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Domenico De Giovanni
Fabio Lamantia
Mario Pezzino

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School of Social Sciences
The University of Manchester
Manchester M13 9PL

Evolutionary tax evasion and optimal regulation under prospect theory

Domenico De Giovanni [*] Fabio Lamantia [†] Mario Pezzino [‡]

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Abstract

We study the dynamics of compliance in a population of agents that decide whether to engage in tax evasion depending on an evolutionary adaptation process. We model taxpayers' preferences by means of Prospect Theory. We also consider an optimal control problem to study the long-run level of tax evasion when a tax authority targets the maximization of the expected stream of tax revenues choosing auditing effort. The analysis provides conditions for the evolution of tax evasion to converge to an asymptotically stable interior equilibrium. Moreover, the study of the intertemporal optimal auditing produces novel and rich results, including the existence of multiple equilibria and discontinuities in the optimal control.

Keywords: Tax Evasion; Prospect Theory; Optimal Control; Auditing; Evolutionary Dynamics

JEL Codes: D8, C61, C73, H26

[*]Department of Economics, Statistics and Finance, University of Calabria (Italy), ddegiovanni@unical.it

[†]Department of Economics, Statistics and Finance, University of Calabria (Italy) and School of Social Sciences, University of Manchester (UK), fabio.lamantia@unical.it

[‡]School of Social Sciences, University of Manchester (UK), mario.pezzino@manchester.ac.uk

1 Introduction

The economic literature has traditionally framed tax evasion as a form of risky decision, a gamble, that individuals face when considering criminal actions.[1] According to this literature, whether individuals decide to evade depends on their degree of risk aversion, the tax system (e.g. the level and progressivity of tax rates) and the auditing system in place (e.g. probability of auditing and penalty if caught evading). These models, however, predict a level of evasion that is far too high compared to empirical and experimental evidence and anticipate tax evasion to decrease if tax rates increase (this is often referred to as the *Yitzhaki puzzle*).[2] Economic (but also psychological, sociological and political) research has recently searched for additional and significant factors that may induce individuals to comply.[3]

Prospect Theory (PT)[4] provides one possible explanation to the puzzle. Moving away from standard expected utility, Bernasconi and Zanardi (2004); Dhami and Al-Nowaihi (2007, 2010) have applied the cumulative prospect theory framework, first introduced in Kahneman and Tversky (1979), to the case of tax evasion.[5] In particular, applying the principles of PT, Dhami and Al-Nowaihi (2007) show that an increase in the tax rate indeed may reduce the incidence of tax evasion, in line with empirical evidence and thus providing a possible solution to the Yitzhaki puzzle.[6]

At the same time, Luttmer and Singhal (2014) argue that most of the possible determinants of tax evasion tend to have recurring, evolving and long-lasting

[1] See for example Allingham and Sandmo (1972); Slemrod and Weber (2012); Slemrod and Yitzhaki (2002); Yitzhaki (1974). See Freire-Serén and Panadés (2013) for a review of the literature.

[2] See Alm (1999); Alm et al. (1992); Frey and Feld (2002); Torgler (2002). The level of risk aversion required to explain the observed levels of compliance is often significantly larger than the amount of risk aversion effectively reported.

[3] We are leaving aside the issue of third-party reporting, where the income earned by individuals is directly reported to tax authorities by the employers. See Kleven et al. (2011).

[4] See Chetty (2009).

[5] See also Piolatto and Rablen (2017); Piolatto and Trotin (2016); Trotin (2012).

[6] The literature considers another possible explanation to the Yitzhaki puzzle. Recent contributions have studied the way social norms and forms of intrinsic motivation (often referred as *tax morale*) may affect individuals' behavior and, ultimately, compliance rates. See Andreoni et al. (1998); Luttmer and Singhal (2014).

effects on individuals' behavior. This observation ultimately calls also for a dynamic analysis of the phenomenon of tax evasion.[7] In other words, it is essential to understand that fiscal and auditing reforms may have both short-run and long-run effects on compliance.

Although tax evasion is widely recognized as a dynamic phenomenon, academics have only recently started studying the dynamic evolution of tax evasion. In this context, the prevailing approach consists in studying the optimal behavior of a representative taxpayer with forward-looking preferences and exogenously given auditing rules. Examples in such stream of the literature are Dzhumashev and Gahramanov (2011); Levaggi and Menoncin (2013); Lin and Yang (2001) and the more recent contribution in Levaggi and Menoncin (2016). An alternative approach, that considers the dynamic evolution of tax evasion with boundedly rational agents in an evolutionary context, has been recently employed by Antoci et al. (2014); Petrohilos-Andrianos and Xepapadeas (2016). Both approaches have their own features and merits. However, the evolutionary setup has the ability to explain behavioral heterogeneity in the population and allows for an endogenous auditing process.

This paper extends the framework of tax evasion under PT to a dynamic evolutionary setting. In line with the behavioral stance proposed by PT, evolutionary dynamics considers individuals to be boundedly rational, assumed to be "programmed" to behave honestly or dishonestly.[8] However, through social interaction agents can over time change their conduct.

The contribution of this paper is threefold. First, we propose a dynamic framework that allows to describe the evolutionary dynamics of tax evasion

[7]See Turner (1991) for a review of the literature of the evolution of norms proposed in social psychology. Wenzel (2005) also provides evidence that tax morale affects compliance and, more importantly, that compliance in one period can affect tax morale and, consequently, compliance in the next. Theoretical models of the dynamics of tax evasion and social norms are discussed in Besley et al. (2015); Kim (2003); Traxler (2010) and, more recently, by Lamantia and Pezzino (2017). See also Nordblom (2017) and, for a review of the contributions on behavioral dynamics of tax evasion, see Pickhardt and Prinz (2014).

[8]Frey (1999) shows that in a population there may be taxpayers who simply do not look for opportunities to evade taxes. On similar lines, Long and Swingen (1991) (p130) argue that some individuals are not naturally predisposed to evade taxes. This is in line with experimental evidence that shows that some individuals never choose to evade taxes (see Feld and Tyran, 2002), even in the absence of enforcement.

and identify the effects of tax reforms (e.g. changes in tax rates or auditing approaches) and the effects of the bounded rationality of taxpayers under prospect theory on the long-run equilibrium of the model. For a given auditing scheme that depends on the current level of tax evasion, and assuming an exogenous auditing probability, we show that an interior asymptotically stable equilibrium where only a portion of the population engages in tax evasion exists only if the auditing effort of the tax authority is assumed to be increasing in the level of evasion in the population. Intuitively, if the likelihood of auditing increases with tax evasion and more agents decide to evade, in the following period the higher probability of being audited reduces the prospect of evading taxes and limits the diffusion of the dishonest behavior.

As for the second contribution of this paper, we identify and solve the intertemporal maximization problem of a tax authority that targets intertemporal tax revenue maximization. Our analysis is in spirit similar to the one described in Petrohilos-Andrianos and Xepapadeas (2016). Taxpayers are assumed to be boundedly rational and the tax authority is assumed to be rational and following the principles of expected utility theory.[9] As Petrohilos-Andrianos and Xepapadeas (2016), we assume that the regulator and the agents have different degrees of rationality, with an intertemporal optimizing regulator and myopic agents following a replicator dynamics. However, in contrast to Petrohilos-Andrianos and Xepapadeas (2016), where individuals' payoffs are still valued through their expected utility, we employ the more realistic framework given by prospect theory. In addition to that, in this paper, we also perform a different type of dynamic analysis. In fact, Petrohilos-Andrianos and Xepapadeas (2016) solve the regulator's control problem with the Maximum Principle and characterize the stability of the inner equilibrium. The analysis performed in this paper is broader and aimed at understanding the global dynamics of the system.

The third and, perhaps, most important contribution of this paper lies in our

[9] This is a standard assumption in the literature; see, for example, Dhami and Al-Nowaihi (2010).

results. Our analysis shows how the long-run evolution of the controlled dynamical system is affected by the way taxpayers may react to auditing policies and, in particular, by the way they may distort the probability of being audited. An increase in the distortion of auditing probability towards an overestimation of low probabilities makes the system change from a situation in which the whole population engages in tax evasion in the long-run to scenarios in which the level of tax evasion converges to an interior (asymptotically stable) equilibrium in which only a portion of the population behaves dishonestly. Scenarios characterized by the presence of a Skiba point, that is with multiple locally stable equilibria each with their own basin of attraction, are also possible. In such cases, the system's initial conditions define which equilibrium prevails. To the best of our knowledge, the possibility that the long run evolution of tax evasion might depend on the initial evasion level has never been documented. This creates a novel testable hypothesis for future empirical research to explore. Also, for a given level of tax evasion, an increase in the tax rate will have two effects. First, it will increase the individuals' prospect of behaving dishonestly (in line with those contributions in the literature that have discussed the Yitzhaki puzzle). At the same time, however, it will also increase the regulator's incentive to invest more in auditing. Being a rational, forward-looking agent, the auditor internalizes the intertemporal advantages of increasing auditing and the combined effect of an increase in tax rate is to reduce the likelihood of equilibria with extreme levels of tax evasion. Finally, the analysis produces, for sufficiently high levels of the tax rate, the possibility of the existence of a discontinuity in the regulator's optimal control created by a threshold level of tax evasion. For low levels of tax evasion, the forward-looking regulator will be willing to incur in relatively low auditing costs to lower the prospect of dishonest behavior. For higher levels of tax evasion, the auditing costs are increasing (at an increasing speed) in tax evasion and there may be a threshold level of evasion that would make the regulator suddenly decide to drastically reduce auditing effort. Initial conditions will play once again an important role. Depending on whether the initial level of tax evasion is below or above the threshold, the system will converge respectively to an interior equilibrium or a boundary equilibrium where either all individuals or no individual will engage in tax evasion.

The paper is organized as follows. In Section 2 we introduce the model. In Section 3 we analyze the evolution of tax evasion for a general, but endogenously given, auditing probability function. In Section 4 we study the optimal enforcement problem in which a tax authority optimally controls the intertemporal maximization of future streams of tax revenues when the evolution of tax evasion is described by replicator dynamics. Section 5 concludes.

2 The model

We consider a population of agents (taxpayers), earning the same income W and subject to the same tax rate r. Each agent may decide either to be honest, that is, declare the entire income, or to evade by declaring $D < W$, so that $E = W - D > 0$ is the amount the agent evades.[10]

With probability p an evader is audited and sanctioned. Sanction is proportional to evasion: if detected, the sanctioned agent pays $\lambda r E$, where $\lambda \geq 1$ measure the additional fine if found guilty. Summing up, if the agent is not found guilty, then his net income is:

$$Y^N = W(1-r) + rE;$$

On the other hand, if audited, then agent's net income is:

$$Y^A = W\,(1-r) - \lambda r E.$$

[10]The assumption that all individuals choose the same exogenous level of evasion is clearly a simplification; however, this is in line with the empirical evidence reported in Andrighetto et al. (2016). The authors compare tax evasion in Sweden and Italy and show that tax evasion in the two countries takes very different forms. In Sweden taxpayers tend to report either 100% of their income (full honesty) or very small amounts (full tax evasion). In Italy, instead, taxpayers tend to select intermediate levels of their income. In what follows, the effect of a change in parameter E could be interpreted, therefore, as a change in the cultural background of individuals or, simply, to a different population.

2.1 Taxpayers' preferences

We adopt the framework of Prospect Theory (PT) of Kahneman and Tversky (1979) as employed in Dhami and Al-Nowaihi (2007, 2010). We standardize agents' net income using the after-tax income $(1-r)W$ as reference point. This implies that agents are interested in the utility coming from their net income relative to the reference point. Using this change of variable, honest agents have a relative income equal to zero while evaders get a relative income equal to $Z^A = Y^A - (1-r)W = -\lambda rE$ if detected and to $Z^N = Y^N - (1-r)W = rE$ if not detected.

In line with PT, individuals may perceive auditing probability in a distorted way. Specifically, they may be influenced by a probability weighting function, $w(p) : [0,1] \to [0,1]$, increasing in p, that assigns weights to each auditing probability. In this paper, we shall consider the Prelec weighting function[11]

$$w(p) = e^{-[(-\log p)^{\alpha}]}. \tag{1}$$

For the value function (utility) $v(z)$ associated to outcome z (i.e. Z^q, $q = A, N$) we assume:

$$v(z) = \begin{cases} z^{\beta} \text{ if } z \geq 0 \\ -\theta\,(-z)^{\beta} \text{ if } z < 0 \end{cases} \tag{2}$$

where $\theta > 1$ measures loss aversion and $\beta \in [0,1]$ measures declining sensitivity of the utility.[12] If an agent evades, his utility is then:

$$V = w(p)v(-\lambda rE) + w(1-p)v\,(rE)\,,$$

otherwise he has utility $V^0 = w(0)v(0) = 0$.

[11]In general the Prelec probability weighting function assumes the form $w(p) = e^{-\xi[(-\log p)^{\alpha}]}$, with $\alpha > 0$ and $\xi > 0$. Here, we focus on the case $\xi = 1$ and $0 < \alpha \leq 1$ for direct comparison with Dhami and Al-Nowaihi (2007, 2010).

[12]In particular β model the concavity in the domain of gains and the convexity in the domain of losses of the utility with respect to the reference point. Tversky and Kahneman (1992) suggest to use $\beta = 0.88$ and $\theta = 2.25$).

2.2 Evolutionary setup

This section describes a dynamic model of tax evasion based on the evolution of agent types in a population. The population's state at time t is the share of evaders at time t, henceforth denoted by $x(t)$. The fraction of honest agents in the population is $1-x(t)$. We assume that the auditing probabilities depend on the current state of the system, that is $p(t) = p\left(x(t)\right)$. This gives the regulator the ability to adjust the auditing probabilities according to the current state of the population.[13]

We shall consider in the next section the optimal control problem of a tax authority that intends to maximize a flow of tax revenues selecting the audit probability. For now, we shall consider simply the case that audit probability may be increasing or decreasing in the level of evolution. The probability of audit may increase in the level of tax evasion in the population because the tax authority may find it increasingly easier to detect evasion or it may be under increasingly political pressure. Similarly, it is possible to conceive situations in which the probability of auditing may decrease with the level of evasion. Galbiati and Zanella (2012), for example, assume that the probability of auditing may be decreasing in the incidence of tax evasion in a population if there is a limited amount of resources available for the tax authority to access.[14]

According to the static model described above, the expected prospect of evaders at time t is given by:

$$V^E\left(x(t)\right) = w\left(p(t)\right) v(-\lambda r E) + w\left(1-p(t)\right) v\left(rE\right). \qquad (3)$$

[13] We are essentially assuming, rather realistically, that the regulator/tax authority commits to an audit effort/probability only for a period and revise its decision the following period after assessing the current level of tax evasion in the population. See Khalil (1997) for an analysis of the principal-agent model when the principal may or may not commit to a level of auditing effort.

[14] Because of this auditing resources constraint, the probability of being audited for an individual may depend on the compliance level of others in the population. If the tax authority would invest more effort to audit an individual who has reported a suspiciously low level of income, it could have fewer resources to audit other individuals in the same population. It follows that the audit probability may be decreasing with the level of evasion.

The replicator dynamics for $x(t)$ is:

$$\dot{x}(t) = x(t)\,(1 - x(t))\,V^E\,(x(t))\,. \tag{4}$$

In evolutionary game theory, the replicator equation is a standard way to model imitative behavior: agents are assumed to be *boundedly-rational*, in the sense that they do not maximize their overall expected benefits from tax evasion, but at any instant of time they just compare their current "utility" with that of a randomly chosen agent from the population. Switching to the strategy of the sampled agent occurs with positive probability if this switching is perceived as conveying more benefits. For details on replicator dynamics, we refer the reader to Weibull (1997).

2.3 Optimal enforcement

We assume that the regulator can select the effort put into auditing in order to control the dynamical system (4), with the long-term objective of maximizing the present value of future streams of net tax income. Without loss of generality, we assume that there is a one-to-one correspondence between regulator effort and auditing probability for each type of evaders. While innocuous, this assumption allows us to treat the auditing probability, $p(t)$, as the control variables of the optimization problem. Also, we assume that the cost of selecting an auditing probability p is quadratic, that is $c(p) = \gamma p^2$.[15] The tax authority

	Compliance	*Evasion*
Audit	rW	$r(W - E) + \lambda r E$
No audit	rW	$r(W - E)$

Table 1: Summary of taxes and fines collected by the regulator.

collects tax and fines as indicated in Table 1, and is subject to auditing cost. The net tax revenue, is defined as

[15]Petrohilos-Andrianos and Xepapadeas (2016) consider a linear cost function. In spite of the tractability of the linear specification, they argue that a quadratic function would provide a more realistic description of auditing costs.

$$NTR(t) = TR_A(t) + TR_N(t) - c\,(p(t)) \tag{5}$$

where:

1. $TR_A(t)$ is the expected gross tax revenues at time t coming from honest and audited agents, that is:

$$TR_A(t) = (1 - x(t))\,rW + p(t)x(t)\,(\lambda rE + r\,(W - E))\,;$$

2. $TR_N(t)$ is the expected gross revenue at time t coming from non-audited agents, that is:

$$TR_N = r(1 - p(t))x(t)(W - E).$$

The regulator's intertemporal problem consists in selecting the feedback rule, $p(t) = p\,(x(t)) \in [0, 1]$, such that the following objective functional

$$\int_0^{+\infty} e^{-\delta t} NTR(t)dt \tag{6}$$

is maximized subject to the replicator state equations (4) and the additional constraint $x(t) \in [0, 1]$.

3 Analysis of the uncontrolled dynamical system

Recall that

$$Z^A = -\lambda rE < 0 \text{ and } Z^N = rE > 0. \tag{7}$$

Note that we always have $v(Z^A) < 0$ and $v(Z^N) > 0$. With this notation, replicator equation (4) reads:

$$\dot{x}(t) = x\,(1 - x)\,\big(w(p(x))v(Z^A) + w(1 - p(x))v\,\big(Z^N\big)\big)\,. \tag{8}$$

Model is trivial if V^E in (4) is independent of x, which occurs when auditing probability and utilities are independent of the share of evaders in the society. In this case, starting from any initial condition, all agents will eventually be honest (if $V^E < 0$) or dishonest (if $V^E > 0$) or stick at the initial condition (if $V^E = 0$).

In general, the replicator equation (8) admits two types of equilibria: boundary values $x_0 = 0$ and $x_1 = 1$, which are always equilibria of the system, and inner equilibria. Boundary equilibria represent monomorphic configurations of the population in which all agents are either honest or dishonest. A point $x^* \in (0, 1)$ is an *inner* equilibrium of (8) if it satisfies the following *iso-prospect* condition:

$$V^E(x^*) = 0, \tag{9}$$

which states that at an inner equilibrium the each taxpayer is indifferent between evading taxes and being honest. The stability properties of these boundary equilibria are summarized in the following proposition. All proofs are provided in the Appendix.

Proposition 1 *Given the replicator equation (8), equilibrium $x_0 = 0$ is locally asymptotically stable whenever*

$$w(p(0))v(Z^A) + w(1 - p(0))v\left(Z^N\right) < 0$$

and equilibrium $x_1 = 1$ is locally asymptotically stable whenever

$$w(p(1))v(Z^A) + w(1 - p(1))v\left(Z^N\right) > 0$$

The interpretation of the stability conditions is immediate. Equilibrium x_0 is stable if the expected prospect of evading, given that agents weight the outcomes with a probability weighting function consistent with a null share of evaders, is negative. Similarly, equilibrium x_1 is stable if the expected prospect of evading, given that agents weight the outcomes with a probability weighting function consistent with a share of all evaders, is positive.

An inner equilibrium x^* represents a polymorphic configuration in which the expected prospect of evading is equal to the expected prospect of being honest, which is normalized to 0. In general, inner equilibria need not to be unique. Notice that when the auditing probability p as a function of x is continuous and onto $(0,1)$, i.e. $p(x)$ ranges in the whole interval $(0,1)$, by the properties of the probability weighting function it is

$$\lim_{p\to 0} w(p)v(Z^A) + w(1-p)v\left(Z^N\right) > 0 > \lim_{p\to 1} w(p)v(Z^A) + w(1-p)v\left(Z^A\right),$$

so that at least one inner equilibrium x^* satisfying (9) exists.

With respect to the stability of inner fixed point x^*, we can state the following proposition (we assume that $w(p)$ is differentiable with $w'(p) > 0$ for all $p \in (0,1)$).

Proposition 2 *Assume that an equilibrium $x^* \in I \subseteq (0,1)$ of the replicator equation (8) exists and that $p(x)$ is strictly increasing [decreasing] and differentiable in I. Then x^* is a locally asymptotically stable [unstable] equilibrium for the replicator equation (8).*

Corollary *If $p(x)$ is strictly monotone on $[0,1]$ then at most one inner equilibrium exists.*

The stability condition that links the monotonicity of the auditing probability $p(x)$ with the stability of an inner equilibrium has a clear economic intuition. Suppose that $p(x)$ is strictly increasing in x and the system is subject to a small displacement x from the inner equilibrium x^*, with $x^* < x$ [with $x^* > x$]. Then, it is $V^E(x) < 0$ $[> 0]$ so that evaders are worse off [better off] at x and the fraction of evaders reduces [increases] towards equilibrium x^* according to equation (8).

Before ending this Section, we provide additional details on the influence of the main parameters on the inner equilibrium x^*.

Proposition 3 *Assume that an equilibrium* $x^* \in I \subseteq (0,1)$ *of the replicator equation (8) exists and that the value function is given in (2), with* Z^A *and* Z^N *in (7). Then:*

- *tax rate* r *and amount of evasion* E *have no influence on* x^**;*
- *if* $p'(x^*) > 0[< 0]$*, then the higher the penalty* λ*, the lower [the higher]* x^**;*
- *if* $p'(x^*) > 0[< 0]$ *and* $\lambda > 1$*, then the higher the preference parameter* β*, the lower [the higher]* x^**;*
- *if* $p'(x^*) > 0[< 0]$*, then the higher the preference parameter* θ*, the lower [the higher]* x^**;*

The fact that the tax rate r and the amount of evasion E have no influence on x^* implies that, given a static functional form for the probability of auditing, a change in fiscal policy or in the depth of tax evasion has no effect on the incidence of tax evasion in a population. Given the specification of the value function (2), an increment of r or of E changes in equal proportions the losses and the gains, so the overall increment has a neutral effect on the expected value of the prospect. This may appear surprising, but we shall show in the next section that this will not be true if we allow the tax authority to optimally control the dynamic problem of maximizing tax revenues. The result that an increase in λ has a negative effect on x^* is intuitive. An increment in the penalty term λ increases the potential loss associated with evading taxes and implies a lower expected value of the prospect; thus, under the assumption that the auditing probability increases in x, to remain in equilibrium it is necessary to have a lower share of tax evaders to balance the increment in the penalty. If individuals become more risk averse, i.e. higher θ, they will find evading taxes less rewarding and we should expect a smaller long-run number of individual in a population engaging in tax evasion. An increment in β impacts both the loss and the gain of tax evasion; however, its impact is stronger on losses when $\lambda > 1$.

The next Proposition addresses the influence of α, i.e. the parameter that regulates the deformation in the probability weighting function, on the inner equilibrium x^*.

Proposition 4 *Assume that an equilibrium $x^* \in I \subseteq (0,1)$ of the replicator equation (8) exists, the probability weighting function is given by the Prelec function in (1) and $p'(x^*) > 0 [< 0]$, then*

- *If $p(x^*) \in \left(0, \frac{1}{e}\right)$ then the higher α, the higher [the lower] x^*, regardless of the values of $v(Z^A)$ and $v(Z^N)$;*
- *If $p(x^*) \in \left[\frac{1}{e}, \frac{e-1}{e}\right)$ then the relationship between α and $x^*$is ambiguous and depends of the values of $v(Z^A)$ and $v(Z^N)$, namely on the shape of value function in (2), the amount of evasion E, the tax rate r and the penalty λ;*
- *If $p(x^*) \in \left[\frac{e-1}{e}, 1\right)$ then the higher α, the lower [the higher] x^*, regardless of the values of $v(Z^A)$ and $v(Z^N)$.*

The results of Proposition 4 are particularly important in light of the results of the next section, where the replicator equation models the state variable of the regulator's optimal control problem.

4 Analysis of the controlled dynamical system

In this section, we present the key results of our analysis when the regulator possesses the ability to perform optimal auditing in the spirit of the optimal reinforcement model presented in Section 2.3. Here, our main interest is to provide new insights on the optimal auditing policy and its impact on the evolution of tax evasion.

Despite its simplicity, the problem of maximizing the objective functional (6) subject to the replicator dynamics (4) does not admit a closed form solution, and we rely on numerical techniques to approximate value functions and optimal auditing policies. We use the semi-Lagrangian approach to approximate the

Hamilton-Jacobi-Bellman equation characterizing the solution of our problem. This involves: *i*) replacing the original continuous-time problem with an approximated discrete-time problem obtained by applying Euler scheme in time; *ii*) deriving the corresponding discrete time Bellman equation to be satisfied by the approximated problem; and *iii*) approximating the infinite dimensional discrete-time problem with a system of nonlinear equations using standard finite element space approximation.[16]

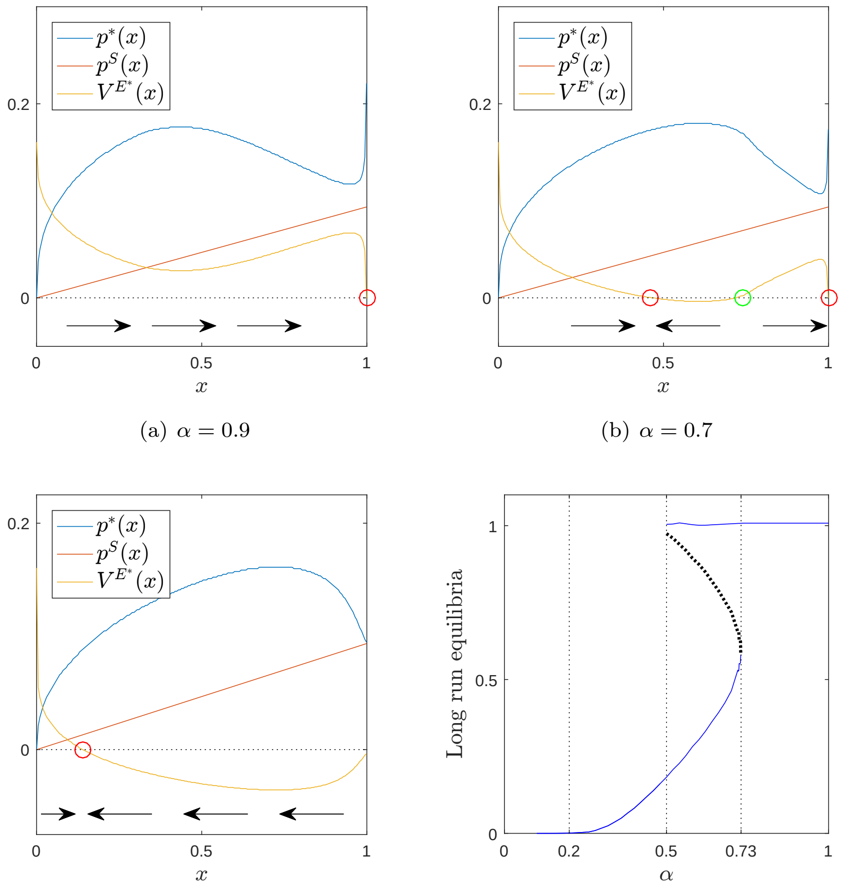
W	E	λ	γ	β	θ
5	0.5	1.5	1	0.88	2.25

Table 2: Parameter values used in the analysis. β and θ are fixed as suggested by Tversky and Kahneman (1992).

Although it would be interesting to analyze numerical setups based on calibrations performed on real-world data, our main interest in this section is to provide the main insights about the optimal auditing rules and their effects in the long-run. Thus, unless otherwise stated, we base our analysis on the parametric setup presented in Table 2. We have, however, performed a series of robustness check with different numerical setups, all confirming the main insights we present below.

The optimal auditing rule and the long-run evolution of the share of evaders depend on the relative balance between two main forces. First, the incentive that makes taxpayers willing to evade, which is strong when the tax rate is high, and weak when the tax rate is low (in line with the empirical evidence that considers the Yitzhaki puzzle). Second, the incentive that makes the regulator willing to reinforce auditing. For constant auditing costs, this incentive is strong when the tax rate is high and weak when the tax rate is low. The regulator willingness to reinforce auditing does depend on the balance between the cost and the expected benefit of auditing one more taxpayer. A high tax rate implies

[16] The approximation scheme we use is quite standard, and a complete description of the algorithm used is far beyond the scope of this paper. We refer to the specialized book Falcone and Ferretti (2014) for more details about the implementation. Applications of Semi-Lagrangian schemes to deterministic optimal control problems in economics can be found, for instance, in Grüne and Semmler (2004); Santos and Vigo-Aguiar (1998) and, more recently, in De Giovanni and Lamantia (2018).



(a) $\alpha = 0.9$ (b) $\alpha = 0.7$ (c) $\alpha = 0.48$ (d)

Figure 1: Panels 1(a)-1(c): Optimal auditing policy, optimal static auditing rule and optimal evaders' prospect when $\alpha = 0.9, 0.7$ and 0.48, respectively. Red bullets mark stable equilibria. Green bullets mark Skiba points. Panel 1(d): Bifurcation diagram with bifurcation parameter $\alpha \in (0, 1]$. Blue curves display the location of stable equilibria. Dashed curve shows the position of the unstable equilibrium, which constitutes the boundary of the basin of attraction when multiple stable equilibria exist. In all panels, the tax rate is set to $r = 0.25$ and the remaining parameter values are those in Table 2.

a high auditor's expected benefit of auditing, thus strengthening the regulator's willingness to reinforce auditing.

Before analyzing the optimal auditing feedback policy, let us consider the benchmark case in which, absent any dynamic consideration, a regulator maximizes the static objective function (5) choosing the following static optimal auditing rule,

$$p^S(x) = \frac{x\lambda r E}{2\gamma}. \tag{10}$$

From a static perspective, (10) shows that the optimal auditing probability is linear and strictly increasing in the share of evaders. In addition, it increases in the tax rate (the regulator has a greater incentive to detect tax evasion), penalty of detection and depth of evasion. Not surprisingly, auditing decreases if the auditing cost parameter γ increases.

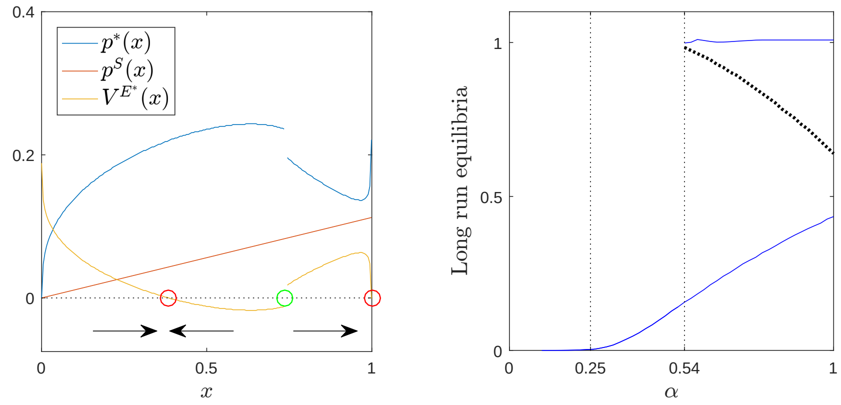
Let us now consider the regulator's intertemporal optimization problem. In Figure 1 we fix the tax rate to $r = 25\%$ and let the degree of probability deformation α vary. Here the tax rate is sufficiently low, whence the regulator's incentive to reinforce auditing is weak, while the taxpayer's willingness to pay taxes is relatively strong, depending on the degree of probability deformation. First of all, we observe that optimal feedback auditing policies display a pattern which is increasing in x only if the share of evaders is sufficiently low. This is in contrast with the strictly monotonic pattern of the static rule (10). To explain this phenomenon, in panels 1(a)-1(c) we compare: *i*) the optimal policy $p^*(x)$ that solves problem (6) under the dynamic constraint (4); *ii*) the optimal static auditing rule $p^S(x)$ in (10); *iii*) the prospect $V^{E^*}(x)$ of a representative evader under the optimal auditing policy $p^*(x)$. From those figures, we observe that the dynamic auditing policy is always greater than the static rule: a forward-looking regulator recognizes the need of an auditing policy stronger than the static rule in order to discourage future evasion consequent to taxpayers' imitating behavior. At low levels of x the majority of taxpayers is honest, but the prospect of becoming evaders is positive. This situation makes the regulator willing to rise the auditing, so as to reduce the prospect of becoming evaders and thus discouraging future evasion. This pattern is evident in panels 1(a)-1(c). However, as tax evasion increases, evaders' prospect decreases, while the regulator incurs in higher and higher auditing costs to further decrease the evader's prospect. Because of the convexity of the auditing costs at the point in which $p^*(x)$ reaches its maximum value, further reducing the evaders' prospect becomes so costly that it is more economically convenient, from the regulator's point of view, to let the evader's prospect increase.

The long-run evolution of the controlled dynamical system depends on how taxpayers react to the auditing policy. Indeed, an important feature of our dynamical model is that individuals may distort the probability of being audited. This distortion is introduced by the Prelec function and, specifically, by parameter α, which measures the probability deformation. With the observed optimal auditing probability $p^*(x) \in (0, \frac{1}{e})$ it turns out, as described in Section 3, that such values of α models situations where taxpayers overestimate the probability of being audited and underestimate the probability of not being audited, with these effects more pronounced for low levels of α. Thus, the lower the value of α which characterizes taxpayers, the higher the risk taxpayers perceive from the possibility to evade. In other words, evading taxes becomes less desirable. This explains why the three optimal auditing policies presented in panels 1(a)-1(c) have a different impact on the long-run evolution of the share of evaders, even though they show the same qualitative pattern. The reduction of the inner stable equilibrium as α is reduced is clearly in agreement with the results in Proposition 4.

For example, panel 1(a) considers a weak probability deformation ($\alpha = 0.9$). Suppose the system starts at a low level of x. The auditor has the incentive to rise auditing since at those levels of x auditing costs are sustained by expected future incomes. This reduces evaders' prospect. However, the share of evaders is increasing since the prospect is positive. Thus, in this situation, the system will end up with all agents being evaders since taxpayers' reaction to an increase in auditing probability is not sufficiently strong to make evaders' prospect negative. A different situation is shown in panel 1(b), where the probability deformation is moderately strong, $\alpha = 0.7$. In this case, the long-run state of the system depends on its initial value. Panel 1(b) shows the existence of two stable equilibria. The green bullet indicates the (Skiba) point that delimits the basin of attraction of each equilibrium. The system will end up with an entire population of evaders if the initial share of the evaders is greater than the Skiba threshold, and with the inner equilibrium otherwise, whose stability is guaranteed by the strictly increasing optimal auditing policy $p^*(x)$ in that interval as determined in Proposition 2. To elaborate, suppose again that the initial share of evaders is low. In this case, an increase in the auditing probability makes the evader's prospect decrease at high rates. This is due to greater (with respect to the previous case) taxpayers' concern about the risk of being caught in tax evasion. When the evaders' prospect reaches zero, there is no economic incentive for the share of evaders to move away from the equilibrium, since evaders and honest taxpayers share the same prospect. Conversely, if the initial state of the system is high, the auditor finds more convenient to let the population move towards the monomorphic situation where all taxpayers evade. Panel 1(c) presents yet a different dynamic pattern. The probability deformation is strong ($\alpha = 0.48$) and taxpayers perceive the option to evade as a very risky affair. Consequently, the auditor can easily manipulate evaders' prospect also when the share of evaders is very high. As a result, only one inner equilibrium exists.

To summarize, the bifurcation diagram for α varying in the interval $(0, 1]$ in panel 1(d) gives a complete picture of how different degrees of probability deformation affect the dynamic evolution of the share of evaders. For low levels of α only equilibrium $x_0 = 0$ is stable, with a long-run state of only honest agents. As α is increased, a transcritical bifurcation occurs with a stability exchange between the boundary equilibrium $x_0 = 0$ and an inner stable equilibrium (blue curve), which attracts the generic trajectory in $(0, 1)$. For $\alpha \approx 0.5$, another transcritical bifurcation takes place, between the boundary equilibrium $x_1 = 1$, which becomes stable, and an inner equilibrium (dashed curve) that is unstable in the interval $(0, 1)$ and delimits the basins of attraction of the two stable equilibria, namely the inner equilibrium (blue curve) and the boundary equilibrium $x_1 = 1$ (horizontal blue segment). As α is further increased, a saddle-node bifurcation takes place, through which the two inner equilibria are destroyed. After this last bifurcation, only one stable equilibrium remains, which is $x_1 = 1$, with a long-run presence of only tax evaders.

In order to assess the impact of a higher tax rate, in Figure 2 we set $r =$



(a) $\alpha = 0.9$

(b)

Figure 2: Panels 2(a): Optimal auditing policy, optimal static auditing rule and optimal evaders' prospect when $\alpha = 0.9$. Red bullets mark stable equilibria. Green bullets mark Skiba points. Panel 2(b): Bifurcation diagram with bifurcation parameter $\alpha \in (0, 1]$. Blue curves display the location of stable equilibria. Dashed curve shows the position of the boundary of the basin of attraction when multiple stable equilibria exist. In both panels, the tax rate is set to $r = 0.3$ and the remaining parameter values are those in Table 2.

30%. Compared with the case analyzed in Figure 1, here taxpayers have a stronger incentive to evade and the auditor a stronger incentive to perform auditing. To see the change in the auditor's behavior due to the modified balance between the two forces, in panel 2(a) we present the optimal auditing schedule when $\alpha = 0.9$ (for the reader reference, this should be compared with panel 1(a), where the same degree of probability deformation is considered). This panel describes a novel feature of our analysis, as there may be a level of tax evasion in the population that creates a discontinuity in the optimal audit policy. When the share of evaders is lower than the discontinuity threshold, the regulator's willingness to strengthen auditing dominates taxpayers' incentive to evade. Auditing costs are expected to be sustainable thanks to the benefits of a strong auditing policy; essentially the increased future remuneration due to a high tax rate will compensate current auditing costs. Observe, indeed, that for such values of x the optimal auditing schedule in panel 2(a) is larger of that in panel 1(a). This allows the auditor to reduce evaders' prospect up to a point in which it reaches zero. At that point, there is no incentive to move away as both evaders' and honest taxpayers' prospects are equal. As a result, the share of evaders converges to an inner equilibrium. Observe that this equilibrium is not a possibility in panel 1(a). Conversely, if the share of evaders is above the discontinuity threshold, then taxpayers' incentive to evade dominates. Increasing auditing costs cannot be sustained by the expected benefits of having a larger number of honest taxpayers and the auditor finds more convenient simply to "give up" and let evaders' prospect exceeds honest taxpayers' prospects. In such a situation, the share of evaders increases and its long-run dynamics converge to equilibrium $x_1 = 1$. The discontinuity threshold thus acts as the boundary of the basin of attraction of two stable equilibria: the socially desirable inner equilibrium and the socially undesirable right-border equilibrium.

To summarize, panel 2(b) completes the picture by letting the degree of probability deformation vary. The explanation of the various bifurcations involved is similar to that of panel 1(d), although here the previous saddle-node bifurcation does not occur. Comparison of panels 2(b) and 1(d) suggests that with a sufficiently high tax rate, situations like the one described in panel 1(a), where the only long-run equilibrium is given by the whole population deciding to evade taxes, are ruled out. The intuition is that a higher tax rate induces the regulator to incur higher auditing costs in order to increase expected tax revenues in the following period. Doing so, the system moves away from more extreme scenarios and allow the dynamics to converge (depending on the initial conditions) to a state where only a share of agents evades.

5 Conclusions

The paper studied the dynamics of compliance in a population of boundedly rational agents that decide whether to engage in tax evasion depending on an evolutionary adaptation process where payoffs are assumed to have the standard and realistic features of prospect theory utilities. The analysis first studied the case in which the auditing probability was exogenously given and dependent on the level of tax evasion in the population. The study showed that an interior locally asymptotically stable equilibrium level of tax evasion, where only a portion of the population engages in tax evasion, can exist only if the auditing probability is assumed to be increasing in the level of tax evasion.

The study of the intertemporal optimal auditing produced novel and rich results, including the existence of multiple equilibria and discontinuities in the optimal control. Specifically, the analysis showed how the long-run evolution of the controlled dynamical system may depend on how taxpayers react to auditing policies and, in particular, on the way they may distort the probability of auditing. If taxpayers give increasing weight to low auditing probabilities this will increase the likelihood of the existence of interior long-run equilibria in which only a portion of the population behaves dishonestly. When scenarios with multiple equilibria are also possible, then the system's initial conditions define the long run configuration of the population. Finally, the analysis produced, for sufficiently high levels of the tax rate, the possibility of the existence of a discontinuity in the regulator's optimal control created by a threshold level of tax evasion.

Indeed, our analysis shows how a drastic reduction in auditing effort may be the result of the rational decision of a regulator who intends to maximize tax revenues and not necessarily the outcome of corrupt or illegal decisions. Indeed, the model highlights the fact that the observation of feeble auditing efforts in some countries does not necessarily imply the capture of a regulator; high auditing costs and forward-looking decision making could be a reason why some tax authorities may decide to reduce auditing effort while facing high levels of tax evasion.

This paper leaves unexplored the case in which the level of tax evasion might be chosen endogenously. While the economic results provided in this paper are robust to a wide range of levels of tax evasion, we acknowledge that allowing taxpayers to choose the level of evasion certainly deserves more attention and we leave this extension for future research.

6 Appendix - Proofs of the propositions

Proof of Proposition 1. It follows directly by imposing that the slope of $F(x)$, defined as the RHS of (8), is negative in a right [left] neighborhood of x_0 [x_1]. *QED*

Proof of Proposition 2. Employing the equilibrium condition, the slope of the RHS of equation (*8*) simplifies to

$$F'(x^*) = -x^*(1-x^*)p'(x^*)\left[v(Z^N)w'(1-p(x^*)) - v(Z^A)w'(p(x))\right]$$

where it is immediate to observe that the quantity in square brackets is positive. Therefore, the sign of $F'(x^*)$ is the opposite to the sign of $p'(x^*)$, thus proving the statement. *QED*

Proof of Proposition 3. Apply implicit differentiation on the *iso-prospect* condition (9) and the equilibrium condition to obtain the various results. *QED*

Proof of Proposition 4 To see this, write the equilibrium condition $V^E(x^*;\alpha) = w(p(x^*),\alpha)v(Z^A) + w(1-p(x^*),\alpha)v\left(Z^N\right) = 0$ and consider the implicit function $x^*(\alpha)$, which defines the equilibrium share of evaders in a neighborhood of x^* as α varies. Consider then

$$\frac{dx^*(\alpha)}{d\alpha} = -\frac{\partial_\alpha V^E(x^*;\alpha)}{\partial_x V^E(x^*;\alpha)} = -\frac{\partial_\alpha w(p(x^*),\alpha)v(Z^A) + \partial_\alpha w(1-p(x^*),\alpha)v\left(Z^N\right)}{p'(x^*)\left[\partial_p w(p(x^*),\alpha)v(Z^A) - \partial_p w(1-p(x^*),\alpha)v\left(Z^N\right)\right]}$$

Thus, when $p'(x^*) > 0$, the denominator in the last expression is always negative and so

$$\frac{dx^*(\alpha)}{d\alpha} > 0 \Leftrightarrow \partial_\alpha w(p(x^*),\alpha)v(Z^A) + \partial_\alpha w(1-p(x^*),\alpha)v\left(Z^N\right) > 0$$

Working out the conditions for the Prelec function, the sign of $\partial_\alpha w(p,\alpha)$ changes in $p \in (0,1)$. Assuming $p'(x^*) > 0$, the following cases arise

- if $p(x^*) \in \left(0, \frac{1}{e}\right)$, then $\partial_\alpha w(p(x^*), \alpha) \leq 0$ e $\partial_\alpha w(1 - p(x^*), \alpha) > 0$ so that $\frac{dx^*(\alpha)}{d\alpha} > 0$, regardless of the values in the utilities $v(Z^A)$ and $v(Z^N)$;
- if $p(x^*) \in \left[\frac{1}{e}, \frac{e-1}{e}\right)$ then $\partial_\alpha w(p(x^*), \alpha) > 0$ and $\partial_\alpha w(1 - p(x^*), \alpha) > 0$ so that the sign of $\frac{dx^*(\alpha)}{d\alpha}$ depends on the actual values of $v(Z^A)$ and $v(Z^N)$;
- if $p(x^*) \in \left[\frac{e-1}{e}, 1\right)$, then $\partial_\alpha w(p(x^*), \alpha) > 0$ and $\partial_\alpha w(1 - p(x^*), \alpha) \leq 0$ so that $\frac{dx^*(\alpha)}{d\alpha} < 0$, regardless of the values in the utilities $v(Z^A)$ and $v(Z^N)$.

QED

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