riders inside the group as in (30), and an assumption is that for every agent if the probability of the presence of at least one free rider between the N-n agents that harvest more is close to 1, $P_n(F \geq 1) \approx 1$, then (32) holds; additionally, considering that there exists at least one period s in [0,T] such that the condition in (31) is verified, for every period after time s, at least one agent inside the group stops cooperating.

The process just exposed auto-fuels time after time and leads, for a sufficiently large period of interaction, to the disappearance of the cooperative actions within the group reaching a non-cooperative equilibrium in which all agents harvest $h_{\max}$ despite their previous intentions of cooperation. This process is triggered by the presence of present-biased preferences.

6. Extensive cases: condition for a cascade of defections

Thus far, this work has demonstrated that within a context populated by conditional cooperators with heterogeneous myopic discount factors, present-biased preferences can lead to the application of a triggered strategy that directs the agents to excessively increase their harvesting level, even if their motivations were cooperative. With the restrictive case, this work has demonstrated the occurrence of cascading defections, assuming blindness, no-awareness of the bias of others, and the absence of tolerance for the presence of free riders.[15] Furthermore, this work has considered the dominant Nash strategy as the only implementable defective strategy. However, conditions that are wider and less restrictive will be defined next. Specifically, the conditions regarding the two decisive decision-making elements of the defection will be defined. First, the model will define the condition for the critical level of estimated free riders inside the group (i.e., the given number of supposed free riders that damage the agent such that she will not be available to cooperate further). The model will define even the condition for the estimated probability of the number of free riders that exceed the critical level considered sufficiently high by the agent to defect. In the restrictive case, the number of estimated free riders evaluated sufficient to defective was just one but with a probability of presence estimated that was close the certitude. With the extensive model in this paragraph, the number of estimated free riders and the probability to stop cooperating will be less restrictive. Second, the model will be less restrictive even regarding the definition of the behavioral strategy adopted, including non-cooperative behaviors not limited to the adoption of the dominant Nash strategy.

6.1 Condition regarding the critical value to defect

[15] $P_n^d(F \geq 1)$ accurately expresses this absence of tolerance because it expresses that the presence of just one free-rider (or the belief that there is a free-rider also because of an erroneous evaluation) is sufficient to trigger the defection.

Only on rare occasions do agents behave under certainty; in the restrictive case, the implementation of a defection strategy occurred for a probability of the presence of free riders close to certitude, which it is too restrictive to fit well with reality. However, an assumption is that the agent can choose to stop cooperating in the absence of certitude as well, without any change in the conclusion drawn in the cascade of the aforementioned defections. Notably, having at least one agent that stops cooperating at every period is sufficient to assume that the probability $P_n^d(F \geq 1)$ must be positive:[16]

$$0 < P_n^d(F \geq 1) \leq 1 \qquad \forall\ n \in N. \tag{39}$$

Furthermore, an assumption adopted in the model is that the agent can consider an estimated presence of only one free rider is inadequate to start a trigger strategy, but she may choose to defect for more than one estimated free rider. In this case, agent *n* is willing to accept the presence of a physiological number of free riders, q_n, inside the group.

The nature of this physiological number of free riders can also be extended to include those who erroneously behave as free riders. This implies that the agent accepts the presence of a given number of agents within her group of harvesting who behave in a manner compatible with free-rider intentions. This extension opens the opportunity of introducing heterogeneity within the model, namely, making it possible to have both pure naïve agents and agents that are conscious of the possibility of an erroneous implementation of a free-riding harvested amount. For naïve agents, q_n represents merely the acceptable number of free riders within the group, whereas for the second one, it represents the acceptable number of individuals that behave as if free riders, including those who erroneously act as free riders.[17] A sufficiently large probability that

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[16] It is trivial that if the defection occurs for a probability of the presence of a free-rider lower than one, the result is the same as obtained when the defection begins only in presence to the certitude.

[17] For the simplicity of narration, for both types of agents, q_n refers to the physiological number of free-riders within the group (without specifying the peculiarity of the case of the no-full naïve agents).

the estimated number of free riders is greater that q_n will induce the agent to defect.

Hence, $P_n(F > q_n)$ is defined as the probability—estimated by the agent *n*—of the presence of more free riders than the physiological one, among the *N-n* agents who, with their higher harvesting, cause damage to agent *n* such that

$$P_n(F > q_n) = \sum_{q=q_n+1}^{F_n} P(F = q). \tag{40}$$

Conditions necessary for the defective choice are as follows:

$$P_n(F > q_n)_s \geq P_n^d(F > q_n) \text{ with } q_n < F_n, \tag{41}$$

where $P_n(F > q_n)_s$ is the probability evaluated at time *s* in [0,*T*] such that the agent stops cooperating when at time *s*, the condition in (31) is verified, and the estimated number of agents that harvest a compatible free-rider amount exceeding the physiological amount for a sufficiently large probability of at least $P_n^d(F > q_n)$, where

$$0 < P_n^d(F \geq q_n) \leq 1 \quad \forall\ n \in N. \tag{42}$$

The only condition over q_n is that it must be lower than F_n, that is, the *conditio sine qua non* must have a conditional cooperant. Notably, if hypothetically the agent takes the non-cooperative amount only if the number of evaluated free riders is greater that F_n, she is willing to defect for an evaluated presence of free riders between the *N-n* agents that damage her greater than the number of free rider that she has assumed to be present in the group of *N* agents, but this is not a real possibility of defecting. In this case, the behavior is the behavior of an unconditional cooperant that *a priori* and independently by other elements always chooses the cooperative amount.

Now, continuing to refer to the strategy defined in (33), but where the condition for harvesting h_{max} at time $t > s$ is $P_n(F \geq q_n)_s \geq P_n^d(F \geq q_n) \wedge h_j(s) > h_n^c(s)$, in other cases, the agent cooperates.[18] Additionally, assuming the condition expressed in (41) and (42), obviously, when an assumption is $q_n \geq 0$, given the cardinal order defined in (38), for n that approaches to 1 in the (40), it will be that

$$\overrightarrow{\lim_{n \to 1}} P_n(F > q_n) = 1. \tag{43}$$

Thus, also when extending the properties of the agent's behavior to condition (41) and (42), at least one agent in each period is in the condition to defect because given the result obtained in Proposition 1 that guarantees the existence of a time s in $[0,T]$ such that $h_j(s) > h_n^c(s)$, and given that $0 < P_n^d(F \geq q_n) \leq 1 \;\forall\; n \in (1, N)$, the result in (43) ensures that the condition in (41) is verified. Therefore, the following can be asserted:

Lemma 3: If each agent assigns a positive $p_n(f)$ for every other agent, and for each agent, the probability of an excessive number of free riders that implies the defection is $0 < P_n^d(F > q_n) \leq 1$ with $q_n < F_n$; then, for every period after time s, at least one agent inside the group will stop cooperating.

This leads to a decrease in the cooperative behaviors with the passing of interactions, and this decrease depends not on the real presence of an excessive number of free riders but on the impossibility to distinguish the free-rider attempts from the cooperative but present-bias choices.

[18]The set of strategies that leads to cascading defections is wider and does not require the strict adoption of Nash dominant harvesting, as is presented in this work.

6.2 Conditions for the harvesting strategy

Until now, the only strategy set considered prescribed, as a defective choice, the non-cooperative dominant strategy, $h_n(t) = h_{max}$; thus, it is possible to consider a wider range of defective strategies. This work will show that when an agent adopts a tit-for-tat strategy, the result may be a cascade of defections, even if the defective choice is different from the non-cooperative dominant choices. Notably, the following is sufficient: consider the adoption of a strategy that prescribes that when the conditions given by (31) and (41) occur, the agent increases her harvesting of an amount arbitrarily greater than those of the precedent period and that the new amount also guarantees a harvesting greater than the cooperative amount. If after the increase, the defective conditions no longer hold true, the agent maintains a harvesting amount not lower than the previous amount, $h_n(t-1)$, provided that this amount is greater than the cooperative amount for period t, to maintain the non-cooperative behavior. Otherwise, she will harvest an amount arbitrarily greater than the cooperative amount, to maintain the decision to stop cooperating after the defection conditions are verified the first time; additionally, the increase in the harvesting occurs each time that the defective conditions are verified, to avoid the permanence of the damaging situation. In this case, the strategy can be so defined:

$$h_n(t) = \begin{cases} h_n^c(t) & t \leq s_m \\ h_n(t-1) + \epsilon_n(t) & t > s_m \vee t = s+1 \text{ if } h_n(t-1) > h_n^c(t) \\ max\{h_n^c(t) + \epsilon_n(t), h_n(t-1)\} & \text{otherwise} \end{cases} \tag{44}$$

$$\text{with } \; t \in [0,T], \qquad s_m = min(S_n), \qquad s \in S_n \subseteq [0,T],$$

where S_n is the set of all the periods s in $[0,\mathrm{T}]$ such that conditions (31) and (41) are simultaneously verified. Furthermore, the arbitrary increase must be a strictly positive amount just sufficient to have $h_n(t) > h_n^c(t)$ and $h_n(t) > h_n(t-1)$, defined as follows:

$$\epsilon_n(t) = f\big(t, h_n(t)\big) > 0 : \; h_n(t) > h_n^c(t) \; \wedge h_n(t) > h_n(t-1). \tag{45}$$

As shown in Proposition 1, there exists at least a time t_b in $[0, \mathrm{T}]$ such that $h_n(t_b) > h_n^c(t_b)$ when the agent has cooperative but biased preferences, and t_b is defined as the first period in which, because of the heterogeneity in the bias discount factor, given the implication of (23), $h_j(t_b) > h_n^c(t_b)$ with $j \neq n$; and at time t_b, at least one agent is in the position to defect in the next round, in Lemma 3, because at time t_b, at least for the agent in the first position in the order expressed in (38), the condition in (41) is verified. Hence, the following is possible to define:

$$\exists\, t_b \subseteq [0, T] \Leftrightarrow A_{t_b}\colon P_n(F > q_n)_{t_b} \geq P_n^d(F > q_n) \ \wedge\ h_j(t_b) > h_n^c(t_b), \tag{46}$$

where A_{t_b} is the order as in (38) defined at time t_b.

Lemma 3 has already revealed that (46) holds true at least for one agent in each period after time t_b when $P_n(f) > 0$, $0 < P_n^d(F > q_n) \leq 1$ and $q_n < F_n$. Notably, assuming strategy set (44), which includes the dominant Nash strategies and all the amounts that respond to a defective intention of the agent, for all the agents within the group of *N*, and defining an order as in (38), for every order A_t for t in $[t_b, T]$, given (42) and (30), at least for the agent in the first position of the order, the probability of the presence of an excessive number of free riders approaches certitude. Hence, we obtain that

$$\forall t \in [t_b, T]\ \exists\, A_t \mid \text{ for } n \to 1\ \ lim\, P_n(F > q_n) = 1. \tag{47}$$

Therefore, it is possible to assert Proposition 3:

Proposition 3: In every period $t \in [t_b, T]$, at least one agent is under the condition to increase the harvesting amount in the next period *t*+1, adopting a non-cooperative behavior, such that referring to the strategies set defined in (44) implies that

$$\forall\, t \in [t_b, T]\ \exists\, n \in N :\ t = s\,, s \in S_n.$$

Consequently, if at time *t*, with $t \in [t_b, T], \exists\, n \in N :\ h_n(t) = h_n^c(t)$; then,

$$\exists\, n \in N :\ h_n(t+1) > h_n(t)\ \wedge\ h_n(t+1) > h_n^c(t+1).$$

Thus clearly, during each period, some agent increases her harvesting, moving away from the cooperative behavior. This implies a tendency over time to change the order of the agents derived from their harvesting levels, with a translation of the already defective agents to higher positions in the order. In this manner, the agents who are still cooperative take their place on the lower-side positions, observing, time-by-time, the increase in the probability that implies defective choices. This phenomenon determines the increase in agents that defect by their cooperative behavior over time.

Notably, assuming the condition revealed in the model, it is given a context that for its peculiarities has always at least one agent in the stage of increasing her harvesting over the cooperative level. Therefore, with the passage of interactions, the cooperative agents decrease inducing other agents to defect. Agents defect because of their own lower harvesting and the increase in the value of the probability as expressed in (40) until the level in which the condition expressed in (41) is verified. The consequence of the dynamics exposed is a general progressive increasing of amounts harvested, and a progressive decay of the cooperative behaviors within the group.

7. Conclusion and final remarks

This work has shown that when the agents are conditional cooperators, the present bias, in the absence of appropriate information or institutions that facilitate the coordination, can trigger a cascade of defections from the cooperative strategy such as those observed in the controlled experiments. Moreover, this work shows the conditions and dynamics under which the number of individuals that choose to stop cooperating increases over time.

The paper demonstrates that if agents estimate the presence of free riders within the group of harvesters using their long-term memory, without information regarding the real number of free riders, the adoption of defective strategies is generated by the misunderstanding regarding the real intention of the present-biased agents and by the restricted self-knowledge regarding their own present-biased preferences.

Thus, when agents behave conformably to their biased preferences, without any instrument of coordination that sustains their existing desire of cooperation, they direct a suboptimal allocation of the amount harvested, damaging themselves and others.

Therefore, the existence of a cascade of defections, which is also observe in presence of the cooperative and prosocial preferences, can be explicated by the dynamics triggered by present-biased behaviors when the harvesters cannot distinguish biased choices from free-rider attempts. In this case, the decline in cooperation in the management of commons could be mitigated by adopting instruments designed to oppose the effect of present-biased preferences. Therefore, the drop in cooperative behaviors can also be an effect of the absence of institutional instruments to improve the coordination in the face of intertemporal cognitive biases.

The model presented responds to the following idea: a true representation of human behavior in the social intertemporal dilemma requires the inclusion of the complexity in the decision-making process, and in particular, of the cognitive factors that affect the choices. This occurs because the social dimension of human nature must be considered when common resources are involved. Notably, on the one hand, the adoption of sustainable and cooperative behavior in relevant social dilemmas depends on the degree of consciousness of the effect of the agents' behaviors on others, showing interest in and care for the common resources. This propensity finds form in the cooperative and other-regarding motives. On the other hand, the choices reflect the capability of a correct evaluation of costs and benefits derived from their decisions. The intertemporal decision-making process that directs the choices is also how individuals solve social dilemmas. Within this process, the social preferences are realized. Thus clearly, the cognitive aspects and the behavioral traits of the intertemporal choices, such as present bias, are fundamental elements in the representation of social dilemmas. Thus, the analysis of present-biased preferences in the intertemporal dynamic is essential to obtain a full understanding of the dynamics of harvesting (and overharvesting) from the commons. This understanding is also necessary to define and create suitable instruments that can sustain cooperative preferences.

The results obtained in this work show with clarity that the cognitive factors that affect the intertemporal ability of the agents are greatly involved in the abandonment of cooperative interaction over time. However, this is a part of the complexity of human decisions, where all the causes of a given behavior interact. Present bias is one piece of the puzzle that, together with the free-rider opportunities, explicates the phenomena observed. Notably, the rapidity of the cascading defections depends on several factors. In particular, the presence of heterogeneity in the intentions can contribute to a new complexity of the dynamic. However, the presence of free riders, together with the cooperative present-biased agents, can only be an additional factor in the rapidity of the abandonment of cooperative behaviors. Of course, decay in cooperative intentions can also occur independently from the present bias if the real free riders are present in an excessive quantity, per se. Although these elements affect the rapidity and complexity of the defective cascade, this work did not define this speed. Instead, this work attempted to show that the observable and observed decay of cooperative choices in common resource dilemmas are not a unique, unequivocal signal of an increase in the free-riding intentions but can also result from present-biased preferences and myopic behaviors of cooperative agents.

In conclusion, present-biased preferences can lead to the application of a trigger strategy that can direct the community to excessively increase their harvesting level, even if their other-regarding motives were cooperative. Therefore, a decrease in cooperative intentions can also be the effect of the absence of coordination instruments in the presence of the cognitive bias that affects human behaviors.

These conclusions are relevant and useful for policymakers whose goal is to support cooperative and sustainable behaviors in the management of common resources.

Notably, sustaining the diffusion of the prosocial preferences, if the adoption of cooperation in the commons is a perquisite, the results desired cannot be offered if the individuals and the community lack the necessary instruments for the wise management of resources in the presence of the risk connected to present-biased preferences.

Notably, human behavior follows complex dynamics and decision-making processes. The cognitive dimension plays a crucial role, and present bias is one of the elements that, moving far from pure rational behavior, increases the complexity of human interaction in the commons. For these reasons, further research should investigate the interrelation between these cognitive intertemporal elements and the social dimension of human nature.

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