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# Computational Models of Tax Evasion with Heterogeneous Agents

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# Computational Models of Tax Evasion with Heterogeneous Agents

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A thesis submitted July 2020
in conformity with the requirements for the degree of
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at the Department of Economics
**Università Ca' Foscari Venezia**

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# Contents

# II Appendices

# Part I

# Doctoral Thesis

# Introduction

The fundamental purpose of my dissertation is to further understand the roles played by taxpayer heterogeneity and social influence in tax-evasion dynamics, and to derive normative insights about optimal policy design considering both rational and non-rational taxpayers. How should fiscal policies be designed under the consideration of heterogeneous taxpayers? What is the role of social dynamics in public policy implementation? Which are the implications of rationality and (bounded) non-rationality of taxpayers in policy design?

To answer these and similar questions, the first objective of the current thesis is to build on recent developments from behavioral economics, experimental economics and economic psychology to derive models with heterogeneous agents which have strong empirical and analytical micro-foundations. Mathematical models of individual and collective taxpayer behavior, however, are often too complex to be fully characterized analytically. In order to overcome this obstacle, we incorporate state-of-the-art computational models, such as agent-based modeling, to simulate taxpayer behavior under different fiscal environments and to study the potential implications of diverse policy implementations.

The second objective of my research concerns the optimal fiscal policy design under the consideration of taxpayer heterogeneity and social influence dynamics, with a normative focus. Acknowledging that taxpayer behavior evolves according to different dynamic processes, which depend on how taxpayers adapt their expectations about future enforcement regimes and penalty possibilities, we employ recent insights from game theory and network theory applied to social networks and information diffusion to capture the effects and repercussions of social influence dynamics. It is of utmost importance for policymakers to understand not only the individual decision-making processes of taxpayers, but also the emergence of aggregate behaviors as a consequence of idiosyncratic beliefs, social interactions, policy announcements, taxpayer expectations, diffusion of tax-related information, enforcement measures and potential policy implementations.

The third objective of the current dissertation aims to design optimal fiscal policies in diverse economic scenarios where a social planner faces strategic tax evaders who are able to observe and react against the implemented fiscal policies. It may straightforward to realize that harsher audit and penalty rates may affect taxpayer behavior. However, taxpayers' expectations, social influence and non-pecuniary factors also play prominent roles in both individual and collective taxpayer behaviors. The existing literature recognizes that taxpayer behavior is influenced not only by the probability of being audited and the possible incurred penalties, but also by tax rates, feelings of regret, uncertainty, risk aversion, psychic costs of evading, peer effects, social interactions, reciprocity, social norms, the behavior of fellow taxpayers, the efficiency of government expenditures, the perceived power of the government, tax morale and the degree of trust that citizens place in the authority; to mention a few. Following, a central challenge is how to derive appropriate policy recommendations while taking into account the different ways in which taxpayers may behave, react, optimize and carry out their respective decision-making processes.

Consequently, the research presented in this work combines a set of interdisciplinary tools. We employ insights and findings from behavioral economics, experimental economics and economic psychology to derive models that formally characterize the prevalent theoretical and empirical results in tax-evasion literature. We also consider recent developments from network theory and computer simulations to model taxpayer social networks and to thoroughly study peer-to-peer communication, the spread of information and beliefs along the links of the network, and the resulting social influence dynamics. Moreover, we aim to apply sophisticated game-theoretic techniques to properly identify the key individuals and key links in a taxpayer network which ought to be targeted by a social planner or policymaker in order to minimize the aggregate level of tax evasion.

## 0.1 The gap in tax-evasion literature

There are two main theoretical approaches to tax evasion considered in the literature: economic and behavioral. On the one hand, economic literature considers the rational decisions of individuals as in Becker (1968), Allingham and Sandmo (1972) and Yitzhaki (1974). This research line comprises both mathematical and computational models to formally characterize taxpayer behavior. On the other hand, behavioral literature considers intrinsic and extrinsic drivers of tax compliance, namely trust and power, as in Kirchler et al. (2008). This literature strand encompasses both laboratory and field experiments to study taxpayer behavior. The first research question considered in the current dissertation is: how to design a parsimonious model of individual tax compliance on self-reported income considering both intrinsic and extrinsic motivations for tax compliance?

This subsection surveys the key contributions to tax-evasion literature from different perspectives: mathematical modeling, computer simulations, laboratory environments and field experiments. The formal study of tax evasion started with the seminal papers of Becker (1968), Allingham and Sandmo (1972) and Srinivasan (1973), who modeled tax evasion in a setting where rational agents seek to maximize their expected utility based on tax rates, audit probabilities and penalty fees which are applied to evaded taxes. Further progress was made by Myles and Naylor (1996), who included group conformity and social norms, and by Andreoni et al. (1998), who developed the mathematical modeling of tax evasion by taking into consideration tax morale, social dynamics and the psychological cost for cheating. Bearing in mind that micro-founded models of individual tax compliance may be *too complex* to be fully characterized analytically, Mittone and Patelli (2000) proposed a novel way to look at tax evasion from a computational point of view by developing agent-based models of tax compliance. Eventually, a comprehensive range of diverse parameters was embodied in the computational models: social norms and enforcement dynamics (Davis et al. (2003)), psychological costs under repetitive dynamic choices (Mittone (2006)), individual heterogeneity and subjective audit rates (Korobow et al. (2007)), diverse utility functions (Hokamp and Pickhardt (2010); Calimani and Pellizzari (2014)), back auditing and social-norm updating (Hokamp (2014)), heterogeneous occupations and endogenous attitude formations (Hashimzade et al. (2014, 2016)) and the spreading of information and peer effects inside a taxpayer network (Andrei et al. (2014)).

Notwithstanding, even if the expected utility models presented a solid benchmark to study taxpayer behavior, they consistently overestimated tax evasion levels. Several experiments disproved the results from standard economic models to occur in real life, as in Slemrod (1985), Alm, Jackson and McKee (1992) and Alm, McClelland and Schulze (1992). Indeed, the latter found evidence that taxpayers may fully comply with their tax payments even in the absence of audits; something which would be hard to conceive under rational behavior. A fair share of empirical literature followed the paramount contribution by Kirchler et al. (2008), who combined behavioral and economic motives for taxpayers in a single framework, commonly known as the 'slippery slope'. This framework relates two main drivers of taxpayer behavior: power as a factor of enforced compliance and trust as a predictor for voluntary disclosures. A considerable number of experiments have thus studied how perceived government power and quality may influence tax compliance, such as endowing taxpayers with additional tax knowledge (Eriksen and Fallan (1996)), favorable interaction between taxpayers and tax authorities (Cullis and Lewis (1997); Adams and Webley (2001)), excessive auditing (Bergman (2003); Frey (2003); Mendoza et al. (2017)), governmental corruption (Torgler and Schneider (2009); Cule and Fulton (2009); Alm et al. (2016); Litina and Palivos (2016); Boly and Gillanders (2018)), public good provisions (Fochmann and Kroll (2016)) and governments whose legitimate power is low (Gobena and Van Dijke (2016)). Extensive research has delved deeper into numerous components of tax morale and their impact in tax compliance, such as pro-social donations (Frey and Meier (2004)), religiosity (Torgler (2006)), demographic and cultural components (Cummings et al. (2009); Lubian and Zarri (2011); Kountouris and Remoundou (2013); Hofmann et al. (2017)), relative consumption (Goerke (2013)), fairness (Cornelissen et al. (2013)), social esteem and stigma (Casal and Mittone (2016)), legality (Blaufus et al. (2016)), peer effects (Alm et al. (2017)) and taxpayer attitudes (Guerra and Harrington (2018)). Field experiments have also made important contributions to the formal study of tax compliance and evasion. Kleven et al. (2011) performed a tax experiment in Denmark and found that increasing marginal tax rates discouraged tax compliance. Kastlunger et al. (2013) found how excessive enforcement may aggravate tax evasion. Dwenger et al. (2016) studied individual compliance with local church taxes in Germany, which are legally binding but no audit schemes are enforced to monitor payments, and found that 20% of the individuals fully complied even in the absence of audits. Notably, this field experiment confirmed the behavior of taxpayer compliance obtained 'in vitro' by Alm, McClelland and Schulze (1992).

More closely related to our work, the 'slippery slope' framework (Kirchler et al. (2008)) laid the foundations in which compliance with the government may be linked through two different channels: by the perceived power and quality of authorities (extrinsic) or by an individual's tax morale (intrinsic). Extrinsic influences are related to the coercive enforcement of tax compliance through governmental power, which can be described in terms of audit schemes, penalties, retaliation and fixation of tax rates, and the government's potential to detect tax evasion and to punish illegal behavior. Intrinsic motivations are understood as the voluntary compliance persuaded by trust in the government or by the desire to conform with moral values and social norms; which are independent of audit probabilities, effective tax rates and applicable penalty fees. Prinz et al. (2014), Lisi (2014) and Pellizzari and Rizzi (2014) derived the first computational models of tax compliance at a societal level with heterogeneous agents. Although these models successfully replicated the well-known 'slippery slope' framework, they did not include a micro-founded explanatory model for rational agents attempting to optimize an expected utility in function of audit probabilities, tax rates, penalty fees, and other parameters. For the case of self-reported income, Kogler et al. (2015) empirically proved that trust and power significantly predict tax compliance regardless of their underlying motives: trust induces voluntary compliance, power stimulates enforced disclosures, and there is no crowding out effect between the two. Dwenger et al. (2016) found substantial intrinsic motivation to comply and, likewise, found no crowding out effect between extrinsic and intrinsic motivations to comply. Accordingly, our research incorporates these behavioral insights and empirical findings in our micro-founded mathematical model of self-reported income tax compliance.

Summarizing, existing economic models provide a benchmark to study taxpayer behavior, but they are unable to replicate both micro-economic and macro-economic behavioral patterns. Laboratory and field experiments offer crucial insights, but do not inherently possess a model to fit their results. A key difference between our work and previous literature relies on the fact that we mathematically model individual taxpayer behavior and do not restrict our analysis to aggregate values of tax compliance. Consequently, our potential contribution to the fields of economic and behavioral literature is to provide a parsimonious, micro-founded model with behavioral insights which is able to replicate the individual taxpayer behavior as in Alm, McClelland and Schulze (1992) and Dwenger et al. (2016), and it is also capable of modeling the aggregate behavioral patterns of society as in Kirchler et al. (2008), Kastlunger et al. (2013), Prinz et al. (2014) and Kogler et al. (2015). Conclusively, our work potentially manages to narrow the gap between diverse tax-evasion literature strands.

## 0.2 The latent potential of the tax authority

Income tax evasion and under-reporting are among the most distressing problems faced by tax authorities. Income under-reporting undermines the governmental capability to collect taxes and to raise fiscal revenues. Scartascini and Castro (2015) claimed that income tax evasion depletes annual expected tax collections by more than 50% in developing countries. Moreover, Gamannossi degl'Innocenti and Rablen (2020) confirmed that developed nations are not immune to this problem, and may lose up to 20% of their expected fiscal revenues each year. Buehn and Schneider (2012) estimated the average size of tax evasion originating from under-reported income and indirect taxes to be 3.2% of the GDP among OECD countries. Likewise, Kukk et al. (2020) concluded that between 10% and 40% of self-employed individual income declarations are under-reported by taxpayers across EU countries.

The problem of income tax evasion has been extensively covered in the literature from the taxpayer's point of view. Different theoretical models have been built considering expected utility theory, prospect theory, rank-dependent expected utility theory, Choquet expected utility theory and cumulative prospect theory. Moreover, a broad range of potential factors and parameters have been studied as well: regret and disappointment, uncertainty, non-additive probabilities, risk aversion, ambiguity, over-weighting the detection probability, endogenous reference levels, social interactions, psychic costs of tax evasion, perception of fairness, social customs, tax morale, public goods and various potential utility functions[1]. Nonetheless, even when the individual decision-making process of tax compliance is a well-studied subject (see Section 2.2), the strategies from the tax authority's point of view have been typically overlooked.

As discussed in the previous section, income tax compliance may be enforced by the tax authority (so-

[1]For a detailed review of this literature, please refer to the survey by Hashimzade et al. (2013).

cial planner) or it may originate from voluntary motivations inherent of taxpayers (agents or individuals). Following, tax compliance is influenced not only by enforcement and penalty levels, but also by the applicable tax rates, the appropriate use of public money by the government, feelings of regret, uncertainty, risk aversion, psychic costs of evading, the behavior of fellow taxpayers, peer effects, social interactions, reciprocity, social norms, the efficiency of government expenditures, tax morale and the degree of trust that citizens place in the authority; to mention a few. Although there is no general consensus about the roles played by the vast majority of tax compliance motives, Casal and Mittone (2016) upheld that literature does agree on the deterrence effect derived from enhanced audit schemes. That is, a higher perceived audit rate, *ceteris paribus*, would induce taxpayers to be more compliant. The second research question investigated in the current thesis is the following. Given a finite budget (number) of audits to be enforced during each period, which is the optimal way to target taxpayers such that the mean subjective probability of being audited is maximized across the entire taxpayer network?

The tax authority may influence taxpayer behavior both directly and indirectly. In the first case, the tax authority may directly target a taxpayer whether by enforcing an audit or by sending a *threat-to-audit* message. In the second case, indirect effects may arise from peer-to-peer communication, endogenous social effects and spillover reactions to enforcement measures. In other words, direct effects are the outcome of the interaction between the tax authority and the taxpayers, while indirect effects are the aftermath of the social interactions among taxpayers.

There is relevant literature related to how the tax authority may induce direct effects over the group of taxpayers. On the one hand, agent-based models have studied the impact of audit enforcement schemes in taxpayer social networks. Hokamp and Pickhardt (2010) designed an agent-based model with social interactions which allowed for information transmission along the taxpayer network. Andrei et al. (2014) showed that the topological structure of the taxpayer network has a significant impact on the aggregate dynamics of tax compliance. Hashimzade et al. (2014, 2015) analyzed the emergence of group beliefs, taxpayer behavior and compliance decisions in networked agent-based models, where the transmission of information flowed through peer-to-peer interactions in a social network. Hashimzade et al. (2016) proposed a network-based audit strategy, improving compliance compared to random audits. Moreover, Gamannossi degl'Innocenti and Rablen (2020) derived a unique Nash Equilibrium of optimal tax evasion in terms of a Bonacich (Bonacich (1987)) centrality measure; in their context, more central agents tended to evade more.

On the other hand, the tax authority may also spark a positive reaction among taxpayers by interacting with them. Field experiments have confirmed the capability of threat-to-audit letters as a tool to incentive tax compliance (Slemrod et al. (2001); Alm et al. (2009); Kleven et al. (2011); Pomeranz (2015); Boning et al. (2018); Lopez-Luzuriaga and Scartascini (2019); Drago et al. (2020)). In particular, Alm et al. (2009) found that the influence of post-audit peer-to-peer communication on taxpayer behavior is dependent on whether taxpayers are informed about the audit rates or not. Whillans et al. (2016) claimed that the tax authority may induce taxpayer compliance by framing the idea of income as a responsibility. Salmon and Shniderman (2019) argued that tax authority's messages should not be ambiguous, that is, the tax authority should clearly announce the specific scope of the enforcement scheme in order to be effective.

Tax surveys and additional field experiments have provided further insights to the study of taxpayer behavior. Peer-to-peer communication has been thoroughly investigated (Ostrom (2000); Stalans et al. (2006); Ashby et al. (2009); Onu and Oats (2015)). Alm et al. (2009) found that the effect of audits is not limited to those actually audited. Alm et al. (2017) showed that taxpayers take into account the actions of their peers, from whom they receive information or with whom they may interact. Indeed, social norms and peer-effects have become a fundamental aspect of tax compliance modeling by linking individual taxpayer behavior to endogenous social patterns. Galbiati and Zanella (2012) found robust evidence of endogenous social effects on tax evasion among self-employed taxpayers in Italy. Gächter and Renner (2018) concluded that the dynamics of taxpayer compliance are strongly path-dependent and, once a norm or equilibrium is reached, it is considerably difficult to re-establish or augment the aggregate compliance level. Moreover, policy enforcement not only has a direct effect on its target, but also accomplishes spillover effects throughout the network. This effect ramifications have been studied in threat-to-audit messages (Boning et al. (2018); Lopez-Luzuriaga and Scartascini (2019)), business taxes in firms (Riedel et al. (2019)) and in a field experiment regarding TV license fees in Austrian households (Drago et al. (2020)). In particular, Drago et al. (2020) found significant spillover effects of compliance behavior positively correlated to geographical proximity and to the centrality of the targeted households.

Looking at the same problem from a different perspective, game-theoretic approaches bring an unparalleled opportunity to model both direct and indirect effects of audit policies from the point of view of the tax authority, who intends to hamper income under-reporting and tax evasion. There are at least two well-known game-theoretic approaches to model aggregate Nash Equilibrium in a network-based society: local-*aggregate* games and local-*average* games. In local-*aggregate* games (as in Ballester et al. (2006)), agents take into account the absolute actions of their peers. In local-*average* games (as in Ushchev and Zenou (2020)), agents take into consideration the average actions of their neighbors whenever deriving their own optimal action to exert, and where individuals have a taste for conformity with the social-norm[2]. Our approach to tax evasion is thus defined as in a local-*average* game where agents attempt to follow a social norm. Consequently, a number of relevant studies are taken into consideration to derive the optimal audit policy in a local-*average* game-theoretic framework. First, the social interactions inside the taxpayer network are considered in the sense of Hokamp and Pickhardt (2010) and Andrei et al. (2014). Second, the potential capability of threat-to-audit messages and analogous techniques to curb income under-reporting is dully noted. The tax authority aims to influence taxpayer attitudes as in Whillans et al. (2016), while keeping in close attention the correct manner to emit messages proposed by Alm et al. (2009) and Salmon and Shniderman (2019). Moreover, following Scartascini and Castro (2015), the effectiveness of these messages is consolidated by introducing the corresponding measures (i.e. not lying to the citizens). Third, the optimal audit policy extends the notions of network-based strategies (Calimani and Pellizzari (2014); Hashimzade et al. (2016); Gamannossi degl'Innocenti and Rablen (2020)) and elucidates a plausible manner in which the tax authority may re-establish the path-dependent aggregate tax compliance level discussed by Gächter and Renner (2018). Moreover, the theorized optimal strategy targets taxpayers in function of the network structure as in Drago et al. (2020) and Gamannossi degl'Innocenti and Rablen (2020).

The optimal solution consists on emitting a credible threat-to-audit message which ensures taxpayer heterogeneity with respect to productivity. Immediately afterwards, the tax authority strategically targets taxpayers in function of their individual productivity and their position inside the network. Following, the tax authority audits a key group of taxpayers which, by being targeted, triggers a series of spillover effects across the network. This chain reaction eventually leads to maximize the mean subjective audit rate among all taxpayers. Additionally, the unique steady state Nash Equilibrium of the mean subjective audit probability is mathematically characterized. Acknowledging that this is not the first game-theoretic audit policy which has been recommended, to the best of my knowledge, it is the first one to be robust against expected and non-expected utility theories, taxpayer heterogeneity and invariant to any individual payoff or utility function. In such a manner, the network-based approach studied in this dissertation gives a novel solution to an old problem, while taking into consideration the most recent insights from experimental and behavioral economics in a game-theoretic framework.

## 0.3 Concealing wealth offshore and international tax evasion

Curbing tax-evasion has been a permanent issue on the policy agenda ever since the advent of taxation systems. In recent decades, the acceleration and liberalization of financial flows has led to a globalization of the issue whereby tax-evaded wealth circulates through complex chains of jurisdictions and legal entities before finding shelter in tax havens (Garcia-Bernardo et al. (2017)). Although the real amount of wealth concealed through tax havens is unknown, the general consensus agrees that it is a sizable figure. As stated in Zucman (2013), at least 50 percent of all deposits held through offshore financial centers belong to households. Hence, tax havens are primarily used as a channel of tax evasion by households, and not simply as a tool for tax avoidance by firms. Furthermore, the author estimated that about 8% of the global household financial wealth was held through entities incorporated offshore at the end of 2008. Estimates about the value of assets hidden offshore go from the lower bound of 5.9 trillion USD in 2008 considering only financial wealth as in Zucman (2013), to the more aggressive estimate of up to 32 trillion USD in 2010 taking into account all types of assets as in Henry (2012). According to Zucman (2013) and Alstadsæter et al. (2018), the amount of global household financial wealth concealed offshore is equivalent to about 10% of the world's GDP.

This escalating problem eventually led to diverse inter-jurisdictional fiscal policies aiming to crackdown tax havens. The European Union Savings Directive, enforced in 2005, obliges cooperating jurisdictions to

[2] Ushchev and Zenou (2020) warn that optimal policies may differ whether the social planner believes agents play a local-*aggregate* game or a local-*average* game.

disclose the financial information of entities whose owner is a EU resident. In April 2009, G20 countries urged each tax haven to sign at least 12 tax information exchange agreements (TIEA's) under the threat of economic sanctions. The Foreign Account Tax Compliance Act (FATCA), signed in March 2010, requires all non-US financial institutions to report the assets and identities of all U.S. citizens and residents to the U.S. Department of the Treasury. The OECD introduced the Common Reporting Standard (CRS) in June 2018, a multilateral agreement on automatic exchange of information (AEOI) involving 108 countries worldwide. Nonetheless, not all jurisdictions signed. Also, some countries agreed to the CRS, but have not enforced any additional measures to facilitate tax information exchange[3]. Non-universal multilateral agreements, however, might induce non-cooperative offshore financial centers to reclaim the 'tax haven business' at the expense of cooperative jurisdictions (Elsayyad and Konrad (2012)). Following, the efficiency of these policies has been questioned. The existing literature suggests that all previously implemented coordinated fiscal policies have been systematically circumvented by tax evaders (Zucman (2013); Johannesen and Zucman (2014); Caruana-Galizia and Caruana-Galizia (2016); Omartian (2017); Alstadsæter et al. (2018); Casi et al. (2020)). In particular, Johannesen and Zucman (2014) evidenced that the 2009 G20 crackdown led to a reallocation of tax-evaded funds. Analogously, the CRS did not put an end to international tax evasion, but produced a further relocation effect in the dynamics of wealth concealment (Casi et al. (2020))[4]. Consequently, it would be overconfident to assume that the fight against tax evasion and wealth concealment has come to an end.

The G20 crackdown on tax havens in 2009 and the OECD Common Reporting Standard (CRS) have attempted to put an end to international tax evasion and wealth concealment. Albeit these and similar policies have helped to deter tax evasive behavior to some extent (Zucman (2013); Johannesen and Zucman (2014); Braun and Weichenrieder (2015); Caruana-Galizia and Caruana-Galizia (2016); Omartian (2017); Bennedsen and Zeume (2018); Johannesen et al. (2018); Andersson et al. (2019)), they left the door open for the relocation of funds and deposits to alternative financial offshore centers. Our third research question investigates the optimal strategy from the point of view of a (global) social planner who seeks to maximize the global detection probability of cross-country tax evasion. In order to do so, the social planner establishes tax treaties between jurisdictions which enable tax information exchange and allow for wealth concealment detection. Given a limited number of treaties to be implemented, which would be the optimal allocation of treaties among country-pairs in the global network of tax evasion?

In order to provide an appropriate answer for our last research question, a detailed understanding of tax-evasion mechanics and dynamics is required. However, until recently, the lack of data and the secretive nature of wealth concealment schemes had prevented a thorough economic and quantitative analysis of this phenomenon. In the interest of this matter, we build on recent insights from network theory and on the rich dataset made available by the 'Panama Papers'. The Panama Papers refer to the 11.5 million leaked documents (2.6 Terabytes of information) consolidated by the International Consortium of Investigative Journalists in early 2016, which provide information on a set of 213,634 offshore financial entities created by Mossack-Fonseca, one of the leading providers of offshore financial services. Offshore financial entities allow to conceal wealth from a source country, the one of the owner of the entity, to a host country, the one where the entity is incorporated, in such a way that the identity of the owner remains (partly) hidden. Incorporating offshore financial entities can thus be seen as tax-evasion links in a network of countries. Adopting this context, we provide a quantitative analysis of the resulting network. Our study uncovers that the global network of tax evasion, far from being a random collection of bilateral links, has the structural features of a complex system[5] (in the sense of Albert and Barabasi (2002)). Therefore, policy aiming to deter cross-country tax evasion must adopt a systemic approach to properly address this problem. Additionally, our analysis provides quantitative phenomenological intuitions about the most central actors in the global tax-evasion network, as evidenced by the Panama

[3] The list of countries which did not sign the Common Reporting Standard include several jurisdictions from the EU *black list* of tax havens (American Samoa, Fiji, Guam, Palau, Trinidad and Tobago and U.S. Virgin Islands) and from the EU *grey list* of tax havens (Bosnia and Herzegovina, Botswana, Swaziland, Jordan, Maldives, Mongolia, Namibia and Thailand). Link to EU list of tax havens: https://ec.europa.eu/taxation˙customs/sites/taxation/files/eu˙list˙update˙18˙02˙2020˙en.pdf. Last revised: February 18, 2020.

[4] The authors shed light on the possibility that the United States have emerged as an attractive destination for cross-country deposits. The U.S. have neither signed nor committed to endorse the CRS. Moreover, the U.S. hold two tax havens explicitly mentioned in the Panama Papers (Nevada and Wyoming), plus an anecdotal offshore financial center (Delaware).

[5] The global network of tax evasion has a hierarchical organization characterized by a core-periphery structure and a fat-tail degree distribution. Moreover, the dynamics of network formation are consistent with a preferential-attachment process, which is characteristic of complex networks.

Papers. These findings may potentially be used to identify tax havens that ought to be priority targets of tax evasion deterrence policies.

Taking advantage of the natural experiment induced by the G20 2009 crackdown on tax havens, we investigate the impacts of fiscal treaties on the formation of tax-evasion links. We perform an econometric analysis of the determinants of network formation and of the impact of tax treaties thereupon. Our results show negative and statistically significant effects of tax information exchange agreements on link formation and link activity of tax evasion between non-havens and tax havens, and between offshore financial centers. These results are consistent with those of Johannesen and Zucman (2014) and Omartian (2017). In particular, we show that efficient treaties are those that contain an information exchange clause and that link offshore financial centers to 'non-haven' countries. Moreover, since a share of cross-country transactions are not related to illegal activities, our estimates present lower bounds for the deterrence effect of TIEA's on tax evasion. Hence, even if tax information exchange mechanisms are limited and have plenty of room for improvement, they are a useful tool to deter offshore wealth concealment and tax evasion.

Keeping in mind the third research question, we consider a social planner whose objective is to maximize the global detection probability of tax evasion and wealth concealment. In this perspective, we develop a theoretical model to deliver normative insights on optimal deterrence strategies for a social planner facing a strategic tax-evader in a Stackelberg competition. Our main formal result in this setting is that the objective of the social planner turns out to be mathematically equivalent to that of finding the subgraph of a network with maximal Bonacich centrality. This problem has recently received a lot of attention in network and graph theory. In our context, we provide both mathematical and numerical results which show that the optimal policy is to enforce tax information exchange agreements between jurisdictions following a hub-like structure (quasi-star or quasi-complete graphs) targeting offshore financial centers according to their Bonacich centrality in the global network of tax evasion (Corbo et al. (2006); Belhaj et al. (2016)). This result reinforces the need to adopt a systemic perspective on tax evasion as the Bonacich centrality of the network does not depend on local properties of the network but on its global structure. The specific structure of the optimal tax information exchange agreements (TIEA's) treaty-network is dependent on the level of influence that the social planner can exert over the network (see Section 3.3). Consequently, our theoretical model potentially guidelines the optimal sequence of TIEA-type treaties to be implemented in order to strategically deactivate the remaining tax havens.

## 0.4 A brief summary of the current doctoral thesis

The first chapter attempts to close the gap between economic and behavioral literature on self-reported income tax evasion. We present a parsimonious micro-founded model for individual taxpayer compliance, distinguishing between intrinsic and extrinsic motivations for tax compliance. In this study, we model taxpayer behavior as a combination of two factors: trust as an intrinsic measure of voluntary disclosures, and power as an extrinsic predictor of enforced compliance. Intrinsic motives may include trust in the government, desire to conform with moral values, peer-effects, social norms and tax morale. Extrinsic influences are related to governmental power, which can be described in terms of audit schemes, penalties, retaliation, tax rates, or the government's potential to detect tax evasion and to punish illegal behavior. The model derived in the first chapter is able to replicate both individual and aggregate patterns of taxpayer behavior, even when the audit rate is null. A key difference between our work and previous literature relies on the fact that we mathematically model individual taxpayer behavior, and do not restrict the analysis to aggregate values of tax compliance. Notwithstanding, the analytical model becomes too complex to be fully characterized. Therefore, we derive the most important properties of the model for salient scenarios. On top of that, we make use of an agent-based model to explore a spectrum of fiscal conditions which allows us to study the effects of different parameters on taxpayer behavior.

The behavioral and psychological foundations of taxpayer decision-processes are comprehensively considered in the first chapter. Namely, tax compliance may be externally enforced by the social planner (also referred to as tax authority) or it may originate from voluntary motives which are intrinsic of taxpayers (also referred to as agents or individuals). This notion builds a theoretical link to the second chapter of the present dissertation.

The second chapter offers a potential contribution to the fields of public economics and game theory by presenting an optimal audit strategy from the point of view of the tax authority. Even when the individual decision-making process of tax compliance is a well-studied subject, the strategies from the tax authority's point of view have been typically overlooked. In the second chapter, a social planner intends to hamper income under-reporting within a network of heterogeneous taxpayers who are engaged in social interactions. Individuals update their subjective probability of being audited during the next period by endogenizing the information received from their peers. For a given fixed budget (number) of audits, the tax authority seeks to find the optimal allocation of audits in a networked society where taxpayers exchange information at the end of every period. Our work develops a two-step game-theoretic optimal audit strategy from the tax authority's point of view, which consists of a credible threat-to-audit message followed by a network-based audit policy. The function of the tax authority's announcement is to ensure taxpayer heterogeneity with respect to productivity. Subsequently, the tax authority targets taxpayers in function of their individual productivity and their position in the network, triggering a series of spillover effects which eventually maximize the mean perceived subjective probability of being audited among all taxpayers. Moreover, the optimal audit strategy is robust to expected and non-expected utility theories, taxpayer heterogeneity, and it is invariant for any taxpayer utility function. Employing recent insights from experimental and behavioral economics in a game-theoretic framework, the proposed network-based fiscal policy potentially gives a novel solution to an old problem. Analytically, the unique steady state Nash Equilibrium of the mean subjective audit probability is mathematically characterized. Computationally, it is determined that the proposed enforcement regime is robust to an ample range of societal settings, initial conditions and parameter specifications.

The recurring problem of tax evasion is contemplated from a worldwide point of view in the third chapter. The international liberalization of financial flows has accelerated the legal and illegal circulation of wealth across the globe. Tax-evaded wealth may now pass through complex chains of offshore financial centers and entities before finding shelter in non-cooperating tax havens. This escalating problem has led to diverse coordinated attempts to crackdown offshore financial activities: the EU Savings Directive, the 2009 G20 London summit and the OECD Common Reporting Standard. Notwithstanding, the efficiency of said policies has been questioned. There exists conclusive evidence that these fiscal policies have been circumvented by tax evaders and offshore financial service providers through a deliberate reallocation of tax-evaded funds. In order to improve upon this state of play, we build on recent insights from network theory and on the rich database made available by the 'Panama Papers' to investigate the micro-economic dynamics of tax evasion. We model offshore financial entities documented in the Panama Papers as links between jurisdictions in the global network of tax evasion. Adopting this context, we provide a quantitative study of the resulting network structure. Our analysis highlights that the structural features of the network demonstrate that international tax evasion is a complex (non-random) system, and thus that deterring policies must adopt a systemic approach to tackle the problem. This notion establishes a methodological connection between the second and third chapters. That is, both papers consider the systemic optimal fiscal policy derived by a social planner who seeks to curb tax evasion in a taxpayer network.

The third chapter interlinks the fields of public economics and network theory. In particular, we derive a theoretical model to deliver normative insights on optimal deterrence strategies for a social planner facing a representative (or aggregate) strategic tax evader in a Stackelberg competition. The social planner's objective is to maximize the global detection probability of tax evasion and wealth concealment by enforcing a finite number of tax information exchange agreements between countries inside the network. A principal result in this setting is that the objective of the social planner is mathematically equivalent to finding the subgraph which maximizes the sum of Bonacich centralities within the network. This result reiterates the need to adopt a systemic perspective on international tax evasion, as the Bonacich centrality of the network does not depend on local properties of the network, but on its global structure. In this respect, we show that the optimal coordinated policy is to enforce tax information exchange agreements between jurisdictions following a hub-like structure targeting offshore financial centers according to their Bonacich centrality in the inter-temporal network of global tax evasion. Furthermore, the specific features of the optimal treaty-structure (quasi-star or quasi-complete graphs) are dependent on the level of influence that the social planner is able to exert over the network. Relying on computer simulations, we identify through centrality measures those tax havens that ought to be priority policy targets, as evidenced by the Panama Papers.

The general structure of the doctoral thesis is designed as follows. Chapter 1 presents a micro-founded model of intrinsic and extrinsic tax compliance, from the taxpayers' point of view. This chapter comprehensively integrates recent findings from behavioral economics and economic psychology into a mathematical model to further understand taxpayer behavior under diverse policy settings. Chapter 2 derives an optimal audit policy from the social planner's point of view, who seeks to maximize the average subjective audit rate among all taxpayers in a network. Moreover, said optimal fiscal policy combines behavioral insights with game-theoretic techniques and applied network theory to properly deal with taxpayer heterogeneity. Chapter 3 presents a macro-oriented tax evasion model from the viewpoints of both a tax evader and a social planner in a Stackelberg competition. An analytical solution to the social planner's problem is derived and implemented through a calibrated policy model with strong micro-foundations and game-theoretical insights. Further, a brief Conclusion chapter closes the first part of the dissertation by commenting the main findings and the policy implications of our work. In the second part of the thesis, two appendices are included. These appendices are composed by two complementary papers, related yet independent of the present dissertation, which have been published as chapters in two edited books in applied network theory and agent-based modeling techniques.

#### Modeling intrinsic and extrinsic taxpayer behavior

Chapter 1 attempts to fill the gap between economic and behavioral literature on tax evasion. We propose a micro-founded model whose results are consistent with the 'slippery slope' framework and with the expected utility theory. Individual taxpayers face the problem of deciding the fraction of income they wish to disclose to the government, based on their trust and perceived power of authorities. Trust is modeled as the voluntary compliance originated by tax morale, and power is shaped by the perceived enforcement; mainly motivated by individual risk aversion. Furthermore, we make use of agent-based simulations to replicate the 'slippery slope' conditions and to test the effects of different parameters on tax evasion. Compliance is primarily enhanced by tax morale and risk aversion, while it is secondarily motivated by higher audit probabilities and penalty fees. Tax rates, however, play a negative effect on tax compliance, as agents are less willing to pay taxes whenever facing larger obligations. Additionally, we study taxpayer behavior when the audit rate is zero and when agents are inclined to make charitable donations. Above all, we derive the conditions under which individuals would fully-evade, partially evade, fully-comply or even over-comply as charitable giving in the absence of audits.

#### Optimal audit policies with heterogeneous agents

Chapter 2 considers a tax evasion game where the tax authority intends to prevent income under-reporting within a network of heterogeneous taxpayers who are engaged in social interactions and exchange information. This paper proposes a two-step game-theoretic optimal audit strategy from the point of view of the tax authority, which consists of a credible threat-to-audit message followed by a network-based audit policy. Subsequently, the tax authority targets taxpayers in function of their individual productivity and their position inside the network, triggering a series of spillover effects which eventually maximize the mean perceived subjective probability of being audited among all taxpayers. Moreover, the optimal audit strategy is robust to expected and non-expected utility theories, and it is invariant for any taxpayer utility function. Additionally, computer simulations determined that the proposed enforcement regime is robust to an ample range of parameter specifications and settings.

#### The network structure of global tax evasion

Chapter 3 builds on recent insights from network theory and on the rich dataset made available by the Panama Papers in order to investigate the micro-economic dynamics of tax evasion. We model offshore financial entities documented in the Panama Papers as links between jurisdictions in the global network of tax evasion. A quantitative analysis shows that the resulting network, far from being a random collection of bilateral links, has key features of complex networks such as a core-periphery structure and a fat-tail degree distribution. We argue that these structural features imply that policy must adopt a systemic perspective to mitigate tax evasion. We offer three sets of insights from this perspective. First, we show that the optimal deterrence strategies for a social planner facing a strategic tax evader in a Stackelberg competition can be characterized using the notion of Bonacich centrality. Second, we show that efficient tax treaties must contain exchange information clauses and link tax havens to non-haven jurisdictions. Third, we identify through centrality measures tax havens that ought to be priority policy targets.

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# Chapter 1

# Modeling intrinsic and extrinsic taxpayer behavior

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**Abstract**

This paper attempts to fill the gap between economic and behavioral literature on tax evasion. We propose a micro-founded model whose results are consistent with the 'slippery slope' framework and with the expected utility theory. Individual taxpayers face the problem of deciding the fraction of income they wish to disclose to the government, based on their trust and perceived power of authorities. Trust is modeled as the voluntary compliance originated by tax morale, and power is shaped by the perceived enforcement; mainly motivated by individual risk aversion. Furthermore, we make use of agent-based simulations to replicate the 'slippery slope' conditions and to test the effects of different parameters on tax evasion. Compliance is primarily enhanced by tax morale and risk aversion, while it is secondarily motivated by higher audit probabilities and penalty fees. Tax rates, however, play a negative effect on tax compliance, as agents are less willing to pay taxes whenever facing larger obligations. Additionally, we study taxpayer behavior when the audit rate is zero and when agents are inclined to make charitable donations. Above all, we derive the conditions under which individuals would fully-evade, partially evade, fully-comply or even over-comply as charitable giving in the absence of audits.

**JEL classification:** H26 · H31 · C63 · A12
**Keywords:** Tax Evasion · Power · Trust · Simulations

## 1.1 Introduction

In this paper we attempt to bridge together the two main theoretical approaches to tax evasion: economic and behavioral. Economic literature considers the rational decisions of individuals as in Becker (1968), Allingham and Sandmo (1972) and Yitzhaki (1974); behavioral literature, in turn, considers power and trust as the main drivers of tax compliance as in Kirchler et al. (2008). We present a parsimonious model for individual tax compliance on self-reported income, distinguishing between intrinsic and extrinsic components of taxpayer behavior. In this study, we seek to determine tax compliance as a combination

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of two factors: trust as an intrinsic measure of voluntary disclosures, and power as an extrinsic predictor of enforced compliance.

On the one hand, the intrinsic motives are related to voluntary compliance inspired by trust in government, or a desire to conform to moral values and social norms; which are independent of the audit probabilities, effective tax rates and applicable penalty fees. In this paper, trust is modeled as tax morale, which may be interpreted as the main predictor of voluntary compliance and driven by a degree of perceived procedural and distributive justice. On the other hand, extrinsic influences refer predominantly to the coercive application of tax compliance as a consequence of government power, which may be described in terms of audit schemes, penalties, retaliation and fixation of tax rates. The perceived power of the tax authorities, which consists in the government's potential to detect tax evasion and to punish illegal behavior, turns out to be the main predictor of enforced tax compliance. In our approach, risk aversion is the channel or link through which power affects the behavior of agents. Thus, perceived power of authorities is shaped by individual risk aversion, along with other key parameters such as audit probabilities, tax rates and penalty fees.

There have been important precedents for reconciling theoretical and behavioral literature along the slippery slope framework. Prinz et al. (2014), Lisi (2014) and Pellizzari and Rizzi (2014) formulated mathematical models of tax compliance at a societal level with heterogeneous agents. Although these models successfully replicated the well-known 'slippery slope' framework at the macroeconomic level, they did not include a micro-founded explanatory model with derivable closed-form solutions for individual taxpayers attempting to optimize an expected utility in function of audit probabilities, tax rates, penalty fees, and other parameters. That is, previous models have described taxpayer behavior from the point of view of the state, but not from the point of view of the taxpayers as in Kirchler et al. (2008). A key improvement of our work, compared to the previous literature, relies on the fact that we reproduce both microeconomic and macroeconomic patterns of the 'slippery slope' framework through a micro-founded model of individual taxpayer behavior and do not restrict our analysis to aggregate values of tax compliance.

The structure of this paper is as follows. Section 1.2 surveys the extensive literature on economics of crime and tax evasion. Section 1.3 defines the mathematical model corresponding to the representative taxpayer's decision to evade or comply with its tax obligations. Section 1.4 offers an econometric analysis performed on the Agent-Based simulations of individual taxpayers and their decisions. Section 1.5 summarizes the findings of this paper and discusses some concluding remarks.

## 1.2 Background

Becker (1968) wrote a seminal economic approach to crime and punishment, where the first notions of optimality conditions to combat illegal behavior were derived by entitling individuals with utility functions, costs, behavior shifts and punitive fines. Allingham and Sandmo (1972) and Srinivasan (1973) developed in parallel a formal analysis of tax evasion on self-reported income. In particular, Allingham and Sandmo (1972) adopted the framework from Becker (1968) and employed it to model tax evasion in a setting where rational agents seek to maximize their expected utility based on tax rates, audit probabilities and penalty fees which are applied to evaded taxes. Myles and Naylor (1996) extended the individual tax evasion models to account for group conformity and social norms. Andreoni et al. (1998) argued in favor of implementing morale and social dynamics in economic modeling, as well as a psychological cost for cheating. The authors concluded that it is the perceived audit rate and not the objective audit rate which should be employed to model taxpayer behavior. Additionally, their research extended tax modeling to include for impure altruism and donations to public goods, introducing the 'warm glow' effect of giving.

Even if the expected utility models have shown how rational agents might increase tax compliance proportionately to tax rates, many experiments have disproved this to occur in real life as in Slemrod (1985) and Alm, Jackson and McKee (1992). The latter thoroughly explored why people pay taxes and found a positive relationship between tax rates and evasion, while larger audit probabilities and fine rates increased the amount of taxes paid by individuals. Moreover Alm, McClelland and Schulze (1992) found how a share of individuals fully complied with their tax duties even when the audit probability was zero. Such phenomenon occurred in the presence of a public investment game, where society benefited from tax collections. An alluring result from this laboratory experiment was the finding that tax disclosures follow an almost dichotomous distribution, where most agents either fully comply or fully evade, while only a rather small share of individuals appears to stay in the middle by strategically selecting the optimal fraction of income to declare.

Although persuasive power predicts trust and voluntary compliance, it is very complicated to device policies targeted at enhancing persuasiveness. Eriksen and Fallan (1996) found that whenever taxpayers acquired additional tax knowledge, they tended to increase their perceived tax fairness, and thus take their taxpaying decisions more seriously and frown on tax evasion. Cullis and Lewis (1997) and Adams and Webley (2001) remarked the importance of having an efficient, favorable interaction between taxpayers and tax authorities. Different studies have found how the presence of intrusive, unreasonable or unfair audits may lead to negative effects on tax compliance. Bergman (2003) evidenced how Chilean tax authorities managed to enhance tax compliance by enforcing legitimate power through tax reforms, while policymakers in Argentina were unable to do so by coercive means. Moreover, Frey (2003) found that constant monitoring could be perceived as a lack of trust or resemble a 'cops and robbers' situation. In such cases, when authorities are overly inquisitive or extremely punitive, an increment of power would provoke a decrement in trust. As mentioned by Turner (2005), power can arise from either legitimate or coercive mechanisms. Consequently, the interactions between power and trust can follow different paths depending on the enforcement mechanisms that the government may decide to follow.

Perceived fairness may be divided in three justice categories as in Wenzel (2003): distributive, procedural and retributive. Distributive justice encompasses the equal treatment and similar tax burden for all taxpayers; procedural justice relates to the proper use of money and resources; retributive justice refers to the application of proper sanctions to tax evaders. Wenzel (2005) found evidence of misconceptions whenever individuals tended to converge on the social norm. In some cases, people would undermine their tax compliance as a consequence of wrongly assuming that evasive behavior was the common practice. Another aspect of taxpayers' perceptions about the tax system is the limited liability assumption, where agents can be fined, at most, the entirety of their income. Ueng and Yang (2006) concluded that in the presence of limited liabilities, excessively increasing tax rates would lead to a worse-off state of the economy in a Pareto-sense. Germane to this idea, Andreoni et al. (1998) had previously suggested how unreasonably high fine rates would anyway not be attainable due to bankruptcy or finite maximal losses. Consequently, recent literature has endorsed limited liabilities as a common assumption, as in Piolatto and Rablen (2017).

A paramount contribution by Kirchler et al. (2008) bridged behavioral and economic motives for taxpayers in a single framework, commonly known as the 'slippery slope'. The 'slippery slope' framework relates two main drivers of tax compliance: trust as a predictor for voluntary disclosures and power as a factor of enforced compliance. The authors influentially argued how tax rates may play different roles depending on the level of trust. Under low trust, high tax rates may strike taxpayers as being an unfair treatment; whereas for high trust, higher taxes may be perceived as an additional contribution to the common good. Trust in government may be linked by two different channels: as a taxpayer's perceived quality of authorities or as an individual's tax morale. Through the first channel, government quality influences tax compliance. Torgler and Schneider (2009) looked at tax evasion from a macroeconomic perspective, and argued that the shadow economy may be tackled by improving the institutional quality of authorities and, in such a way, earning taxpayer's confidence. From a similar point of view, Lisi (2014) concluded that in a trustful society tax compliance would be higher, while unemployment would be lower. Further research regarding the role of governmental corruption in tax evasion has been conducted by Cule and Fulton (2009), Alm et al. (2016), Litina and Palivos (2016) and Boly and Gillanders (2018). Through the second channel, tax morale also induces tax compliance. Cummings et al. (2009), Lubian and Zarri (2011) and Kountouris and Remoundou (2013) analyzed demographic and cultural components of tax morale, and how these may influence taxpayer behavior. Lisi (2012) explored the interaction between trust and power and their macroeconomic effects, and suggested that trust is a more powerful motivation for tax compliance than power. Furthermore, extensive research has delved deeper into numerous components of tax morale, such as pro-social donations (Frey and Meier (2004)), religiosity (Torgler (2006)), relative consumption (Goerke (2013)), fairness (Cornelissen et al. (2013), social esteem and stigma (Casal and Mittone (2016)), legality (Blaufus et al. (2016)) and taxpayer attitudes (Guerra and Harrington (2018)). Comprehensively, Luttmer and Singhal (2014) provided an ample definition for tax morale, which encompasses all the mechanisms that may entice compliance above the level expected by a rational agent: intrinsic motivations to comply, reciprocity, peer pressure, social customs, information misconceptions or overestimation of the audit rate.

Mittone and Patelli (2000) proposed a novel way to look at tax evasion from a computational point of view by developing agent-based models (ABM) of tax compliance. An extensive list of computational approaches to tax evasion followed. Davis et al. (2003) studied the evolution of compliant and non-compliant groups involving social norms and enforcement dynamics. Mittone (2006) adapted a model with psychological costs under repetitive dynamic choices made by individuals to study the complex behavior of taxpayers. Bloomquist (2006) highlighted the importance of adopting computational social science techniques to validate models that represent real-world problems which require attention from policymakers. Korobow et al. (2007) linked agents in a networked agent-based model which allowed to measure the individual heterogeneity of taxpayers' perceptions of audit probabilities and fine rates. This approach to tax evasion permitted the authors to computationally examine how peer effects affected the aggregate level of tax compliance in a world with limited knowledge. Hokamp and Pickhardt (2010) improved the ABM framework by endowing agents with an exponential utility function and lapse time effects to study the evolution of alternative government policies to deter tax evasion. Hokamp (2014) incorporated back auditing and aging to study the dynamics of social-norm updating for heterogeneous agents inside a population. Pellizzari and Rizzi (2014) replicated the macroeconomic stylized facts of the 'slippery slope' in an agent-based model with citizenship and perceived governmental power. Calimani and Pellizzari (2014) opted for a power utility function model and provided insights about the optimal audit schemes from a social planner's point of view aiming to curb tax evasion. Hashimzade et al. (2014, 2016) grouped akin agents by occupation and argued in favor of endogenous attitude formations to account for individual perceptions. Notably, Andrei et al. (2014) found that the underlying network structure of agents in an ABM has a direct effect on the aggregate level of tax compliance. Moreover, networks which account for higher connectedness allow for a faster and more efficient spread of information and peer effects, leading to higher levels of aggregate tax compliance.

Field experiments have also had their say in tax compliance and evasion. Kleven et al. (2011) performed a tax experiment in Denmark and found that augmenting marginal tax rates had an increasing effect on tax evasion. Additionally, the authors extended the seminal expected utility model to combine prior audits and threat of audits as incentives to further comply for individuals with self-reported income. Kastlunger et al. (2013) found how excessive enforcement may aggravate tax evasion, experimentally revealing a complex and multifaceted relation between enforcement and compliance. Dwenger et al. (2016) performed a field experiment to study individual compliance with local church taxes in Germany, which are legally binding but no audit schemes are enforced to monitor payments. The experiment showed that around 20% of the individuals fully complied even in the absence of audits, while most of the remaining subjects fully evaded. The authors found substantial intrinsic motivation to comply and found no crowding out effect between extrinsic and intrinsic motivations to comply. Notably, this field experiment confirmed the binary behavior of taxpayer compliance obtained 'in vitro' by Alm, McClelland and Schulze (1992), where the majority of individuals 'bunch' at kink points, namely either full evasion or full compliance.

Tax evasion is an ongoing research topic and extensive literature continues to investigate this practice. For the case of self-reported income, Kogler et al. (2015) presented both procedural and distributive justice as predictors for voluntary compliance and trust, while retributive justice and sanctions predicted enforced compliance and power. The authors empirically proved that trust and power significantly predict tax compliance regardless of their underlying motives: trust induces voluntary compliance, power stimulates enforced disclosures, and there is a negative yet not statistically significant relation between trust and power. That is, there is no crowding out effect between trust and power. The authors also found that demographic characteristics seem to have weak effects on tax compliance. Hofmann et al. (2017) similarly concluded that demographic characteristics have little to no effect on tax compliance after analyzing survey studies from 111 countries. Gobena and Van Dijke (2016) established that procedural justice encourages voluntary tax compliance in developing countries where legitimate power is considered to be low. Non-linearity effects are also present in taxpayer behavior. Fochmann and Kroll (2016) showed that voluntary disclosures increase with respect to public good provisions up to a certain extent, after which they start to marginally decrease. Mendoza et al. (2017) showed how auditing could backfire as exercising additional audits decreases tax evasion up to some extent, after which it commences to acquire a U-shaped effect. Moreover, another complexity level was added by Alm et al. (2017), who showed how taxpayers' behavior is directly affected by their neighbors. In this sense, agents behave proportionately as they perceive their neighbors are behaving.

## 1.3 A taxpayer's decision to evade

The current section studies the optimal actions for a self-reporting taxpayer and how they vary based on individual and societal parameters. Our framework considers the existence of two types of agents: taxpayers and tax authorities (i.e. government). Tax authorities set the societal parameters of the model, namely the tax rate $\tau \in (0\%, 100\%)$, the audit probability $p \in [0, 1]$ and the penalty rates enforced on evaded taxes $\theta > 1$. Each taxpayer is endowed with an exogenous earned income $I > 0$, a tax morale parameter $\kappa \in [0, 0.5]$ and a risk aversion level $\rho \in (0, 1)$. The two latter parameters are worth explaining further. Tax morale is understood as the perceived level of distributive and procedural justice in the sense of Wenzel (2003), Kirchler et al. (2008) and Luttmer and Singhal (2014). That is, tax morale can be interpreted as the attitudes of a taxpayer to comply with the authorities, civic and ethical values, or the perceived level of public expenditure. In this sense, the higher the tax morale index and the higher the fraction of income declared, the greater the utility the taxpayer would perceive. Moreover, tax morale can also be treated as a feeling of shame, in which an agent with high tax morale would suffer a more pronounced drop in utility from performing an illegal activity than a low-morale taxpayer. On the other hand, risk aversion is considered as a degree of relative risk aversion bounded between zero and one in a CRRA utility function as in Hashimzade et al. (2014, 2016). In our framework, the risk aversion parameter is applied on the net income after taxes and penalties, if applicable. Accordingly, a higher risk aversion would yield a lower utility on wealth.

There are two possible post-audit scenarios from the point of view of the taxpayer, either to be audited or not. In case the taxpayer is not audited, with probability $1 - p$, its net income after taxes is defined as $Y(d) = I - \tau dI$, where taxes are paid only on reported income $(dI)$. However, if the taxpayer is audited, with probability $p$, its net income after taxes and penalties is defined as $X(d) = I - \tau dI - \theta\tau(I - dI)$, where the penalty rate $\theta > 1$ applies to undisclosed income (Yitzhaki, 1974). From the taxpayer's point of view, $X(d)$ and $Y(d)$ are solely in function of $d$, given that $I$, $\tau$, $\theta$ and $p$ are exogenous. The objective of the taxpayer is to optimize its utility by choosing the fraction of income to be declared, $d \in [0, 1]$. Following, an agent may decide to illegally hide a fraction of its income if this optimizes its utility. Consider the following utility function for the representative taxpayer:

$$U(d) = (1 + d)^{\kappa} W^{(1-\rho)}, \tag{1.1}$$

where $d \in [0, 1]$ is the fraction of declared income, $W = \{X(d), Y(d)\}$ is the period-wealth (which is, in fact, a function of $d$), $\kappa \in [0, 0.5]$ is the tax morale parameter and $\rho \in (0, 1)$ is the risk aversion level. Considering Equation 1.1, the only parameter over which agents can optimize is the fraction of declared income $d$. This parsimonious representation of power and trust, introduced as tax morale and risk aversion in our setup, relies in the conceptual work of Kirchler et al. (2008) and the empirical findings of Kogler et al. (2015). According to Kirchler et al. (2008), trust in authorities and perceived power are the two main predictors of tax compliance, while there is no formally established relationship between the two of them.

Among the working assumptions of the model, we have that income is strictly positive, $I > 0$, otherwise there would be no tax evasion problem to begin with. Also, the tax rate $\tau$ is neither 0% nor 100%. In the first case, everyone would be fully compliant by definition; in the second case (given the lack of a public game or a re-distributive mechanism) all agents would exit the labor market as their wage would be nominally zero after taxes. This assumption implies that $Y(d) > 0$. Moreover, there are no retrospective audits, and we require limited liability assumptions. Namely, there is no possibility to send tax evaders to prison and the maximum penalty equals the entire income of the taxpayer. Hence, the limited liability assumption implies that $X(d) \geq 0$. For mathematical convenience, wealth $W$ is considered in terms of the smallest denomination within a currency. That is, in our context $W$ is measured in indivisible monetary units, e.g. cents.

To better understand the role of the model parameters in the specified utility function, we introduce the first and second partial derivatives with respect to each parameter. The utility function is strictly concave with respect to wealth, $U'_W > 0, U''_{WW} < 0$; it is increasing and concave-up with respect to tax morale, $U'_\kappa \geq 0, U''_{\kappa\kappa} \geq 0$; and it is decreasing and concave-up with respect to risk aversion, $U'_\rho \leq 0, U''_{\rho\rho} \geq 0$. Also, given a fixed or pre-defined wealth level, the utility function is concave with respect to the fraction of declared income, $U'_d \geq 0, U''_{dd} \leq 0$. Furthermore, in order for agents not to evade systematically, the fine rate must be such that $\theta > 1$ and, under the utility function specified in Equation 1.1, this condition is necessary and sufficient for agents to fully comply whenever audits happen with certainty (see Appendix). Referring to the tax rate function $\tau(\cdot)$, the most common examples of such tax functions may be either a flat (constant) tax rate or a stepped-tax regime, where agents are taxed progressively according to their income. For analytical convenience, we will use a flat tax rate, $\tau$, in what follows. However, the results found in this paper hold for any non-regressive tax function $\tau(\cdot)$.

A remark for the current tax-compliance model is the non-observable income assumption, meaning that the tax authority does not know beforehand the individual's income. If a society would happen to account for a non-negligible matching system for its labor market, the assumption may be relaxed to take into consideration only the non-observable portion of the agents' stipends without sacrificing any of the model's intuitions and results.

**Claim 1.1.** *Given that the utility function in Equation 1.1 is iso-elastic, individuals have a Constant Relative Risk Aversion (CRRA). The latter means that the fraction of wages or profits that they decide to disclose each fiscal period is independent of their income level. (Proof provided in the Appendix.)*

The taxpayer faces the problem of maximizing its expected utility by deriving the optimal fraction of income to be declared, $d^* \in [0, 1]$. Tax compliance decision-making is commonly modeled as a gamble or an investment opportunity involving one risky asset (undisclosed income) and a risk-free asset (disclosed income). Accordingly, the taxpayer may decide to illegally under-report its income to achieve its purpose. The maximization problem with respect to the fraction of declared income, $d$, by each individual $i$ at time $t$, yet discarding the sub-indices for simplicity, may well be defined as:

$$\max_{d} EU[d] = p \cdot U[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)] + (1 - p) \cdot U[I - \tau(d \cdot I)]. \tag{1.2}$$

where the taxpayer faces a probability $p$ of being audited and a complementary probability $1 - p$ of not being audited. Equation 1.2 is analogous to the seminal formulation proposed by Allingham and Sandmo (1972) and modified by Yitzhaki (1974).

A crucial question arises whenever talking about the effects of specific parameters on taxpayer behavior. In particular, policymakers may be interested in knowing how tax compliance is affected by each parameter *ceteris paribus*. In order to formally characterize the maximization problem, we present the first and second partial derivatives of the expected utility function with respect to $p$, $\theta$, $\kappa$, $\rho$, $I$ and $\tau$, respectively.

$$\frac{\partial EU(d)}{\partial p} \leq 0, \frac{\partial^2 EU(d)}{\partial p^2} = 0; \qquad \frac{\partial EU(d)}{\partial \theta} \leq 0, \frac{\partial^2 EU(d)}{\partial \theta^2} \leq 0;$$

$$\frac{\partial EU(d)}{\partial \kappa} \geq 0, \frac{\partial^2 EU(d)}{\partial \kappa^2} \geq 0; \qquad \frac{\partial EU(d)}{\partial \rho} \leq 0, \frac{\partial^2 EU(d)}{\partial \rho^2} \geq 0;$$

$$\frac{\partial EU(d)}{\partial I} \geq 0, \frac{\partial^2 EU(d)}{\partial I^2} \leq 0; \qquad \frac{\partial EU(d)}{\partial \tau} \leq 0, \frac{\partial^2 EU(d)}{\partial \tau^2} \leq 0.$$

In what follows, the expected utility is linearly decreasing with respect to the audit probability, decreasing and concave-down with respect to the penalty rates, increasing and concave-up with respect to tax morale, decreasing and concave-up with respect to risk aversion levels, increasing and concave-down with respect to earned income and decreasing and concave-down with respect to tax rates. Another important aspect of the current framework is the cross-derivatives of the model parameters. Trivially, a model with $n$ parameters has $n(n-1)/2$ different cross-derivatives. Nonetheless, it is the cross-derivative between tax morale and risk aversion that is potentially of greater interest. The cross-derivative of the expected utility function with respect to both tax morale and risk aversion is smaller than or equal to zero (see Appendix). That is, increasing the risk aversion level would decrease the marginal effect of tax morale on the expected utility of taxpayers.

In particular, the result regarding the effect of tax rates on the expected utility is especially relevant for fiscal policy makers. Limited liabilities is a common assumption in tax evasion literature (Piolatto and Rablen (2017)). Assuming limited liabilities, i.e. the minimal net income an individual may receive after taxes and penalties is zero, the expected utility of the representative taxpayer is non-increasing with respect to the applicable tax rate. The implication from this result establishes that, in our context, taxpayers are worse-off whenever tax rates are increased, as suggested by Ueng and Yang (2006). Albeit this result may seem trivial, many tax evasion models which do not account for a limited liability assumption propose an ambiguous effect of tax rates on expected utility. In fact, some models asseverate that, under certain conditions, the expected utility of agents increases whenever they face a larger tax rate. The limited liability assumption postulates that the minimal net income after audits is zero and, analogously, it establishes the notion that the maximal amount of money the government or tax authority may collect in taxes and fines is the entirety of a taxpayer's income. Specifically, a necessary condition for the income in case of an audit to become negative, i.e. for the limited liability assumption to be violated, is that the penalty rate $\theta$ must be strictly larger than $\frac{1}{\tau}$. In real life, however, the limited liability assumption holds almost surely given that tax rates seldom go over 50% and penalty rates frequently oscillate between 1.2 and 1.75 (Hindriks and Myles (2006)). In several expected utility models there is a somewhat counter intuitive property of high tax rates promoting tax compliance. However, this is a non-linear effect that arises given the fact that pecuniary penalties are set by $\theta\tau$; hence increasing the tax rate is in some sense indirectly enhancing the effect of fine rates.

Normally one would be interested in computing the First Order Conditions of the expected utility function with respect to the fraction of declared income $d$, equalize it to zero and derive the optimal fraction of declared income $d^*$ in function of $\{p, \theta, \tau, \kappa, \rho, I\}$. Geometrically, the expected utility function resembles a concave-down parabola, whose width, height, symmetry, shape and rotation are directly and indirectly governed by the aforementioned parameters. The maximization problem specified in Equation 1.2 is analogous to finding the value $d^*$ such that the function $EU(d)$ evaluated at $d^*$ gives the apex of the function $EU(d)$. Nonetheless, deriving a closed-form solution for the optimal fraction of declared income $d^*$ from the maximization problem specified in Equation 1.2 is mathematically unfeasible for $p \neq \{0, 1\}$. Although a closed-form solution does not exist for this particular problem, one can still study the sensitivity of $d^*$ with respect to the other parameters by numerically estimating the partial derivative of $d^*$ with respect to each parameter. This computational technique helps to understand how $d^*$ changes given a change in other parameters.

$$\frac{\partial d^*}{\partial p} \geq 0, \qquad \frac{\partial d^*}{\partial \theta} \geq 0, \qquad \frac{\partial d^*}{\partial \kappa} \geq 0, \qquad \frac{\partial d^*}{\partial \rho} \geq 0, \qquad \frac{\partial d^*}{\partial \tau} \leq 0, \qquad \frac{\partial d^*}{\partial I} = 0.$$

These numerically computed partial derivatives suggest that higher audit probabilities and higher penalty rates would entice taxpayers to declare a larger fraction of their income. Similarly, higher tax morale and risk aversion levels would also incentive taxpayers to disclose a larger share of their income. Nonetheless, taxpayers facing higher tax rates would opt to self-report a smaller fraction of their earnings, while income levels have no effect on the optimal fraction to report to tax authorities.

### Optimality under certain audits and null audits

Considering the expected utility optimization problem specified in Equation 1.2, where the utility function is the one expressed in Equation 1.1, there exist closed-form solutions for two special scenarios: when the audit probability is null ($p = 0$) and whenever the audits occur with certainty ($p = 1$). For all other interior values of $p \in (0, 1)$, the closed-form solution for $d^*$ does not exist. When the audit probability is null, the optimal fraction of disclosed income can be expressed in terms of the tax morale parameter $\kappa$, the level of risk aversion $\rho$ and the exogenous tax rate $\tau$. Following, we define a new parameter $\gamma := \frac{\kappa}{1-\rho}$, understood as a taxpayer's *willingness-to-pay taxes*. The parameter $\gamma$ can be interpreted as an individual's measure of tax morale corrected by its own risk aversion. The *willingness-to-pay taxes* coefficient is increasing with respect to both tax morale and risk aversion. Proposition 1.1 defines the optimal fraction of declared income $d^*$ in function of the individual *willingness-to-pay taxes* and the exogenous tax rate $\tau$.

**Proposition 1.1.** *Whenever the probability of being audited is zero, taxpayers might fully evade, partially evade or fully comply depending on their own willingness-to-pay taxes ($\gamma$) and the tax rate ($\tau$).*

$$[d^*|_{p=0}] = \begin{cases} 0 & \text{if } \gamma \leq \tau, \\ (0,1) & \text{if } \tau < \gamma < \frac{2\tau}{1-\tau}, \\ 1 & \text{if } \gamma \geq \frac{2\tau}{1-\tau}, \end{cases}$$

*where $\gamma := \frac{\kappa}{1-\rho}$ is the willingness-to-pay taxes.*

Consequently, whenever a taxpayer's *willingness-to-pay taxes* is less than or equal to the tax rate, and the audit probability is zero, full-evasion will take place. For values of $\gamma \in (\tau, \frac{2\tau}{1-\tau})$ the optimal taxpayer action is to conceal a fraction of its income and to declare $d^* \in (0,1)$. On the other hand, taxpayers may be fully-compliant even in scenarios where the audit probability is zero. In particular, agents fully comply even in the absence of audits whenever $\gamma \geq \frac{2\tau}{1-\tau}$. Consequently, if the *willingness-to-pay taxes* is high enough with respect to the tax rate, then taxpayers may be fully-compliant even in the absence of audits. Moreover, the term $\frac{2\tau}{1-\tau}$ is increasing with respect to $\tau$. This suggests that if tax rates increase, less taxpayers would be fully-compliant whenever the audit probability is zero.

Proposition 1.1 evidences how taxpayers might comply (and even fully comply) under certain conditions, even if the probability of being audited is zero. This proposition may offer a mathematical explanation for the seminal results found by the experimental approach of Alm, McClelland and Schulze (1992) and by the field experiment of Dwenger et al. (2016). *A priori*, Proposition 1.1 potentially implies that the distribution of optimal actions may have two bunching points at $d^* = 0$ and $d^* = 1$, composed by the continuum of taxpayers whose *willingness-to-pay taxes* are $\gamma \leq \tau$ and $\gamma \geq \frac{2\tau}{1-\tau}$, respectively.

**Proposition 1.2.** *Whenever the probability of being audited is one, taxpayers will fully comply.*

$$[d^*|_{p=1}] = 1.$$

The intuition behind Proposition 1.2 is quite straightforward. The proofs for Proposition 1.1 and Proposition 1.2 are available in the Appendix.

## The 'slippery slope' framework

Kirchler et al. (2008) established that taxpayers in a 'cops and robbers' scenario may be tempted to behave rationally and to weigh audit and penalty rates, whereas in a 'service and clients' scenario they would be more comfortable following the social norm and thus contributing their fair share. Consequently, the authors introduced the 'slippery slope' framework in which a 'service and clients' approach to deter tax evasion is preferred over the classical 'cops and robbers' system where taxpayers are targeted as criminals and not as customers. The micro-founded model introduced in Section 1.3 is also reproducible as a 'slippery slope' in a three-dimensional fashion.

Figure 1.1 illustrates the individual taxpayer disclosures for varying levels of tax morale and risk aversion in a setting with a flat tax rate of $\tau$ =30%, an audit probability of $p$ =5% and a fine rate of $\theta = 2$. Figure 1.1 shows the 'slippery slope' as seen from the front (left image) and from the side (right image). For large values of both enforced and voluntary motivations to comply, tax evasion may be fully eradicated (top steady state in dark red color). However, such stable conditions are not attainable for an entire society in real life. As suggested by Kirchler et al. (2008), the main area of action consists on the section where both enforced and voluntary compliance levels are low (bottom steady state in dark blue color). Germane to this point, Lisi (2014) confirmed the effects of both trust and power on income disclosures, and concluded that trust was a more important driver of tax compliance than power. Moreover, Gobena and Van Dijke (2016) studied tax evasion in developing and industrialized countries, finding a remarkable difference between both situations. The authors suggested that for developing countries, where power and trust is perceived to be low, it would be optimal to focus on enhancing trust with respect to power. Our simulations do not give a symmetric importance to trust and power as in the baseline representation of Kirchler et al. (2008), but instead convey different parametric impacts depending on the initial conditions of the population. That is, policy implementation varies according to whether a society is in the lower or upper part of the slope. Similarly, Prinz et al. (2014) and Kogler et al. (2015) showed that, under certain conditions, the convexity and concavity of the surface could change, but not vanish. Our asymmetric slope indirectly sheds light on the policy critiques introduced by Gobena and Van Dijke (2016), who claimed that optimal policy should be dependent on a country's state of development. Additionally, the steepness of our simulated 'slippery slope' is more pronounced than the conceptual slope pictured in Kirchler et al. (2008). Notwithstanding, this steepness is the result of accounting for two large fractions of the population being either fully evading or fully complying with their tax duties, producing a bimodal behavior of income disclosures. In fact, Alm, McClelland and Schulze (1992) found in a laboratory experiment that 67% of self-reported taxpayer decisions are all-or-nothing, while Dwenger et al. (2016) also found sharp 'bunching' effects at both zero paid taxes and at the exact level of owed taxes. Ultimately, we are able to graphically show the two steady states as in Kirchler et al. (2008), Prinz et al. (2014) and Pellizzari and Rizzi (2014).

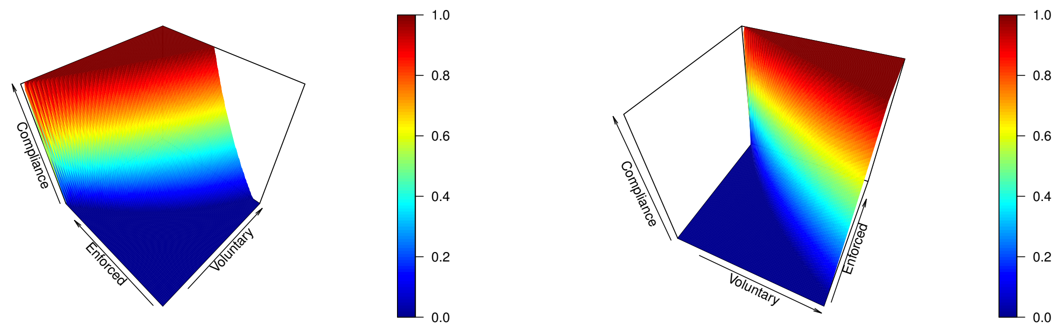



Figure 1.1: Representation of the 'slippery slope' from the front (left) and from the side (right). These images map individual tax compliance ($d^*$) in function of voluntary ($\kappa$) and enforced ($1-\rho$) motivations.

### Tax compliance area

Alm, McClelland and Schulze (1992) and Dwenger et al. (2016) found that a fraction of taxpayers is willing to fully comply with its tax obligations even under the absence of audits. Proposition 1.1 defines the mathematical conditions which help explain why some individuals may opt to disclose their full income even when the audit rate is zero. Building on the third result presented in Proposition 1.1, one can reformulate the full-compliance condition as:

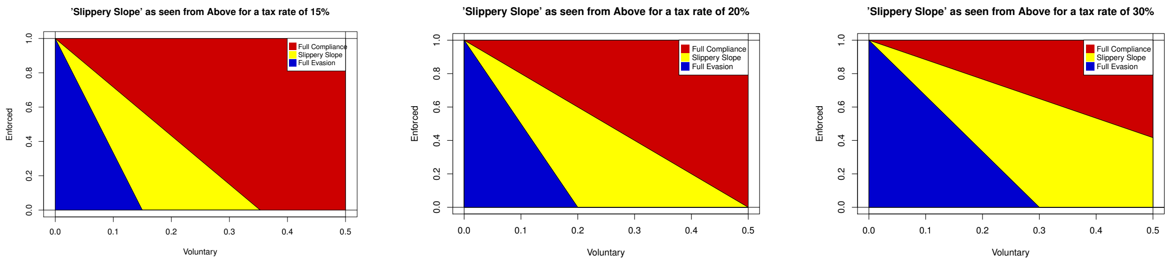
$$\text{if } \gamma \geq \frac{2\tau}{1-\tau} \Rightarrow [d^*|_{p=0}] = 1. \tag{1.3}$$

Substituting the *willingness-to-pay taxes*, $\gamma$, in terms of $\kappa$ and $\rho$ as in Equation 1.3, and applying some basic algebra, one can derive the following linear relation:

$$\text{if } \rho \geq 1 - \kappa \left( \frac{1-\tau}{2\tau} \right) \Rightarrow [d^*|_{p=0}] = 1. \tag{1.4}$$

Equation 1.4 represents a linear function in the ($\kappa$,$\rho$) plane, where the intercept is 1 and the term $\left(\frac{1-\tau}{2\tau}\right)$ is the absolute value of the slope. For increasing tax rates, the slope steepness decreases, making the linear function flatter. Consequently, the conditions under which an individual would fully comply with its tax obligations may be expressed in terms of the taxpayer's tax morale, risk aversion and tax rate. Figure 1.2 shows three 'slippery slopes' where the audit rate is zero and different flat tax rates are considered. The horizontal axis represents voluntary tax compliance (tax morale $\kappa$) and the vertical axis denotes the enforced tax compliance (risk aversion $\rho$). From left to right, the applicable tax rates in Figure 1.2a, Figure 1.2b and Figure 1.2c are 15%, 20% and 30%, respectively. The ($\kappa, \rho$) coordinates where individuals fully comply, partially comply and fully evade are colored in red, yellow and blue, respectively (same color-code as in Figure 1.1). Moving from left to right, we see how the area of full-compliance, colored in red, shrinks with increasing tax rates. For low tax rates (Figure 1.2a), full compliance can be achieved by large-enough voluntary motivations even without enforcement. For scenarios with relatively high trust in authorities, as noted by Kirchler et al. (2008), risk aversion would become irrelevant as agents would stop optimizing rationally and would opt for following the common norm of tax compliance. Notwithstanding, as the tax rate increases (Figure 1.2b and Figure 1.2c), the size of the high-compliance steady state proportionally recedes.

There exists a complex relationship between voluntary and enforced tax compliance, which is itself affected by the tax rate faced by individuals. Bordignon (1993) claimed that agents would be prone to evade taxes unless they faced a non-zero probability of being detected. Nonetheless, this claim is not necessarily true for real life scenarios, as shown by Dwenger et al. (2016). Although Prinz et al. (2014) based their model on the assumption that three fractions of people (full-evaders, optimizing taxpayers and full-payers) always existed, their paper did not test for settings where the audit probability would be set to zero. Figure 1.2 illustrates the presence and survival of all three sets of taxpayers even in the extreme case scenario where audits never occur, and their dynamic evolution with respect to tax rates.




(a) Tax rate: 15% (b) Tax rate: 20% (c) Tax rate: 30%

Figure 1.2: 2-D representation of three 'slippery slope' states, as seen from above. The horizontal axis represents voluntary tax compliance (tax morale $\kappa$) and the vertical axis stands for enforced tax compliance (risk aversion $\rho$). For all three scenarios the audit probability is set to zero, yet some individuals decide to comply, either partially or fully, given their high combined levels of voluntary and enforced compliance.

### Model extension: Donations

The implications of Proposition 1.1 suggest that $d^*$ may be greater than 1 under certain conditions. Whenever the expected utility of declaring $d = 1 + \delta$, with $\delta > 0$, would be greater than that obtained by fully complying, agents would be willing to further contribute through donations or charitable work. Nonetheless, the optimal fraction of declared income is bounded between zero and one. If this assumption would be relaxed from $d^* \in [0, 1]$ to $d^* \geq 0$, the aforementioned parameter $\delta$ could be interpreted as the fraction of wealth that would be optimally overstated even though full compliance has already been achieved. Following, Proposition 1.3 shows the conditions where a taxpayer's expected utility would be better-off by overstating its income. The usual case in real-life scenarios would be that taxpayers cannot overpay their tax duties, as any excess of payments would be refunded back to them. Alternatively, one may interpret this behavior as a charitable donation of magnitude $\tau\delta$.

**Proposition 1.3.** *A taxpayer would be willing to over-comply with its tax obligations by a fraction $\tau\delta$, with $\delta > 0$, whenever the following condition is met:*

$$d^* = 1 + \delta \iff \gamma > \frac{-\ln\left(1 - \dfrac{\tau\delta}{1-\tau}\right)}{\ln\left(1 + \dfrac{\delta}{2}\right)},$$

*where the right-hand term is increasing with respect to the tax rate ($\tau$) and to the 'donation' size ($\delta$).*

*Moreover,*

$$\lim_{\delta \to 0^+} \frac{-\ln\left(1 - \dfrac{\tau\delta}{1-\tau}\right)}{\ln\left(1 + \dfrac{\delta}{2}\right)} = \frac{2\tau}{1-\tau}.$$

For infinitesimally small values of $\delta$, the condition stated in Proposition 1.3 reduces to the result previously derived in Proposition 1.1. Following, there exists an inverse relationship between charitable giving and tax rates. Such opposing effect may be observed in Figure 1.2, where all individuals inside the red-colored area are potentially willing to donate. An implication from Proposition 1.3 is that the conditions under which a taxpayer would be willing to donate a share of its income are independent of the audit rate. Consequently, a philanthropist may carry out charitable actions independently of the audit probability, and depending only on its *willingness to pay taxes* ($\gamma$) and the applicable tax rates. Moreover, taxpayers may be inclined to give donations if their tax morale levels are high-enough; possibly motivated by social norms, reputation, status, 'warm glow' or any other germane intrinsic motive. Noticeably, if the donations would be such that $\delta \geq 1/\tau - 1$ the taxpayer's utility would be zero, given that the concavity of the expected utility function with respect to $d$ bounds self-declarations at $d < 1/\tau$. The latter condition implies that, *a priori*, the distribution of optimal actions $d^* \geq 0$ would be right-skewed with a rapidly decreasing right tail for values of $d^* > 1$. Additionally, the latter distribution would also present the previously established bunching point at $d^* = 0$ for the continuum of taxpayers with $\gamma \leq \tau$. The proof for Proposition 1.3 and further intuition about the distribution of $d^* \geq 0$ is provided in the Appendix.

## 1.4 An agent-based model of tax compliance

The previous section provides some analytical treatment of the model in some important, but special, cases described by $p = 0$ or $p = 1$. We now turn to an agent-based model to investigate other less tractable and more general situations, as well as to extend the analysis to a population of heterogeneous taxpayers who may have different individual levels of tax morale and risk aversion. In order to better understand the effect of each parameter on tax decisions, we simulated individual taxpayer behavior. A total of 10,000 heterogeneous taxpayers were generated, where each taxpayer had a unique set of parameters sampled from a collection of uniform distributions as follows. Respectively, each individual faced a perceived audit probability sampled from $p \sim U(0, 0.10)$, paid an applicable tax rate in $\tau \sim U(0.10, 0.50)$, was subjected to a penalty fee between $\theta \sim U(1, 5)$ times the evaded taxes, with an individual tax morale sampled from $\kappa \sim U(0.10, 0.40)$ and an individual risk aversion level sampled from $\rho \sim U(0.10, 0.90)$. Additionally, taxpayer income was sampled from a uniform distribution ranging from 15,000 to 30,000 units. Notwithstanding, income levels have no impact on the fraction of declared income given that agents have a constant relative risk aversion. Table 1.1 surveys the characteristics of all the relevant parameters employed in our simulations.

Table 1.1: Specifications of individual parameter sampling

| Parameter | Setting | Distribution | Support |
|---|---|---|---|
| $p$: audit_rate | Societal | Uniform | $p \in [0.00, 0.10]$ |
| $\tau$: tax_rate | Societal | Uniform | $\tau \in [0.10, 0.50]$ |
| $\theta$: fines | Societal | Uniform | $\theta \in [1.00, 5.00]$ |
| $\rho$: risk_aversion | Individual | Uniform | $\rho \in [0.10, 0.90]$ |
| $\kappa$: tax_morale | Individual | Uniform | $\kappa \in [0.10, 0.40]$ |
| Number of simulated taxpayers: | | | 10,000 |

The income disclosures resulting from the simulated environments may be statistically analyzed to assess the effect that each parameter has on taxpayer behavior. Following, the dependent variable $d^*$ was regressed on the five variables specified in Table 1.1 in a Tobit model censored at $[0, 1]$, which includes linear and quadratic terms to test for non-linearity, and an error term $\varepsilon$. Equation 1.5 shows the regression model employed to analyze the simulated taxpayer decisions.

$$d_i^* = \alpha + \beta_1\tau + \beta_2\tau^2 + \beta_3 p + \beta_4 p^2 + \beta_5\theta + \beta_6\theta^2 + \beta_7\rho_i + \beta_8\rho_i^2 + \beta_9\kappa_i + \beta_{10}\kappa_i^2 + \varepsilon_i \tag{1.5}$$

The results obtained from this mathematical procedure are presented in Table 1.2. The estimates and significance levels for all parameters under a limited liability assumption are shown in Column 1. Tax rates ($\tau$) have a negative and significant effect on tax compliance, with a positive estimate for its quadratic term. These results suggest that as the tax rate increases, people would tend to evade more yet with decreasing marginal effects. Audit probabilities ($p$) have a positive and significant deterrence impact on tax evasion. The probability of being audited has a direct and linear effect on tax compliance. Fine rates ($\theta$) have a positive and significant effect to enhance income disclosures, yet the estimate is rather small compared to the effect attained by the other parameters. Moreover, fine rates seem to have a decreasing marginal effect. These results confirm previous studies, as Alm, Jackson and McKee (1992), where it is argued that fine rates slightly improve tax compliance but are not the most effective

Table 1.2: Tobit regression for individual declarations $d^* \in [0,1]$

| Variables | Limited Liability (1) | Limited Liability (2) | No Limited Liability (3) |
|---|---|---|---|
| Intercept_1 | 2.2730*** | -0.3041*** | 1.5340*** |
| | (0.0525) | (0.0054) | (0.1027) |
| Intercept_2 | -2.2020*** | -2.1940*** | -1.2610*** |
| | (0.0104) | (0.0011) | (0.0094) |
| $\tau$: tax_rate | -8.4080*** | -9.1140*** | -6.9130*** |
| | (0.0988) | (0.1082) | (0.1769) |
| $\tau^2$: tax_rate$^2$ | 6.7400*** | 7.6800*** | 8.5260*** |
| | (0.151) | (0.1615) | (0.2845) |
| $p$: audit_rate | 3.4050*** | 3.3970*** | 1.9650*** |
| | (0.2215) | (0.2204) | (0.4536) |
| $p^2$: audit_rate$^2$ | 3.2343 | 2.1420*** | 2.5850 |
| | (2.152) | (2.1130) | (4.4270) |
| $\theta$: fines | 0.1121*** | 0.1259*** | 0.1674*** |
| | (0.0081) | (0.0081) | (0.0168) |
| $\theta^2$: fines$^2$ | -0.0092*** | -0.0012*** | -0.0023 |
| | (0.0013) | (0.0013) | (0.0028) |
| $\rho$: risk_aversion | 0.3343*** | 1.1200*** | -0.1271 |
| | (0.0363) | (0.0582) | (0.0739) |
| $\rho^2$: risk_aversion$^2$ | 2.0340*** | 1.7060*** | 1.4550*** |
| | (0.0388) | (0.0429) | (0.0746) |
| $\kappa$: tax_morale | 8.0450*** | 9.8150*** | 5.5080*** |
| | (0.1250) | (0.1591) | (0.1276) |
| $\kappa^2$: tax_morale$^2$ | -7.8960*** | -9.5020*** | -5.7040*** |
| | (0.2411) | (0.2560) | (0.3009) |
| $\rho\kappa$: Interaction | | -2.0220*** | |
| | | (0.1155) | |
| Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05 | | | |

*Notes:* Individual tax compliance predicted by tax rates $\tau$, audit probability $p$, fine rates $\theta$, risk aversion $\rho$, tax morale $\kappa$ and their respective quadratic terms. A total of 10,000 simulations were generated, where $\tau \in [0.10, 0.50]$, $p \in [0, 0.10]$, $\theta \in [1, 5]$, $\rho \in [0.10, 0.90]$, $\kappa \in [0.10, 0.40]$. It is worth mentioning that the highly statistically significant results found are partially inflated given that there are no external effects nor policy shocks in the simulations. Hence, this is an explanatory regression and not a forecasting model.

mechanism to do it. The level of risk aversion ($\rho$) has a positive and significant effect on tax compliance, while its quadratic term reveals increasing marginal effects. Consequently, if risk aversion is low then an increment of it would have a small effect; however, if risk aversion is high then an increment of it would considerably improve taxpayer behavior. Tax morale ($\kappa$) has a positive, significant and very large effect on tax compliance. The impact of tax morale, however, has a decreasing effect for larger values of tax morale. Conversely to risk aversion, if tax morale is low then an increment of it would have a large effect; however, if tax morale is high then an increment of it would modestly increase tax compliance. Similar responses were found by Fochmann and Kroll (2016) for public good provisions. Our results are in line with the findings of Kirchler et al. (2008), who suggested that if a society faces both low trust and low power levels, then the government should prioritize to motivate voluntary compliance as this would induce larger benefits in taxpayer behavior.

A similar model specification is detailed in Column 2, where an interaction effect between risk aversion and tax morale was included in the regression. Once we consider the reciprocal actions between the two main drivers of compliance, the signs and significance levels of the original parameters remain stable. Slight differences arise, as the coefficients for tax rates and tax morale levels attain higher absolute values, whereas the estimates of the risk aversion coefficients diminished. In our simulations there is a negative interaction effect between voluntary and enforced motives, analogous to previous empirical studies (Kastlunger et al. (2013)) and theoretical models (Prinz et al. (2014)). Following, increasing risk aversion levels would hamper the marginal effect of increasing tax morale.

Another interesting robustness exercise is to analyze the same scenarios without assuming limited liabilities. These results are shown in Column 3 of Table 1.2. Although the influence of tax rates keeps being negative and significant, the estimated coefficient is lower than in the case with limited liabilities. Moreover, the quadratic term is larger, meaning that the convexity is more pronounced. As in the two previous specifications, audit rates directly enhance tax compliance. A noticeable difference relates to the fine rates, which slightly increased their estimated value and acquired a linear and direct effect on tax compliance. As a consequence of not imposing limited liabilities, the impact of fine rates does not dissipate as fast as in the baseline scenario in Column 1. The last variation observable in Column 3 is the negative and insignificant effect of risk aversion on tax compliance. This is counter intuitive and may be associated with the fact that its predictive power was absorbed by the audit and fine rate parameters. Another explanation is given in Kastlunger et al. (2013), who found this situation in an experiment with Italian self-reporting taxpayers. The authors detected a negative yet small impact of enforcement on compliance, and attributed the effect to an heterogeneity of intimidated and defiant taxpayers. Following, it may be that such 'intimidated' individuals followed a limited liability mental-accounting, and were willing to lose a defined maximal amount in penalties. Analogously, the 'defiant' subjects would be those whose mental-accounting process did not consider a limited liability assumption, and thus were considering the possibility of losing unlimited quantities of money. Consequently, an increase on tax enforcement may provoke different reactions among heterogeneous groups of taxpayers. Ultimately, the impact of tax morale on compliance is consistent with the one found under limited liability, yet the effects of risk aversion are harder to interpret. Conclusively, the limited liability scenario exemplifies the 'slippery slope' framework more accurately than the case where no limited liability exists.

Although Equation 1.5 does not provide a structural model, the results presented in Table 1.2 help interpret the numerically computed partial derivatives of the optimal fraction of declared income with respect to each model parameter. Harsher audit rates and penalty rates coerce taxpayers to disclose larger fractions of their income. Higher levels of tax morale and risk aversion persuade individuals to comply with tax authorities. Nonetheless, increasing the tax rates may have a negative impact on taxpayers, leading them to under-report their income to optimize their expected utility. Moreover, the regression results expose a negative interaction effect between tax morale and risk aversion. That is, increasing the risk aversion level of taxpayers would lessen the marginal effect of increasing their individual tax morale. Hence, tax authorities may be forced to choose between a policy designed to increase taxpayers' risk aversion or a policy designed to promote tax morale. A similar effect between coercive power and persuasive power in tax compliance was documented in the literature by Prinz et al. (2014).

Marginal effects are useful to assess how the outcome variable changes with respect to a specific predictor *ceteris paribus*. Table 1.3 shows the marginal effects attained by the linear and quadratic terms of the parameters estimated in Equation 1.5 and computed from the results in Column 1 of Table 1.2. Additionally, the marginal effects evaluated at the extreme values of the support are provided for each explanatory variable. Graphical representations of the marginal effects evaluated along the support of each parameter are illustrated in Figure 1.3 through Figure 1.5. The benchmark fraction of declared income by taxpayers is of 68%, computed as the average value of each parameter weighted by its coefficient on the model specified in Equation 1.5.

Table 1.3: Marginal effects of parameters

| Parameter | Linear Marginal effect | Quadratic Marginal effect | Marginal effect at Support Minimum | Marginal effect at Support Maximum |
|---|---|---|---|---|
| $\tau$: tax_rate | -1.2720 | 1.0422 | -0.1147 | -0.3733 |
| $p$: audit_rate | 0.4538 | 0.5843 | 0.0000 | 0.0530 |
| $\theta$: fines | 0.0194 | -0.0018 | 0.0149 | 0.0483 |
| $\rho$: risk_aversion | 0.0454 | 0.2993 | 0.0078 | 0.2819 |
| $\kappa$: tax_morale | 1.1939 | -1.1848 | 0.1061 | 0.2864 |
| Benchmark disclosed income: | | | | 68% |

The marginal effects presented in Table 1.3 indicate that increasing tax rates may escalate tax evasion, which has been previously suggested by Alm, Jackson and McKee (1992) and Kleven et al. (2011). Figure 1.3 shows differing effects of tax rates on taxpayer behavior conditional on whether limited liabilities and binding, or not. Whenever the maximum possible penalty a taxpayer may pay is its entire income, tax rates play a negative effect on tax compliance (black line). However, once we remove this assumption, the relation becomes ambiguous as the marginal effects acquire a pronounced curvature for large tax rate values (red line). Without limited liabilities and for lower values of tax rates, increasing taxes decreases tax compliance; conversely, for high-enough tax rate values an increment in the tax rate commences to augment individual tax compliance (right-end of red line). That is, without limited liabilities, tax rates have an ambiguous effect on tax evasion. The latter outcome conforms to the scenario explored by Allingham and Sandmo (1972) in their seminal model.

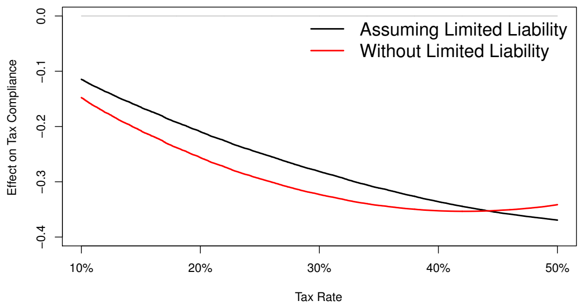



Figure 1.3: Marginal effects of tax rates with (black) and without (red) limited liability assumptions

The marginal effects of tax morale and risk aversion estimated in Table 1.3 are represented in Figure 1.4. Tax morale has a strong concave effect on tax compliance, while the impact of risk aversion appears in a convex manner. An inverse growth relationship between voluntary and enforced compliance has been assessed both empirically by Kastlunger et al. (2013) and theoretically by Prinz et al. (2014). In this sense, an increment in the level of enforcement would decrease the marginal effect of an increment in the voluntary compliance. Therefore, in scenarios with low trust and low perceived power, governments should opt to foster tax morale and voluntary compliance, as the marginal effect in this area of the curve is larger for tax morale than for risk aversion. However, for settings where both trust and perceived power are high, the government might be better-off by increasing the enforcement level, as the marginal gain for risk aversion is larger than the one for tax morale at the right-end side of the curve. Nonetheless, as mentioned by Kirchler et al. (2008), such case would be of little interest as taxpayers would already be in a compliant and stable area of the 'slippery slope'. Additionally, Figure 1.5 shows how audit probabilities and fine rates enhance tax compliance, but their influence is comparatively modest. These outcomes imply that the potential benefits of improving tax morale in a society with low trust and low perceived power would outweigh those of a strengthened enforcement regime. In other words, governments and tax authorities should actively consider switching from a 'cops and robbers' system to a 'service and clients' approach whenever facing low levels of trust and perceived power.

Tax morale may have its origin in government quality or in the individual characteristics of the taxpayers. Reasonably, the former is more relevant from a policy maker's point of view. In particular, perceived government quality may be enhanced by promoting distributive justice (treating taxpayers equally, administering similar tax burdens, maintaining efficient and favorable interactions between taxpayers and tax authorities, providing additional tax knowledge to citizens and approving beneficial tax reforms) or by fostering procedural justice (making proper use of public money and resources, maintaining the institutional quality of authorities, securing public good provisions and fighting governmental corruption). Although our results shed light on the advantages of adopting a 'service and clients' approach over the classic 'cops and robbers' system, there are certain limitations related to this finding. On the one hand, the costs associated with building tax morale cannot be assumed to be the same as those incurred by increasing the number, scope, or duration of tax audits. On the other hand, the design and implementation of public trust-enhancing policies are not trivial issues. A setback to our proposed model is its inability to estimate the net effect of tax benefits between the supplementary costs and the potential additional tax revenues of adopting a 'service and clients' tax policy.

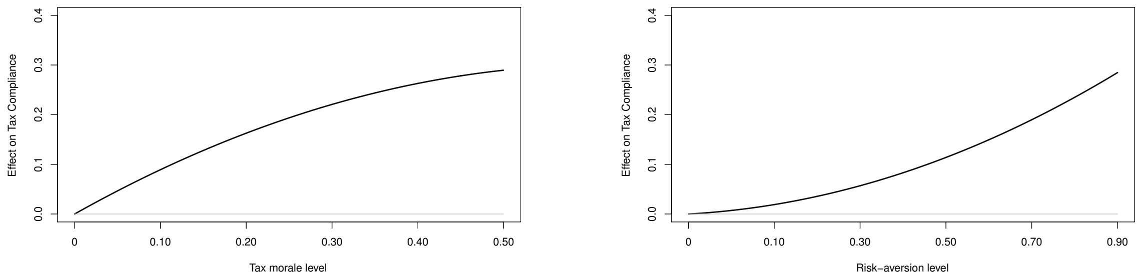



Figure 1.4: Marginal effects of tax morale and risk aversion

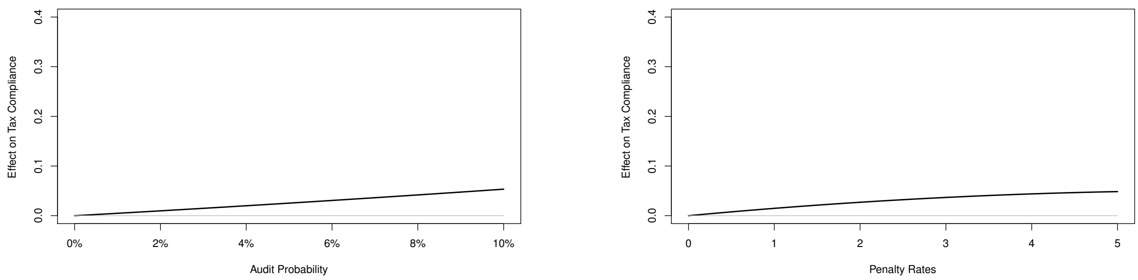



Figure 1.5: Marginal effects of audit probabilities and penalties

### External validation

Simulated environments allow to analyze different facets of taxpayer behavior. Figure 1.6 shows the density distribution of the *willingness-to-pay taxes* ($\gamma$) for different societal configurations, where the tax morale of taxpayers is bounded from above at three different levels: 0.25 (low), 0.50 (mid) and 0.75 (high), while the risk aversion levels remain as before: $\rho \sim U(0.1, 0.9)$. The black line shows how the *willingness-to-pay taxes* follows a humped distribution whenever tax morale is relatively low ($\kappa \sim U(0, 0.25)$). In this case, a large fraction of the population would be unwilling to comply, while a relatively small fraction would be law abiding. The blue line shows a society where mid-levels of tax morale ($\kappa \sim U(0, 0.50)$) can attain similar values to those previously defined in Section 1.3. The distribution becomes much more flatter and includes a heavy tail of highly compliant individuals. Moreover, the red line depicts very high levels of tax morale ($\kappa \sim U(0, 0.75)$) which are beyond the ones defined in our model (initially, tax morale was bounded from above at 0.50 in Section 1.3). This extreme case scenario is merely illustrative to show how the *willingness-to-pay taxes* becomes flatter and with a heavier right-tail as the individual levels of tax morale increase.

Figure 1.7 shows the distribution of individual optimal income disclosures for different levels of tax morale. The simulated data matches remarkably well the experimental results in Alm, McClelland and Schulze (1992) and the outcome from the field experiment by Dwenger et al. (2016). The black line evidences that, for a society with low levels of tax morale, the share of full-evaders is slightly larger than the one of full-compliant taxpayers. Second, for a collective of taxpayers with a midsize tax morale, the blue line shows how a fair share of agents fully-comply, while the share of full-evaders is substantially reduced. At last, an extreme scenario is depicted by a red line. Allowing for unattainable (high) levels of tax morale, the graph shows how a large group of agents converge at full compliance. Nonetheless, this scenario is merely exploratory as the parameter values are not defined within the support of the model for individual tax morale.

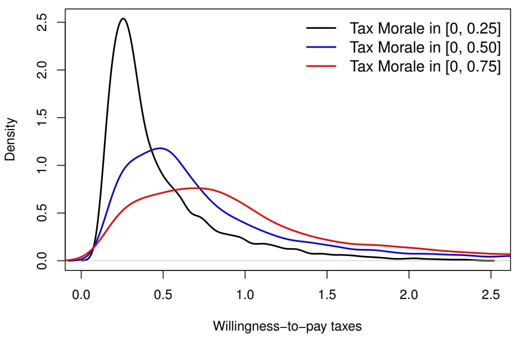



Figure 1.6: Distribution of the *willingness-to-pay taxes*, depending on different levels of tax morale, *ceteris paribus*.

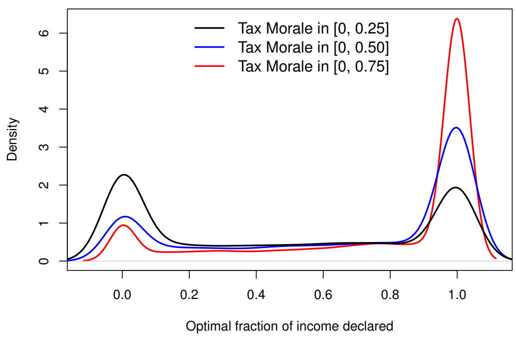



Figure 1.7: Distribution of the optimal fraction of declared income depending on different levels of tax morale, *ceteris paribus*.

## 1.5 Conclusions

There are two broad research lines dealing with tax evasion and the decision-making process of taxpayers. On the one hand, economic literature has attempted to explain this problem through expected utility models, where rational agents choose the optimal amount or fraction of income to disclose to the tax authorities. On the other hand, the behavioral approaches have discovered many interesting findings on how people differently perceive enforcement parameters and display heterogeneous levels of trust in authorities. The 'slippery slope' framework introduced by Kirchler et al. (2008) has triggered a wide debate among economist and psychologists, offering new insights to policymakers who are advised to drop the 'cops and robbers' model and to embrace a 'service and clients' approach. Our paper attempts to bridge both aforementioned strands of research by introducing a micro-founded model which explains many of the stylized facts of individual and collective tax evasion, while staying faithful to the 'slippery slope' paradigm.

This paper interprets trust in authorities as the level of tax morale originated by distributive and procedural justice (Wenzel (2003)). The perceived power of authorities is introduced as the coercive or enforced compliance, driven by the risk aversion level of taxpayers, their perceived probability of being audited, the potential penalty fees, and the applicable tax rates. Some properties of the model can be analytically derived and we show conditions under which agents fully comply even in the (known) absence of audits. Such taxpayer behavior is mainly induced by tax morale under low tax rates, but it is primarily motivated by risk aversion for high tax rates, adding a level of complexity to the 'slippery slope'. Furthermore, conditions were studied to explain the rationale behind altruistic charitable giving. The main results of this paper can be expressed in terms of the *willingness-to-pay taxes*, which may be interpreted as the taxpayer's measure of tax morale corrected for its risk aversion. Following, individual tax compliance is predominantly driven by this metric. Employing agent-based simulations, we further study the marginal effects of the model parameters. Under a limited liability assumption, we find that higher tax rates significantly deter tax compliance. Without a limited liability assumption, however, tax rates have an ambiguous effect on tax evasion. Higher levels of tax morale, as well as higher risk aversion, lead to significantly higher tax compliance. Meanwhile, audit probabilities and penalties have a significant, yet secondary, direct effect on tax compliance. In addition to the analysis on parameter sensibility, many other stylized facts were found, providing some external validity to our model. Namely, the individual responses seem to follow a dichotomous distribution, where most taxpayers either fully evade taxes or fully disclose their income, while only a relatively small fraction of them choose an interior solution.

Our main finding is related to the complex relationship between tax morale, risk aversion and tax compliance. The outcome of our taxpayer simulations hints at a concave impact of tax morale on compliance, while risk aversion imposes a convex effect. Consequently, for societies where trust in government is low and perceived power is also low, then the government should give high priority to finding ways to boost voluntary taxpayer compliance. However, for scenarios where both trust and perceived power are high, then the government might be inclined to increment its perceived power to conduct audits and apply penalties. Nonetheless, as mentioned by Kirchler et al. (2008), the latter is of little interest as in such case people would already be inclined to follow the social norm of complying with the tax authorities. Although our results shed light on the advantages of adopting a 'service and clients' approach, it is important to acknowledge that our model offers limited capability to study the economic and monetary trade-offs between the costs of investing in public trust-enhancing policies versus the potential additional tax revenues. This paper calls for further research on fiscal policy aimed at eradicating tax evasion.

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## Appendix of Chapter 1

### Properties of the utility function

Each taxpayer is endowed with an exogenous earned income $I > 0$, a tax rate $\tau \in (0, 1)$, a penalty rate on evaded taxes $\theta > 1$, a tax morale parameter $\kappa \in [0, 0.5]$ and a level of risk aversion $\rho \in (0, 1)$. Following, the taxpayer must disclose a share $d \in [0, 1]$ of its income to the tax authorities. If the taxpayer is not audited, its net income after taxes is defined as $Y(d) := I - \tau dI > 0$. However, if the taxpayer is audited, its net income after taxes and penalty rates is equal to $X(d) := I - \tau dI - \theta\tau(I - dI) \geq 0$.

The utility function of the representative taxpayer specified in Equation 1.1 is:

$$U(d) = (1 + d)^\kappa W^{(1-\rho)},$$

where $W = \{X(d), Y(d)\}$. The first and second order partial derivatives of the utility function with respect to each parameter $\{W, \kappa, \rho, d\}$ are:

$[W]$ :

$$U'_W = \frac{(1 + d)^\kappa (1 - \rho)}{W^\rho} > 0,$$

$$U''_{WW} = -(1 + d)^\kappa (1 - \rho) \rho W^{-\rho-1} < 0,$$

where the derivative is not well-defined for $W = 0$.

$[\kappa]$ :

$$U'_\kappa = (1 + d)^\kappa \ln(1 + d) W^{1-\rho} \geq 0,$$

$$U''_{\kappa\kappa} = (1 + d)^\kappa \ln(1 + d) \ln(1 + d) W^{1-\rho} \geq 0,$$

where the equality holds only for $d = 0$.

$[\rho]$ :

$$U'_\rho = -(1 + d)^\kappa W^{1-\rho} \ln(W) \leq 0,$$

$$U''_{\rho\rho} = (1 + d)^\kappa W^{1-\rho} \ln(W) \ln(W) \geq 0,$$

where the derivative is not well-defined for $W = 0$, and the equality holds only for $W = 1$. Recall $W$ is expressed in terms of absolute (indivisible) monetary units, e.g. cents.

$[d]$ : (Holding $W$ constant.)

$$U'_d = (\kappa) W^{1-\rho} (1 + d)^{\kappa-1} \geq 0,$$

$$U''_{dd} = (\kappa)(\kappa - 1) W^{1-\rho} (1 + d)^{\kappa-2} \leq 0,$$

where the equality holds only for either $W = 0$ or $\kappa = 0$.

### Properties of the expected utility function

The expected utility function specified in Equation 1.2 is:

$$EU[d] = p \cdot (1 + d)^\kappa [I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{(1-\rho)} + (1 - p) \cdot (1 + d)^\kappa [I - \tau(d \cdot I)]^{(1-\rho)},$$

where $d \in [0, 1]$ is the fraction of declared income, $I > 0$ is the earned income, $\tau \in (0, 1)$ is the tax rate, $\theta > 1$ are the applicable penalty rates, $p \in [0, 1]$ is the audit rate, $\kappa \in [0, 0.5]$ is the tax morale parameter and $\rho \in (0, 1)$ is the risk aversion level. Recall that, given the limited liabilities assumption, $[I - \tau(d \cdot I)] > 0$ and $[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)] \geq 0$. Following, the first and second order partial derivatives of the utility function with respect to each parameter $\{p, \theta, \tau, \kappa, \rho, I\}$ are:

$[p]$:

$$\frac{\partial EU(d)}{\partial p} = (1 + d)^\kappa [I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{1-\rho} - (1 + d)^\kappa [I - \tau(d \cdot I)]^{1-\rho} \leq 0,$$

where the equality holds only for $d = 1$. By definition $[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)] \geq 0$, $[I - \tau(d \cdot I)] > 0$ and $[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)] \leq [I - \tau(d \cdot I)]$.

$$\frac{\partial^2 EU(d)}{\partial p^2} = 0.$$

$[\theta]$ :

$$\begin{aligned}\frac{\partial EU(d)}{\partial \theta} &= -\frac{(p)(1+d)^{\kappa}(\tau)(I - dI)(1-\rho)}{[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{\rho}} \leq 0,\\ \frac{\partial^2 EU(d)}{\partial \theta^2} &= -\frac{(p)\,(1+d)^{\kappa}\,\tau^2(I - dI)^2(1-\rho)(\rho)}{[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{1+\rho}} \leq 0,\end{aligned}$$

where the equality holds only for either $d = 1$ or $p = 0$, and the derivative is not well-defined for $X = 0$.

$[\kappa]$ :

$$\frac{\partial EU(d)}{\partial \kappa} = (p)(1+d)^{\kappa}\ln(1+d)[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{1-\rho} + (1-p)(1+d)^{\kappa}\ln(1+d)[I - \tau dI]^{1-\rho} \geq 0,$$

$$\frac{\partial^2 EU(d)}{\partial \kappa^2} = (p)(1+d)^{\kappa}\ln^2(1+d)[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{1-\rho} + (1-p)(1+d)^{\kappa}\ln^2(1+d)[I - \tau dI]^{1-\rho} \geq 0,$$

where the equality holds only for $d = 0$.

$[\rho]$ :

$$\begin{aligned}\frac{\partial EU(d)}{\partial \rho} =& -(p)(1+d)^{\kappa}[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{1-\rho}\ln(I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)) +\\ & (-)(1-p)(1+d)^{\kappa}[I - \tau dI]^{1-\rho}\ln(I - \tau dI) \leq 0,\\ \frac{\partial^2 EU(d)}{\partial \rho^2} =& (p)(1+d)^{\kappa}[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{1-\rho}\ln^2(I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)) +\\ & (1-p)(1+d)^{\kappa}[I - \tau dI]^{1-\rho}\ln^2(I - \tau dI) \geq 0,\end{aligned}$$

where the equality holds only for $X = 1$ and $p = 1$ simultaneously, and the derivative is not well-defined for $X = 0$. Recall that $X$ is expressed in terms of the smallest denomination of a currency, thus $X = \{0, 1, 2, \dots\}$.

$[I]$ :

$$\begin{aligned}\frac{\partial EU(d)}{\partial I} &= \frac{(p)(1+d)^{\kappa}(1-\rho)(1 - \tau d - \theta\tau(1-d))}{[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{\rho}} + \frac{(1-p)(1+d)^{\kappa}(1-\rho)(1-\tau d)}{[I - \tau(d \cdot I)]^{\rho}} \geq 0,\\ \frac{\partial^2 EU(d)}{\partial I^2} &= -\frac{(p)(1+d)^{\kappa}(1-\rho)(\rho)(1 - \tau d - \theta\tau(1-d))^2}{[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{1+\rho}} - \frac{(1-p)(1+d)^{\kappa}(1-\rho)(\rho)(1-\tau d)^2}{[I - \tau(d \cdot I)]^{1+\rho}} \leq 0,\end{aligned}$$

where the equality holds only for $(1 - \tau d - \theta\tau(1-d)) = 0$ and $p = 1$ simultaneously, and the derivative is not well-defined for $X = 0$.

$[\tau]$ :

$$\begin{aligned}\frac{\partial EU(d)}{\partial \tau} &= \frac{(p)(1+d)^{\kappa}(\theta dI - \theta I - dI)(1-\rho)}{[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{\rho}} - \frac{(1-p)(1+d)^{\kappa}(dI)(1-\rho)}{[I - \tau dI]^{\rho}} \leq 0,\\ \frac{\partial^2 EU(d)}{\partial \tau^2} &= -\frac{(p)(1+d)^{\kappa}(\theta dI - \theta I - dI)^2(1-\rho)(\rho)}{[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{1+\rho}} - \frac{(1-p)(1+d)^{\kappa}(dI)^2(1-\rho)(\rho)}{[I - \tau dI]^{1+\rho}} \leq 0,\end{aligned}$$

where the equality holds only for $d = 0$ and $p = 0$ simultaneously, and the derivative is not well-defined for $X = 0$. Notice that $(\theta dI - \theta I - dI)$ is strictly negative given that $\theta d < \theta + d$. Moreover, $X \geq 0$ and $1 > d\tau$ by definition of the model.

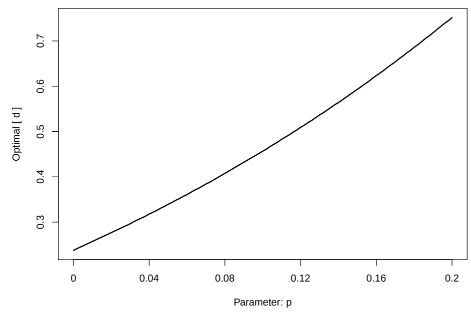
$[\kappa\rho]$ :

$$\frac{\partial^2 EU(d)}{\partial\kappa\partial\rho} = -(p)(1+d)^{\kappa}\ln(1+d)[I-\tau(d\cdot I)-\theta\tau(I-d\cdot I)]^{1-\rho}\ln(I-\tau(d\cdot I)-\theta\tau(I-d\cdot I))+ (-)(1-p)(1+d)^{\kappa}\ln(1+d)[I-\tau(d\cdot I)]^{1-\rho}\ln(I-\tau(d\cdot I))\leq 0,$$

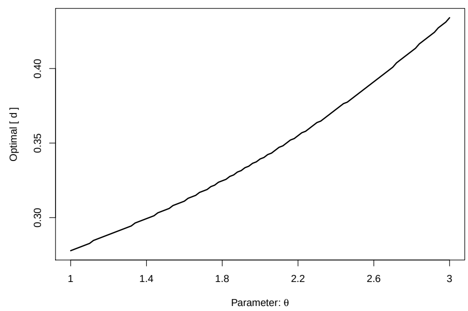
where the equality holds either for $d=0$, or for $X=1$ and $p=1$ simultaneously, and the derivative is not well-defined for $X=0$.

**Numerically estimated partial derivatives of $d^*$**

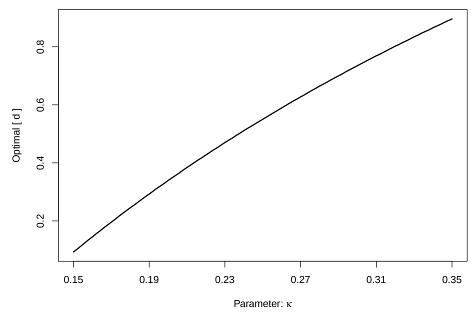
Deriving a closed-form solution for the maximization problem specified in Equation 1.2 is mathematically unfeasible. In what follows, we study the sensitivity of $d^*$ with respect to each model parameter by numerically estimating the partial derivative of $d^*$ with respect to each one.



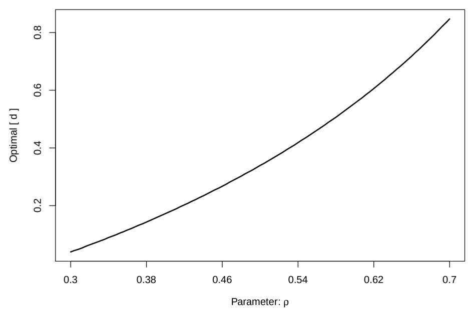

(a) Parameter: Audit probability ($p$)



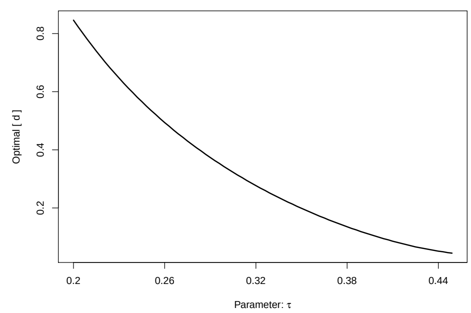

(b) Parameter: Penalty rates ($\theta$)



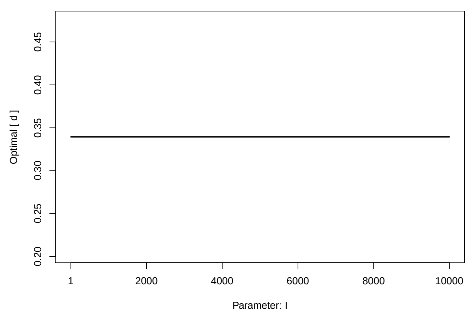

(c) Parameter: Tax morale ($\kappa$)




(d) Parameter: Risk aversion ($\rho$)




(e) Parameter: Tax rates ($\omega$)




(f) Parameter: Income level ($I$)

Figure 1.8: Numerically estimated partial derivatives of the expected utility function with respect to each model parameter. Parameters considered: (a) audit probability ($p$), (b) penalty rates ($\theta$), (c) tax morale ($\kappa$), (d) risk aversion ($\rho$), (e) tax rates ($\tau$), and (f) income level ($I$).

**Proofs**

*Proof of Claim 1.1.* Recalling the power utility function specified in Equation 1.1, it is easy to derive the first and second derivatives with respect to $W$.

$$U = (1+d)^{\kappa} W^{(1-\rho)}.$$
$$U'_W = (1+d)^{\kappa}(1-\rho)W^{(-\rho)}.$$
$$U''_W = (1+d)^{\kappa}(1-\rho)(-\rho)W^{(-\rho-1)}.$$

And so the coefficient of absolute risk aversion $A(W)$ is given by:

$$A(W) = \frac{-u''}{u'} = \frac{-(1+d)^{\kappa}(1-\rho)(-\rho)W^{(-\rho-1)}}{(1+d)^{\kappa}(1-\rho)W^{(-\rho)}},$$

which simplifies to:

$$A(W) = \frac{-u''}{u'} = \frac{\rho}{W}.$$

Following, the coefficient of relative risk aversion $R(W)$ is given by:

$$R(W) = W \cdot A(W) = \rho.$$

□

*Proof of Proposition 1.1.* Assume that the audit probability is set to zero, such that the expected utility form can be expressed as $EU(d) = U(Y(d))$. Then, for each taxpayer $i$ at an arbitrary time $t$, but removing the sub-indices for simplicity:

$$EU(d) = (1+d)^{\kappa}[I(1-\tau d)]^{1-\rho},$$

and

$$\frac{\partial EU(d)}{\partial d} = (1+d)^{\kappa}(1-\rho)[I(1-\tau d)]^{-\rho}(-\tau I) + \kappa(1+d)^{\kappa-1}[I(1-\tau d)]^{1-\rho}.$$

Equalizing the partial derivative to zero and dividing both sides by $(1+d)^{\kappa-1}[I(1-\tau d)]^{1-\rho}$, one gets:

$$(1+d)(1-\rho)(-\tau I) + \kappa[I(1-\tau d)] = 0.$$
$$\Rightarrow (1+d)(1-\rho)\tau = \kappa(1-\tau d).$$

Solving for $d$, one can derive the optimal fraction of declared income whenever the probability of being audited is assumed to be null as a function of $\tau, \rho$, and $\kappa$. One has:

$$[d^*|_{p=0}] = \frac{1 - \frac{(1-\rho)\tau}{\kappa}}{\tau + \frac{(1-\rho)\tau}{\kappa}}, \tag{1.6}$$

where $d^* \in [0, 1]$.

Given that the denominator is strictly positive, the boundary conditions of full-evasion and full-compliance may be computed from the numerator term. A taxpayer will be a full-evader whenever the numerator is smaller or equal than zero. That is, whenever:

$$\frac{1-\rho}{\kappa} \geq \frac{1}{\tau},$$

or analogously, whenever:

$$\frac{\kappa}{1-\rho} \leq \tau.$$

Following, a new parameter $\gamma$ is defined as the *willingness-to-pay taxes*, and may be understood as a taxpayer's measure of tax morale corrected by its own risk aversion: $\gamma := \frac{\kappa}{1-\rho}$. This *willingness-to-pay taxes* is increasing with respect to both tax morale and risk aversion. Consequently, whenever a taxpayer's *willingness-to-pay taxes* is smaller or equal to the tax rate, and the audit probability is zero, full-evasion will take place:

$$\text{if } \gamma \leq \tau \Rightarrow [d^*|_{p=0}] = 0. \tag{1.7}$$

Following, taxpayers may be fully-compliant even in scenarios where the audit probability is zero. Substituting for $\gamma$ in Equation (1.6), agents fully comply even in the absence of audits whenever:

$$\frac{1 - \frac{\tau}{\gamma}}{\tau + \frac{\tau}{\gamma}} \geq 1. \tag{1.8}$$

Applying basic algebra, it is straightforward to derive from Equation (1.8) the following condition:

$$\text{if } \gamma \geq \frac{2\tau}{1-\tau} \Rightarrow [d^*|_{p=0}] = 1. \tag{1.9}$$

Consequently, if the *willingness-to-pay taxes* is high enough with respect to the tax rate, then taxpayers may be fully-compliant even in the absence of audits. The term $\frac{2\tau}{1-\tau}$ is increasing with respect to $\tau$. This suggests that if tax rates increase, less taxpayers would be fully-compliant whenever the audit probability is zero.

From Equation (1.6) and Results (1.7) and (1.9) it is immediate to summarize these conditions as the following expression:

$$[d^*|_{p=0}] = \begin{cases} 0 & \text{if } \gamma \leq \tau, \\ (0,1) & \text{if } \tau < \gamma < \frac{2\tau}{1-\tau}, \\ 1 & \text{if } \gamma \geq \frac{2\tau}{1-\tau}. \end{cases}$$

□

*Proof of Proposition 1.2.* Assume audits are certain, thus making $p = 1$ and allowing to reformulate the expected utility as $EU(d) = U(X(d))$. Then, for each taxpayer $i$ at at arbitrary time $t$, but removing the sub-indices for simplicity:

$$\frac{\partial EU(d)}{\partial d} = (1+d)^{\kappa}(1-\rho)[I(1-\tau d-\theta\tau(1-d))]^{-\rho}[I(-\tau+\theta\tau)] + \kappa(1+d)^{\kappa-1}[I(1-\tau d-\theta\tau(1-d))]^{1-\rho}.$$

Equalizing the partial derivative to zero and dividing both sides by $(1+d)^{\kappa-1}[I(1-\tau d-\theta\tau(1-d))]^{-\rho}$, one can simplify to:

$$(1+d)(1-\rho)(-\tau+\theta\tau) + \kappa(1-\tau d-\theta\tau(1-d)) = 0.$$
$$\Rightarrow (1+d)(1-\rho)(\tau)(\theta-1) = -\kappa(1-\tau d-\theta\tau(1-d)).$$
$$\Rightarrow (1+d)\frac{(1-\rho)}{\kappa}(\theta-1) = d(1-\theta)+\theta-\frac{1}{\tau}.$$

Applying basic algebra and substituting for $\gamma$, it is straightforward to derive $d^*$ as:

$$[d^*|_{p=1}] = \frac{\frac{\theta\tau-1}{\theta-1} - \frac{\tau}{\gamma}}{\tau + \frac{\tau}{\gamma}}, \tag{1.10}$$

which is similar to Equation (1.6). Solving for $\gamma$, the optimal fraction of income declared is equal or larger than one whenever:

$$\gamma \geq \frac{2\tau}{\frac{\theta\tau-1}{\theta-1} - \tau}. \tag{1.11}$$

The denominator on the right-hand side of Equation (1.11) is strictly negative whenever:

$$\frac{\theta\tau-1}{\theta-1} < \tau \Leftrightarrow \theta\tau - 1 < \theta\tau - \tau \Leftrightarrow \tau < 1,$$

which is always the case by assumptions of the model. Thus, recalling that $\gamma$ is strictly positive, and noticing that the right-hand term of Equation (1.11) is strictly negative, then it is always the case that the condition is met. In other words:

$$[d^*|_{p=1}] = 1 \quad \forall\{i,t\}.$$

□

*Proof of Proposition 1.3.* Consider the expected utility whenever taxpayer $i$ chooses to disclose its full income, i.e. $EU[d=1]$. Then, from Equation 1.2 one has:

$$EU[d=1] = p \cdot (1+d)^{\kappa}[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{(1-\rho)} + (1-p) \cdot (1+d)^{\kappa}[I - \tau(d \cdot I)]^{(1-\rho)}.$$

In this scenario there is no uncertainty. Given that the taxes have been paid in full, the net income after audits and penalties is deterministic. Thus, substituting the value of $d$ and applying some algebra:

$$EU[d=1] = p \cdot 2^{\kappa}[I(1-\tau)]^{(1-\rho)} + 2^{\kappa}[I(1-\tau)]^{(1-\rho)} - p \cdot 2^{\kappa}[I(1-\tau)]^{(1-\rho)},$$

giving the following result:

$$EU[d=1] = 2^{\kappa}[I(1-\tau)]^{(1-\rho)}. \tag{1.12}$$

Consider now the expected utility whenever taxpayer $i$ chooses to disclose its full income plus an additional fraction $\delta > 0$, i.e. $EU[d = 1+\delta]$. Then, from Equation 1.2 one has:

$$EU[d=1+\delta] = p \cdot (1+d)^{\kappa}[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{(1-\rho)} + (1-p) \cdot (1+d)^{\kappa}[I - \tau(d \cdot I)]^{(1-\rho)}.$$

Given that the agent has fully disclosed its income (surpassed it, in fact) there is no uncertainty about the audit or no-audit state. Even if audits take place, the agent will not be penalized and no fees will apply, as there was no tax evasion involved. The equation can be simplified to:

$$EU[d=1+\delta] = p(2+\delta)^{\kappa}[I - \tau(1+\delta)I]^{(1-\rho)} + (1-p)(2+\delta)^{\kappa}[I - \tau(1+\delta)I]^{(1-\rho)},$$

$$\Rightarrow EU[d=1+\delta] = (2+\delta)^{\kappa}[p[I(1-\tau-\tau\delta)]^{(1-\rho)} + [I(1-\tau-\tau\delta)]^{(1-\rho)} - p[I(1-\tau-\tau\delta)]^{(1-\rho)}].$$

Giving the following result:

$$EU[d^* = 1+\delta] = (2+\delta)^{\kappa}[I(1-\tau-\tau\delta)]^{(1-\rho)}. \tag{1.13}$$

The next step is to compare the results from Equation 1.12 and Equation 1.13 and to see when it is optimal for a taxpayer to over-comply or endorse charity giving.

$$EU[d=1] < EU[d=1+\delta] \iff 2^{\kappa}[I(1-\tau)]^{(1-\rho)} < (2+\delta)^{\kappa}[I(1-\tau-\tau\delta)]^{(1-\rho)},$$

$$\iff 2^{\kappa}(1-\tau)^{(1-\rho)} < (2+\delta)^{\kappa}(1-\tau-\tau\delta)^{(1-\rho)},$$

$$\iff 1 < \left(\frac{2+\delta}{2}\right)^{\kappa}\left(\frac{1-\tau-\tau\delta}{1-\tau}\right)^{(1-\rho)},$$

$$\iff 0 < \kappa \ln\left(1+\frac{\delta}{2}\right) + (1-\rho)\ln\left(1-\frac{\tau\delta}{1-\tau}\right).$$

Which can be expressed in terms of $\gamma := \dfrac{\kappa}{1-\rho}$ as:

$$EU[d=1+\delta] > EU[d=1] \iff \gamma > -\frac{\ln\left(1-\frac{\tau\delta}{1-\tau}\right)}{\ln\left(1+\frac{\delta}{2}\right)}. \tag{1.14}$$

Moreover, for infinitesimally small values of $\delta$, one can apply L'Hopital's Rule and obtain:

$$\lim_{\delta\to 0^+}\frac{-\ln\left(1-\frac{\tau\delta}{1-\tau}\right)}{\ln\left(1+\frac{\delta}{2}\right)} = \lim_{\delta\to 0^+}\frac{\frac{-1}{\left(1-\frac{\tau\delta}{1-\tau}\right)}\left(\frac{-\tau}{1-\tau}\right)}{\frac{1}{\left(1+\frac{\delta}{2}\right)}\left(\frac{1}{2}\right)} = \frac{\left(\frac{-1}{1}\right)\left(\frac{-\tau}{1-\tau}\right)}{\left(\frac{1}{1}\right)\left(\frac{1}{2}\right)} = \frac{2\tau}{1-\tau}.$$

□

### Further intuition regarding the model extension

Proposition 1.3 defines the conditions under which a taxpayer would be willing to overstate its income, as this would yield a utility greater than that obtained by fully complying. Moreover, given the properties of the utility function, if the donations would be such that $\delta \geq 1/\tau - 1$ the taxpayer's utility would be zero, given that the concavity of the expected utility function with respect to $d$ bounds self-declarations at $d < 1/\tau$. Equation 1.13 shows that a necessary condition for the expected utility to be non-negative is that $1 - \tau - \tau d \geq 0$. Following, for the expected utility to be non-negative it is necessary that $d \leq \frac{1}{\tau}$ and $\delta \leq \frac{1}{\tau} - 1$. In order to provide a better understanding and visual aid of this result, a total of 10,000 simulations were generated, where $\tau \in [0.25, 0.50]$, $p \in [0, 0.10]$, $\theta \in [1, 5]$, $\rho \in [0.10, 0.90]$, $\kappa \in [0.10, 0.40]$. Figure 1.9 shows the histogram and density distribution of the optimal fraction of declared income for $d^* \in [0, 1]$. The distribution presents a predominantly dichotomous response from the taxpayers. On the other hand, Figure 1.10 shows the histogram and density distribution of the optimal fraction of declared income for $d^* \geq 0$. Albeit the responses present the same bunching point at $d^* = 0$ for the continuum of taxpayers with a low *willingness-to-pay taxes*, the distribution is right-skewed with a rapidly decreasing right tail for values of $d^* > 1$. Nevertheless, the model assumptions define the support of the optimal fraction of declared income to be between zero and one, inclusive. That is, we only consider $d^* \in [0, 1]$.

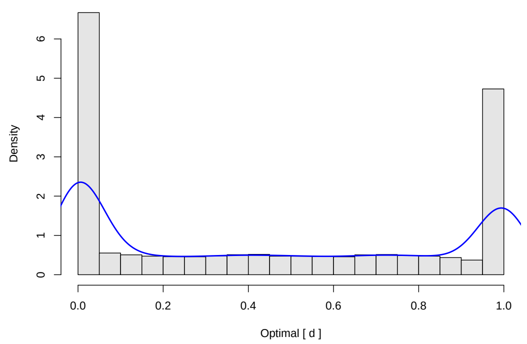



Figure 1.9: Distribution of the optimal fraction of declared income for $d^* \in [0, 1]$.

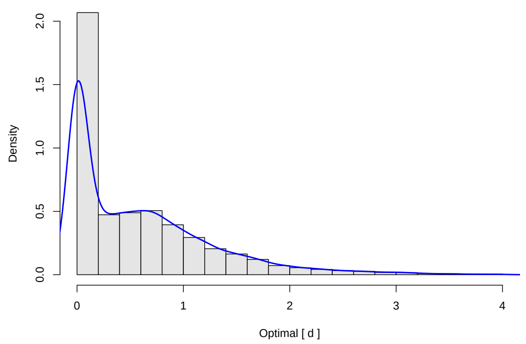



Figure 1.10: Distribution of the optimal fraction of declared income for $d^* \geq 0$.

# Chapter 2

# Optimal audit policies with heterogeneous agents

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**Abstract**

This paper considers a tax evasion game where the tax authority intends to prevent income under-reporting within a network of heterogeneous taxpayers who are engaged in social interactions and exchange information. I propose a two-step game-theoretic optimal audit strategy from the point of view of the tax authority, which consists of a credible threat-to-audit message followed by a network-based audit policy. Subsequently, the tax authority targets taxpayers in function of their individual productivity and their position inside the network, triggering a series of spillover effects which eventually maximize the mean perceived subjective probability of being audited among all taxpayers. Moreover, the optimal audit strategy is robust to expected and non-expected utility theories, and it is invariant for any taxpayer utility function. Additionally, computer simulations determined that the proposed enforcement regime is robust to an ample range of parameter specifications and settings.

**JEL classification:** H26 · D85 · C54
**Keywords:** Tax Evasion · Networks · Quantitative Policy

## 2.1 Introduction

Income under-reporting depletes tax collection and fiscal revenues for tax authorities. According to Buehn and Schneider (2012) the average size of tax evasion originated by under-reported income and indirect taxes amounted to 3.2% of GDP among OECD countries during the period 1999 to 2010. Likewise, Kukk et al. (2020) estimated that between 10% and 40% of self-employed income declarations are under-reported by individuals across EU countries. Gamannossi degl'Innocenti and Rablen (2020) claimed that income tax evasion forces developed countries to annually forsake up to 20% of the taxes which otherwise should have been collected. Moreover, Scartascini and Castro (2015) concluded that the problem is even more pronounced for developing countries, which are sometimes able to only secure less than half of their planned tax collections.

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As stated in Kirchler et al. (2008) income tax compliance may be enforced by the tax authority (also referred to as social planner) or it may originate from voluntary motives appertaining to taxpayers (also referred to as agents or individuals). Following, tax compliance is influenced not only by enforcement and penalty levels, but also by the applicable tax rates, the appropriate use of public money by the government, feelings of regret, uncertainty, risk aversion, psychic costs of evading, the behavior of fellow taxpayers, peer effects, social interactions, reciprocity, social norms, the efficiency of government expenditures, tax morale and the degree of trust that citizens place in the authority; to mention a few. Although there is no general consensus about the roles played by the vast majority of tax compliance motives, the existing literature does agree on the deterrence effect derived from enhanced audit schemes (Alm et al., 1993; Slemrod et al., 2001; Kastlunger et al., 2009; Casal and Mittone, 2016). That is, public economists agree that a higher perceived audit rate, *ceteris paribus*, would induce taxpayers to be more compliant. Nonetheless, even when the individual decision-making process of tax compliance is a well-studied subject, the strategies from the tax authority's point of view have been typically overlooked.

This paper offers a potential contribution to the fields of public economics and game theory by presenting an optimal strategy from the point of view of the tax authority, who intends to hamper income under-reporting[1]. For a given fixed budget (number) of audits, the tax authority seeks to find the optimal allocation of them in a networked society where taxpayers undergo social interactions at every period. The optimal solution consists on emitting a credible threat-to-audit message which ensures taxpayer heterogeneity with respect to productivity. Immediately afterwards, the tax authority strategically targets taxpayers in function of their individual productivity and their position inside the network. Following, the tax authority audits a key group of taxpayers which, by being targeted, triggers a series of spillover effects across the network. This chain reaction eventually leads to the maximization of the global (mean) subjective audit rate among all taxpayers. Additionally, the unique steady state Nash Equilibrium of the mean subjective audit probability is mathematically characterized. Acknowledging that this is not the first game-theoretic audit policy which has been recommended, to the best of my knowledge, it is the first one to be robust against expected and non-expected utility theories, taxpayer heterogeneity and invariant to any individual payoff or utility function. In such a manner, the network-based approach presented in this paper gives a novel solution to an old problem, while taking into consideration the most recent insights from experimental and behavioral economics in a game-theoretic framework.

The paper is organized as follows. Section 2.2 offers a comprehensive literature review on tax-evasion modeling, computational techniques to study taxpayer behavior, major findings from field and laboratory experiments regarding individual tax compliance, and recaps some fundamental insights from game theory and network theory applied to public economics. Section 2.3 presents a game-theoretic approach to tax compliance and studies the optimal strategy from the tax authority's point of view, which is invariant to the decision-making process of the individual taxpayers. Moreover, Section 2.4 offers an extensive analysis of the optimal enforcement scheme and examines its performance under a variety of settings and model extensions. Finally, Section 2.5 summarizes the main findings of this paper, discusses the policy implications of the proposed audit strategy, and enumerates the potential limitations and further research ideas germane to this study.

## 2.2 Literature review

The formal study of tax evasion was pioneered by the work of Allingham and Sandmo (1972), Srinivasan (1973), and Yitzhaki (1974). Their seminal contributions adapted the ideas of Becker (1968) about the economics of crime in a fiscal framework, which served as a cornerstone for the quantitative modeling of tax compliance. Notwithstanding, these influential models were not able to fully replicate taxpayer decision-making. In particular, the levels of tax evasion were systemically overestimated by the seminal models. Thereafter, the expected utility theory was challenged in laboratory experiments designed by Alm, Mcclelland and Schulze (1992) and Alm, Jackson and McKee (1992). The authors found that individual taxpayers exhibit considerable heterogeneity in their behavior and seldom respond as the expected utility theory would hypothesize. Consequently, different extensions have been proposed to

[1] A working assumption in this paper is that third-party reporting is not available. For scenarios where third-party reporting exists, the results derived in this paper would be applicable without any loss of generality to the self-employed and self-reporting taxpayers.

address this shortcoming[2]. Myles and Naylor (1996) called for the need to consider social norms and conformity, while Andreoni et al. (1998) argued in favor of incorporating social interactions to model taxpayer behavior more accurately. Likewise, Yaniv (1999) and Bernasconi and Zanardi (2004) found that prospect theory was able to attain results more in line with empirical evidence.

Computational systems brought a novel technique to model individual decision-making for tax compliance. Mittone and Patelli (2000), Davis et al. (2003), Bloomquist (2004), Mittone (2006) and Korobow et al. (2007) innovated the research on tax evasion by designing the first agent-based models (ABM's) to simulate taxpayers, social interactions, psychological costs of cheating, social norms, a tax authority and different enforcement settings. Computational techniques and behavioral insights from the social sciences became an integral part of tax research after the seminal paper by Kirchler et al. (2008) introduced the 'slippery slope' framework. The authors combined behavioral and economic motives for tax evasion and distinguished between voluntary and enforced compliance. Hokamp and Pickhardt (2010) developed an agent-based model which took into account psychological reasons, social influence among individuals and granted taxpayers an exponential utility function, which yielded more reasonable outcomes. Bloomquist (2011) calibrated the first ABM with real tax data from the Internal Revenue Service department. Prinz et al. (2014) and Pellizzari and Rizzi (2014) provided the first attempts to formalize the 'slippery slope' framework, including taxpayer heterogeneity and considering a wide range of societal parameters. Andrei et al. (2014) markedly improved tax evasion simulations by noticing that the underlying structures of taxpayer networks play a significant role in the dynamics of tax compliance. The authors highlighted a potential role of centrality measures to model aggregate tax compliance.

Audit and penalty rates are not the only policy instruments employable to curb tax evasion. Phillips (2014) argued that game-theoretic insights and representations may also contribute to a more efficient solution. Hashimzade et al. (2014, 2015) and Calimani and Pellizzari (2014) analyzed the emergence of group beliefs, taxpayer behavior and compliance decisions made under uncertainty in an agent-based framework where the transmission of information flowed through peer-to-peer interactions in a social network. Furthermore, Hashimzade et al. (2016) employed predictive tools to design more sophisticated audit strategies, significantly improving compliance compared to random audits. On top of that, social network models have also been adapted to study criminal activity in diverse economic backgrounds, for example, Patacchini and Zenou (2012), Drezewski et al. (2015) and Colladon and Remondi (2017) studied the opportunities for social network analysis to prevent organized crime, such as gang delinquency and money laundering.

In parallel to the aforementioned literature, field experiments and tax surveys have proven to be advantageous methods to further investigate taxpayer behavior. On the one hand, the aftermath of peer-to-peer communication has been thoroughly investigated. Ostrom (2000) asseverated that social norms in games are more effective when players are able to communicate among themselves. Stalans et al. (2006) reported that taxpayers with higher opportunities to evade taxes communicate about tax matters more often than their counterparts. Ashby et al. (2009) suggested that people from the same profession are more likely to interact and exchange information on a frequent basis. Alm et al. (2009) found that peer-to-peer communication about audits influences taxpayer behavior, and that the effect of audits is not limited to those actually audited. Galbiati and Zanella (2012) explored the entire collection of tax audits performed on self-employed workers in Italy for 1987 and found conclusive evidence of endogenous social effects on tax evasion among taxpayers. However, Onu and Oats (2015) remarked that there is still much to be discovered about the frequency and nature of social interactions among taxpayers. Regarding the latter, Mittone et al. (2017) found evidence that Bayesian-updating subjects are apparently unaffected by audits of other taxpayers in their compliance decisions. On the other hand, the tax authority may also spark a positive reaction among taxpayers by interacting with them. Field experiments have confirmed the capability of threat-to-audit letters as a tool to persuade tax compliance (Slemrod et al. (2001); Kleven et al. (2011); Pomeranz (2015)). Notwithstanding, Scartascini and Castro (2015) noted that sending such threatening messages may backfire in the longer run if no additional and corresponding measures are introduced. Moreover, a study by Whillans et al. (2016) found that tax authorities may impact taxpayers' attitudes and incentive them to comply by framing the idea of wealth as a responsibility by means of simple messages.

Social influence and social learning processes have been thoroughly studied since the seminal paper by Degroot (1974). Recently, social norms and peer-effects have become a fundamental aspect of tax-

[2]For a detailed survey of proposed theoretical models, potential utility functions, diverse parameters and specific characterizations of tax compliance models, refer to the survey by Hashimzade et al. (2013).

compliance modeling. Kogler et al. (2015) suggested that perceived social norms are related to both voluntary and enforced compliance. Alm et al. (2017) found that individuals incorporate the behavior of their 'neighbors' when they decide how much income to disclose and how much taxes to pay. That is, taxpayers take into account the actions of their peers, from whom they receive information or with whom they may interact. Currarini et al. (2017) studied linear quadratic games played on a network with peer effects and concluded that the relation between the topology of social networks and behavior should be taken into account when designing policies that target these relations. Extending the notion of peer effects, Garz and Pagels (2018) linked how a pronounced media coverage of celebrities being trialed in Germany for fiscal misconduct provoked an augmented number of self-denunciations and raised the participation of German tax evaders in tax-amnesty programs. Gächter and Renner (2018) studied the emergence of group beliefs and pro-social behavior in public goods games with leaders and followers. Although 'highly visible' taxpayers could affect the initial beliefs of other individuals, the most substantial component of individual attitudes came from the average past behavior of other players. Following, the dynamics of taxpayer compliance are strongly path-dependent and, once a norm or equilibrium is reached, leaders seldom have the power to re-establish or augment the aggregate compliance level. Salmon and Shniderman (2019) claimed that if changes to the enforcement regime are presented in an ambiguous manner, their effect would be negligible. Hence, instead of vaguely announcing that 'more audits will take place', the tax authority should specify how the number of tax audits will be increased, or announce which people will be the specific target of the reinforced scrutiny. Vardavas et al. (2019) found evasion rates to be proportional to the perceived evasion rate in the population. That is, individuals are less prone to comply whenever they perceive that their peers are cheating with their corresponding tax obligations.

Boning et al. (2018) and Lopez-Luzuriaga and Scartascini (2019) remarked that threat-to-audit messages not only have direct effects on their targets, but they also spread throughout the taxpayer network. Mentioned influence is commonly known as indirect or 'spillover' effects, which should always be taken into account by the tax authority and policymakers. Riedel et al. (2019) studied data on business taxes from South Africa and found that audits significantly incremented tax disclosures of non-audited firms. Moreover, these spillover effects of audits diminished with geographical distance and had a short-term effect along time. Drago et al. (2020) designed a field experiment targeting potential evaders of TV license fees in Austrian households. The authors found significant spillover effects of compliance behavior, where untreated households switched from evasive to compliant attitudes in response of having their neighbors targeted by the examiners. Aforesaid spillover effects where positively correlated to geographical proximity and to the centrality of the targeted households. Ortega and Scartascini (2020) advocated that the mechanisms through which policies are informed to the public play a leading role in the effectiveness of an intervention. The authors emphasized that the occurrence of a physical visit by an auditor is more effective than an e-mail warning; and both are more efficient than a simple threat-to-audit letter.

Contemporary literature calls on tax authorities to invest resources to enable policy makers to build taxpayer social networks. Didimo et al. (2019) and Didimo et al. (2020) found decisive support for analyzing taxpayer social networks to discover tax evasion, calibrating their algorithms with real data from the Italian Revenue Agency. Further, Gamannossi degl'Innocenti and Rablen (2020) designed an optimal audit policy aligned with the Ballester et al. (2006) local-*aggregate* game, where agents take into account the absolute actions of their peers. Specifically, the authors derived a unique Nash Equilibrium of optimal tax evasion in terms of a Bonacich (Bonacich (1987)) centrality measure; in their context, more central agents tended to evade more. Moreover, their research demonstrated how higher investments in data-oriented tools would allow tax authorities to optimally select the individuals which ought to be audited. On the other hand, Fortin et al. (2007), Blume et al. (2015), Kline and Tamer (2019), Garcia Alvarado (2019) and Ushchev and Zenou (2020) explored the applications of local-*average* games, where agents take into account the average actions of their neighbors whenever deriving their own optimal action to exert. In particular, Ushchev and Zenou (2020) developed a micro-founded model where individuals have a taste for conformity with the social norm and concluded that using common centrality measures to target taxpayers may not necessarily be efficient. Therefore, optimal policies may differ whether the social planner believes agents play a local-*aggregate* game or a local-*average* game.

## 2.3 Game-theoretic approach to tax compliance

The current section details a game-theoretic mechanism where $n > 1$ individuals face a corresponding tax authority. Taxpayers attempt to maximize their expected utility by computing their optimal level of income to declare. Meanwhile, the tax authority is concerned with maximizing the aggregate fiscal revenues collected from individual tax payments.

### Notation and definitions

Consider $\mathcal{N}$ a set of $n > 1$ agents which coexist in a connected network $\mathbf{g}$. We say a network is connected if there exists at least one path between any two arbitrarily chosen nodes. Moreover, we say two agents are 'neighbors' if they share a direct link between each other. Define $\mathbf{H} = [h_{i,j}]$ with entries $\{0, 1\}$ as the $n \times n$ adjacency matrix of network $\mathbf{g}$, where $h_{i,j} = 1$ if and only if there is a direct connection between agents $i$ and $j$, and $h_{i,j} = 0$ otherwise. Additionally, the network is undirected, which means that $g_{i,j} = g_{j,i}$. The network does not include any self-loops, therefore $g_{i,i} = 0$ for all $i = \{1, 2, ..., n\}$.

Further, define $\mathbf{G} = [g_{i,j}]$ with entries $[g_{i,j}] \in [0, 1]$ as the $n \times n$ row-normalized adjacency matrix obtained from diving each entry of matrix $\mathbf{H}$ by the degree of node $i$. Following this definition, $[g_{i,j}] = [h_{i,j}]/N_i$, where the node-degree $N_i$ represents the number of direct neighbors (links) held by agent $i$. Implementing this matrix representation, one can interpret the value of $[g_{i,j}]$ as the *influence* which agent $j$ exerts on agent $i$. The latter result relates to a social learning process in the sense of Degroot (1974).

### An optimal strategy for the tax authority

Every fiscal year, i.e. the time period between two financial reporting events, taxpayers hold social interactions and share information with their neighbors. This paper assumes social interactions to happen in the sense of Hokamp and Pickhardt (2010) and Andrei et al. (2014). That is, individuals 'talk to' their neighbors with whom they share a direct link and exchange information which helps them to update their subjective audit rate. Accordingly, this assumption implies two things. On the one hand, agents voluntarily disclose information with their neighbors. On the other hand, individuals compute and assimilate the *average* value of the new information received from their neighbors. The latter seems to be reasonable as information circulates locally, and taxpayers are assumed to be bounded-rational. Following, individuals are capable of absorbing a simple mean value instead of having to keep track of otherwise long sequences of information provided by their neighbors. The presence of social interactions leads taxpayers to experience *peer-effects*, as in Alm et al. (2017). The standard model to study peer-effects on individual actions is known as *local-average* model (also called *linear-in-means* model). The name derives from the fact that agents observe the average action of their neighbors and assimilate this value to compute their best response.

Define $x_i \in \mathbb{R}_+$ as the action exerted by player $i$ and $\mathbf{x} := (x_1, x_2, ..., x_n)^\top \in \mathbb{R}^n_+$ the vector of actions corresponding to all players in network $\mathbf{g}$. Depending on the exact equation to be modeled, $x_i$ could be defined as the fraction of income declared, the amount of taxes paid, the optimal evasion rate or any other convenient variable. Define $x_i := \tau d_i I_i$ as the tax payment of player $i$ in monetary terms, where $\tau \in (0, 1)$ is a societal level (flat) tax rate, $d_i \in [0, 1]$ is the fraction of income disclosed by player $i$ to the tax authorities and $I_i > 0$ is the exogenous given gross earned income of taxpayer $i$. In the generalized version of the local-average game, the individual best response $(x_{ig})$ of agent $i$ who lives in group $g$ can be characterized as:

$$x_{ig} = a_{ig}\beta + b_g\gamma + \theta \sum_{j=1}^{n} g_{ij}x_j + \epsilon_{ig}, \tag{2.1}$$

where $a_{ig}$ are the observable individual-specific characteristics of agent $i$, $b_g$ are the exogenous societal-level characteristics which are common for all individuals in group $g$, $\theta$ is the *social interaction effect* which measures an individual's reaction to the average outcome of its neighborhood, $g_{i,j}$ is understood as the *influence* which agent $j$ exerts on agent $i$, and $\epsilon_{ig}$ is an error term.

Further, define the individual-specific *social norm* $\bar{x}_i$ as the average outcome exerted by agent $i$'s neighbors weighted by the influence exerted by each player $j \neq i$ on taxpayer $i$. Following, the social norm per each agent $i$ in network $\mathbf{g}$ may be expressed as:

$$\bar{x}_i = \sum_{j=1}^{n} g_{ij}x_j. \tag{2.2}$$

Hence, an agent's social norm is dependent on the outcomes exerted by its neighbors and also on its position inside network $\mathbbm{g}$. In matrix form notation, the social norm may be expressed as:

$$\bar{\mathbf{x}} = \mathbf{G}\mathbf{x}. \tag{2.3}$$

Substituting Equation 2.2 into the utility function specified in Equation 2.1 yields:

$$x_{ig} = a_{ig}\beta + b_g\gamma + \theta\bar{x}_i + \epsilon_{ig}, \tag{2.4}$$

where $\bar{x}_i$ stands for the previously defined *social-norm* value in the neighborhood of $i$. According to Blume et al. (2015) and Kline and Tamer (2019), local-average games as specified in Equation 2.4 have a corresponding linear-quadratic utility function of the form:

$$U_i(x_i, \mathbf{x}_{-i}, \mathbbm{g}) = \pi_i x_i - \frac{1}{2}x_i^2 - \frac{\theta}{2}(x_i - \bar{x}_i)^2, \tag{2.5}$$

where $x_i$ is the action or outcome exerted by agent $i$, $\mathbf{x}_{-i}$ is the vector of outcomes or actions exerted by all other players, $\mathbbm{g}$ is the social network and $\pi_i > 0$ is an individual *productivity* parameter which compels an agent to increase its optimal outcome or action. The first two terms describe the utility of exerting $x_i$ as an action whenever there are no social interactions. The first term characterizes the individual preference of a taxpayer to make larger tax payments, which could be motivated by higher risk aversion or tax morale levels, feelings of reciprocity, shame, reputation, social customs or any other germane intrinsic motivation. The second term ensures that the optimal solution is bounded, that is, not infinite, by imposing a marginally decreasing utility on tax payments. The remnant term $\theta(x_i - \bar{x}_i)^2/2$ measures a taxpayer's utility reduction as a result from failing to conform with others. This last term may be understood as a measure of *peer-group pressure*. In particular, Galbiati and Zanella (2012) studied real data on self-employed workers in Italy and found robust evidence to support that the social-effect term, $\theta$, is strictly larger than zero among self-reporting taxpayers.

Formally, the objective of the tax authority is to design a fiscal policy such that the value of $\mathbf{e}^\top\mathbf{x}$ is maximized, where $\mathbf{e} := (1, \ldots, 1)^\top \in \mathbb{R}^n$ is a column-vector of ones with dimension $n$. Nonetheless, this task cannot be mathematically characterized by means of *local-average* games given that the tax rate $\tau$ is not individual-specific[3], income $I_i$ is not a fiscal policy parameter and $d_i$ is dependent on an ample set of criteria and conditions such as psychic costs of tax evasion (Baldry (1986); Gordon (1989)), regret and disappointment (Loomes and Sugden (1987)), perception of fairness (Cowell and Gordon (1988)), uncertainty (Kischka and Puppe (1992)), non-additive probabilities (Chateauneuf (1994)), social customs (Myles and Naylor (1996)), risk aversion (Bernasconi (1998)), ambiguity (Snow and Warren (2005)), overweighting the detection probability (Arcand and Rota-Graziosi (2005)), tax morale (Dell'Anno (2009)), and endogenous reference levels (Rablen (2010)), to mention a few.

Although there is no general agreement on the implications of each tax compliance parameter or the relationship that exists between them, it is generally accepted that an enahnced auditing scheme can encourage taxpayers to increase their tax payments (Alm et al., 1993; Slemrod et al., 2001; Kastlunger et al., 2009; Casal and Mittone, 2016). Consequently, it could be optimal for the tax authority to design a fiscal policy aimed at maximizing the subjective probability of being audited among taxpayers. Define $\hat{\mathbf{p}} := (\hat{p}_1, \hat{p}_2, ..., \hat{p}_n)^\top$ as the vector of subjective audit rates of all players in network $\mathbbm{g}$ at an arbitrary time $t$, where $\hat{p}_i \in [0, 1]$ for all $i \in \{1, 2, ..., n\}$, and $\mathbf{e} := (1, \ldots, 1)^\top \in \mathbb{R}^n$ as a column-vector of ones with dimension $n$. Following, the value of the global (mean) subjective audit rate among all taxpayers in network $\mathbbm{g}$ is given by $\frac{1}{n}\mathbf{e}^\top\hat{\mathbf{p}}$.

**Claim 2.1.** *From the point of view of the tax authority and in a local-average game, the following two problems are mathematically equivalent:*

$$\text{argmax}_{\{\mathcal{A}\}}\, \boldsymbol{e}^\top\boldsymbol{x} = \text{argmax}_{\{\mathcal{A}\}}\, \frac{1}{n}\boldsymbol{e}^\top\hat{\boldsymbol{p}},$$

*where $\mathcal{A}$ is the set of possible actions of the tax authority (e.g. audit probabilities, endogenous and exogenous audits, sequence of audits or targeted audits), $\boldsymbol{x} := (x_1, x_2, ..., x_n)^\top \in \mathbb{R}^n_+$ is the vector of actions corresponding to all players in network $\mathbbm{g}$, $\hat{\boldsymbol{p}} := (\hat{p}_1, \hat{p}_2, ..., \hat{p}_n)^\top$ is the vector of subjective audit rates of all players in network $\mathbbm{g}$ and $\boldsymbol{e} := (1, \ldots, 1)^\top \in \mathbb{R}^n$ is a column-vector of ones with dimension $n$.*

[3] In practice, tax rates are not necessarily flat. Commonly tax rates are stepped and progressive according to income. Nonetheless, tax rates are not individual-specific. Therefore $\tau$ is not an individual-specific parameter.

The implications of Claim 2.1 assure that, in the current local-average game-theoretic framework, the objective of the tax authority is equivalent to maximizing the global (mean) subjective audit rate across the taxpayer network. On the grounds that the dynamics of the subjective audit rates ($\hat{p}$) follow the definition of social interactions in the sense of Hokamp and Pickhardt (2010) and Andrei et al. (2014), the best-reply function of agent $i$ for $\hat{p}_{ig}$ in a local-average game is of the form:

$$\hat{p}_{ig} = a_{ig}\beta + b_g\gamma + \theta \sum_{j=1}^{n} g_{ij}\hat{p}_j + \epsilon_{ig}, \tag{2.6}$$

where the individual characteristics ($a_{ig}$) may include income, age, gender, risk aversion, tax morale, etc. and the societal attributes ($b_g$) may comprise the enforcement regime characteristics such as the true audit probability, penalty fines, tax rates, etc. As before, $\theta$ denotes the social interaction effect and $\epsilon_{ig}$ is an error term. Although the third term of Equation 2.6 refers to a social learning process in the sense of Degroot (1974), it is mathematically equivalent to the social norm definition presented in Equation 2.2. It is worth mentioning that there are two types of social norms, descriptive and injunctive. A descriptive norm relates to the perception of 'what is', while an injunctive norm refers to the perception of 'what is should be'. In this line, the players are not trying to decipher whether tax evasion is good or bad (injunctive) but whether other taxpayers are doing it or not (descriptive). Therefore, the third term of Equation 2.6 may be cautiously interpreted as a *descriptive* social norm. Hence, let $\bar{\hat{p}}_i$ be the individual-specific 'social norm' audit rate in neighborhood $i$, and defined as:

$$\bar{\hat{p}}_i = \sum_{j=1}^{n} g_{ij}\hat{p}_j, \tag{2.7}$$

where $\bar{\hat{p}}_i$ is the average subjective audit rate communicated by agent $i$'s neighbors and weighted by the influence exerted by each player $j \neq i$ on taxpayer $i$. Likewise, $\bar{\hat{p}}_i$ can be depicted as the individual-specific *socially learned* or *socially estimated* subjective audit probability. Acknowledging that denoting this term as a social norm might be misleading, not deviate from local-average games literature, we will refer to the socially learned parameter $\bar{\hat{p}}_i$ as a (descriptive) social norm and allow the internally computed beliefs $\hat{p}_i$ to be considered as individual actions or outcomes. Moreover, Equation 2.7 may be expressed in matrix form notation as:

$$\bar{\hat{\mathbf{p}}} = \mathbf{G}\hat{\mathbf{p}}. \tag{2.8}$$

Optimal policies may differ whether the social planner believes agents play a local-*aggregate* game or a local-*average* game. However, given that probabilities should be averaged and and not aggregated, it is logical to assume that the social influence effects should be modeled as in a local-*average* game and not as in an local-*aggregate* game in the sense of Ballester et al. (2006). Following, without any loss of generality and for any time $t$, agents voluntarily disseminate their subjective audit rates to their neighbors during social interactions. Thereafter, taxpayers discover the social-norm value of the subjective audit probability ($\bar{\hat{p}}_i$) among their neighbors. Following, the best-reply function of agent $i$ for $\hat{p}_{ig}$ in a local-average game can be rewritten as:

$$\hat{p}_{ig} = a_{ig}\beta + b_g\gamma + \theta\bar{\hat{p}}_i + \epsilon_{ig}, \tag{2.9}$$

where $\bar{\hat{p}}_i$ is the previously introduced 'social norm' value for the subjective audit rate in taxpayer $i$'s neighborhood. Intuitively speaking, $\hat{p}_{ig}$ is constituted by three different factors: individual, societal and local (neighborhood). Individual aspects of the subjective audit rate may comprise prior beliefs and empirical probabilities of being audited, societal elements may include the true audit rate $p$ and existing audit schemes, while local components are constituted by the subjective audit rates communicated to each taxpayer by its neighbors. Subsequently, the corresponding linear-quadratic utility function for agent $i$ at an arbitrary time $t$ (removing the sub-index $t$ for simplicity) may be defined as:

$$U_i(\hat{p}_i, \hat{\mathbf{p}}_{-i}, \mathbf{g}) = \pi_i\hat{p}_i - \frac{1}{2}\hat{p}_i^2 - \frac{\theta}{2}(\hat{p}_i - \bar{\hat{p}}_i)^2. \tag{2.10}$$

The interpretation of Equation 2.10 is analogous to that of Equation 2.5. However, it is not so intuitive to understand the notion of how a belief can bring economic utility to an individual. In the first term, the taxpayer receives the utility of assuming a sufficiently large $\hat{p}_i$. This stems from the idea that taxpayers are risk averse and assuming too low a subjective probability would cause them to act recklessly and take unnecessary risks, or to choose a level of risk greater than their risk appetite. Indeed taxpayers are risk averse (Segal and Spivak, 1990; Bernasconi, 1998) and tend to overweight the probability of unlikely extreme outcomes (Quiggin, 1982). Evidence that taxpayers overestimate or overweight their audit probabilities has been recorded in the tax evasion literature (Bernasconi, 1998; Alm, Mcclelland and Schulze, 1992). For the second term, too high a subjective probability would incentive taxpayers to pay more taxes than the amount that would be rationally optimal and, therefore, would generate a loss of utility. Finally, the third term measures the loss of utility of not conforming to the socially learned audit rate, which is present through social influence and peer pressure. However, since there is no individual-specific characteristic which *ex ante* compels agents to assume a larger value of the subjective audit rate ($\hat{p}_i$), individuals are initially homogeneous with respect to *productivity* ($\pi_i$) by construction.

**Claim 2.2.** *If individuals are ex ante homogeneous, that is if $\pi_i = \pi_j$ for all $\{i, j\} \in \{1, 2, ..., n\}$, then the Nash Equilibrium outcome levels will be identical for all players, independently of the network structure.*

In other words, when productivity is identical for all individuals, the outcome of a local-average game does not depend on the network $\mathbf{g}$ (Patacchini and Zenou, 2012; Ushchev and Zenou, 2020). Conceptually, there is no reason why individuals should be *ex ante* heterogeneous, as the true audit rate ($p$) is set by a societal parameter and identical for all agents. This situation generates a crucial predicament since, in our local-average game context, the tax authority relies on agent heterogeneity to successfully design an optimal enforcement scheme.

To work out this impasse, the tax authority addresses the network of taxpayers by means of a *threat-to-audit* message. The efficiency of threat-to-audit messages has been proven in diverse environments (Slemrod et al. (2001); Alm et al. (2009); Kleven et al. (2011); Pomeranz (2015); Boning et al. (2018); Lopez-Luzuriaga and Scartascini (2019); Drago et al. (2020)). In particular, Alm et al. (2009) concluded that audit enforcement is an effective tool conditional to the taxpayers being aware of the current audit regime. Specifically, the authors found that the influence of post-audit peer-to-peer communication on taxpayer behavior is dependent on whether taxpayers are informed about the audit rates or not. Consequently, the tax authority should opt for pre-announcing audit rates credibly and by emphasizing the audit frequency in the previous period. Therefore, the tax authority hereby designs a simple message which frames the idea of income as a responsibility, in the spirit of Whillans et al. (2016). Moreover, following the recommendation by Salmon and Shniderman (2019), the announcement may include uncertainty but cannot be ambiguous, that is, the tax authority should clearly announce how the regime will change or which agents will be the specific target of the new enforcement scheme.

The threat-to-audit message received from the tax authority requires agents to compute their heterogeneous subjective audit rate ($\hat{p}$), which is derived endogenously for each individual. The explicit message or announcement may be phrased as:

**Tax authority:**

Dear citizen,
A new audit regime is in place. Last year the societal audit probability was of $p$ and equal for all taxpayers. As of now, the probability of being audited will be proportional to the income level of each taxpayer. Hence, the individual-specific audit rate for each taxpayer $i$ is now defined as:

$$p_i = p \cdot \frac{I_i}{\sum_{j=1}^{n} I_j} \cdot n, \tag{2.11}$$

where $p$ is the homogeneous true audit rate from last year, $I_i$ denotes the gross earned income of taxpayer $i$, $n$ is the total number of individuals in the society, and $p_i \in [0, 1]$ for all $i \in \{1, 2, ..., n\}$.

Computing the sum over all $i$ and dividing by $n$ on both sides, it is easy to see that the average initial subjective audit rate is equal to $p$. In other words, the tax authority is not modifying the total number of audits to be enforced, but it simply claims that it is shifting the taxpayers' audit probabilities.

Albeit authors sometimes disagree on which is the principal attribute which motivates taxpayers to comply (tax morale, risk aversion, reciprocity, social values, reputation, income, etc.) many of them are non-observable and impractical to be estimated. Therefore, this paper considers income, or observable income[4], as a principal explanatory variable for tax payments in absolute terms, as reported in Alm, Jackson and McKee (1992). Furthermore, we consider agents can perceive their individual income with respect to the societal average income as in Pellizzari and Rizzi (2014). Following, the assumption behind the framing message is rather logical: individuals with eye-catching incomes might naturally attract the attention of the tax authority, while low-income agents potentially may be less profitable to audit[5].

Following the threat-to-audit message emitted by the tax authority, agents must first perform an intermediate step and compute their income heterogeneity with respect to society. Denote an auxiliary variable $\alpha_i$ determined by an agent's income divided by the average income of all the agents in the network; analogous to the transformation occupied in Equation 2.11. The value of such individual-specific heterogeneity level $\alpha_i$ is defined as:

$$\alpha_i = \frac{I_i}{\sum_{j=1}^{n} I_j} \cdot n. \tag{2.12}$$

The interpretation of $\alpha_i$ would be a taxpayer's exogenous-given *income productivity* with respect to society. For example, if taxpayer $j$'s earned income would be twice the average income level, then $a_j$ would be 2. Computing the sum over all $i$ and dividing by $n$ on both sides, it is easy to see that the average productivity ($\bar{\alpha}$) is equal to 1, i.e. the total productivity of the network has not been modified.

The communicated threat-to-audit message comes in handy for the tax authority at this point, for agents are heterogeneous with respect to the income productivity vector ($\boldsymbol{\alpha}$). First, let the productivity vector ($\boldsymbol{\pi}$) be redefined as the *income productivity* vector ($\boldsymbol{\alpha}$), that is $\boldsymbol{\pi} := \boldsymbol{\alpha}$. For mathematical convenience, redefine as well the taste for conformity as $\lambda := \frac{\theta}{1+\theta}$, with $0 \leq \lambda < 1$. Replacing the individual productivity and the taste for conformity in terms of $\alpha_i$ and $\lambda$ into Equation 2.10, the individual utility function is given by:

$$U_i(\hat{p}_i, \hat{\mathbf{p}}_{-i}, \mathrm{g}) = \alpha_i \hat{p}_i - \frac{1}{2}\hat{p}_i^2 - \frac{1}{2}\Big(\frac{\lambda}{1-\lambda}\Big)(\hat{p}_i - \bar{\hat{p}}_i)^2. \tag{2.13}$$

The Nash Equilibrium action for each taxpayer $i$ can be determined by deriving the value of $\hat{p}_i$ that maximizes the utility function defined in Equation 2.13, which takes into account the exogenous vector of outcomes for all other agents ($\hat{\mathbf{p}}_{-i}$) and the given network ($\mathrm{g}$) structure. Deriving the First Order Conditions with respect to $\hat{p}_i$ one obtains:

$$\frac{\partial U_i(\hat{p}_i, \hat{\mathbf{p}}_{-i}, \mathrm{g})}{\partial \hat{p}_i} = \alpha_i - \hat{p}_i - \frac{\lambda}{1-\lambda}(\hat{p}_i - \bar{\hat{p}}_i) = 0. \tag{2.14}$$

Solving for $\hat{p}_i$, the best-reply function for each agent $i$ is given by:

$$\hat{p}_i = (1-\lambda)\alpha_i + \lambda \bar{\hat{p}}_i, \tag{2.15}$$

also characterized as:

$$\hat{p}_i = (1-\lambda)\alpha_i + \lambda \sum_{j=1}^{n} g_{ij}\hat{p}_j. \tag{2.16}$$

The matrix representation of Equation 2.16 gives:

$$\hat{\mathbf{p}} = (1-\lambda)\boldsymbol{\alpha} + \lambda \mathbf{G}\hat{\mathbf{p}}. \tag{2.17}$$

Solving for $\hat{\mathbf{p}}_i$ the Nash Equilibrium ($\hat{\mathbf{p}}^*$) is defined by:

$$\hat{\mathbf{p}}^* = (1-\lambda)[\mathbf{I} - \lambda \mathbf{G}]^{-1}\boldsymbol{\alpha}. \tag{2.18}$$

**Proposition 2.1.** $(1-\lambda)[\boldsymbol{I} - \lambda \boldsymbol{G}]^{-1}$ *is well-defined and row-normalized for any given* $\lambda \in [0, 1)$.

The latter implies that $(1-\lambda)[\mathbf{I} - \lambda \mathbf{G}]^{-1}$ is well-defined and row-normalized for any value of $\theta > 0$, which has been empirically proven to be true in tax compliance contexts (Galbiati and Zanella, 2012).

[4]Income levels may be estimated to great accuracy by considering individual-specific characteristics, such as: consumption, housing, education, ability-type, etc. Moreover, the working assumption in this paper is not that income is perfectly observable. The working assumption is that the tax authority can rank agents by income-productivity levels.

[5]Theoretically, the outcome from the optimal audit strategy is invariant and independent of which individual-specific characteristic is being targeted by the threat-to-audit message, as long as it is observable (estimable) and comparable.

Denote by $\mathbf{M} = [m_{i,j}]$ a $n \times n$ matrix such that:

$$\mathbf{M} := (1-\lambda)(\mathbf{I} - \lambda\mathbf{G})^{-1}, \tag{2.19}$$

where $\mathbf{I}$ is a $n \times n$ identity matrix and $\lambda \in [0, 1)$. The term $(\mathbf{I} - \lambda\mathbf{G})^{-1}$ can be interpreted as a *social comparison multiplier* (Gamannossi degl'Innocenti and Rablen, 2020), which is related to the Bonacich (Bonacich (1987)) centrality of each player. This social multiplier measures the mechanism through which a player's actions 'feed through' into other players' actions. $\mathbf{M} = [m_{i,j}]$ can be interpreted as the matrix of *marginal effects* (Ushchev and Zenou, 2020), where $[m_{i,j}]$ is proportional to the weighted number of walks from agent $i$ to $j$ and a walk of length $k$ is weighted by $\lambda^k$. Whenever considering social networks of tax evasion, policy implementations do not only inflict direct effects on individuals, but also spread out indirectly throughout the network. Such indirect reactions, also known as spillover effects, have been documented among taxpayers by Boning et al. (2018), Lopez-Luzuriaga and Scartascini (2019), Riedel et al. (2019) and Drago et al. (2020).

Applying the definition of matrix $\mathbf{M}$ from Equation 2.19, the Nash Equilibrium is characterized by:

$$\hat{\mathbf{p}}^* = \mathbf{M}\boldsymbol{\alpha}. \tag{2.20}$$

Ultimately, recurring to Equation 2.8 the equilibrium social norm ($\bar{\hat{\mathbf{p}}}^*$) is given by:

$$\bar{\hat{\mathbf{p}}}^* = \mathbf{G}\mathbf{M}\boldsymbol{\alpha}. \tag{2.21}$$

**Proposition 2.2.** *Since $\boldsymbol{G}$ is a row-normalized adjacency matrix, the Nash Equilibrium exists, it is unique and it is interior for any $\lambda$ such that $\frac{\lambda}{1-\lambda} > 0$. That is, for any $\lambda \in (0, 1)$.*

**Claim 2.3.** *On average, for $\lambda \in (0, 1)$, rational Nash Equilibrium and stochastic decision behavior converge on exactly the same results in local-average games.*

As a consequence of Claim 2.3, in our context, the Nash Equilibrium is not affected whether taxpayers follow heuristic rules or optimize under bounded rationality (see Appendix). Indeed, the Nash Equilibrium in effort of a network static game is, on average, equivalent whether individuals compute their own productivity rationally or stochastically following a Markovian process (Ushchev and Zenou, 2020). Furthermore, as anticipated by Claim 2.2, it is easy to verify how both the Nash Equilibrium ($\hat{\mathbf{p}}^*$) and the social-norm equilibrium ($\bar{\hat{\mathbf{p}}}^*$) are expressed in terms of the so-called individual *income-productivity* vector ($\boldsymbol{\alpha}$) and the network structure. The latter implies that if all taxpayers would be homogeneous, that is if $\alpha_i = \alpha_j$ for all $\{i, j\} \in \{1, 2, ..., n\}$, then the equilibrium outcome levels would be the same for all taxpayers and independent of the network structure; hence making network-based policies inoperative.

The tax authority is concerned with maximizing the aggregate fiscal revenues. In order to do so, the explicit objective of the tax authority in our context is to maximize the global subjective (perceived) audit rate across the entire taxpayer network. The global optimum from the tax authority's point of view is its first-best outcome, $\hat{\mathbf{p}}^o$. First-best outcomes and restorations in local-average games are thoroughly studied problems. In particular, for any local-average game as the one characterized by Equation 2.13, the first-best outcomes and restorations are well-defined.

**Proposition 2.3.** *Given a local-average game characterized by the following individual utility function:*

$$U_i(\hat{p}_i, \hat{\boldsymbol{p}}_{-i}, \mathrm{g}) = \alpha_i \hat{p}_i - \frac{1}{2}\hat{p}_i^2 - \frac{1}{2}\Big(\frac{\lambda}{1-\lambda}\Big)(\hat{p}_i - \bar{\hat{p}}_i)^2,$$

*for each $i \in \{1, 2, ...n\}$, the first-best outcome, $\hat{\boldsymbol{p}}^o$, is a solution to:*

$$\hat{\boldsymbol{p}} = (1-\lambda)\boldsymbol{\alpha} + \lambda\boldsymbol{G}\hat{\boldsymbol{p}} + \lambda\boldsymbol{G}^\top(\boldsymbol{I} - \boldsymbol{G})\hat{\boldsymbol{p}},$$

*whose solution is unique, and it is given by:*

$$\hat{\boldsymbol{p}}^o = \left[\boldsymbol{I} + \frac{\lambda}{1-\lambda}(\boldsymbol{I} - \boldsymbol{G})^\top(\boldsymbol{I} - \boldsymbol{G})\right]^{-1}\boldsymbol{\alpha}.$$

Proposition 2.3 evidences that the first-best outcome ($\hat{\mathbf{p}}^o$) is expressed in function of the productivity ($\boldsymbol{\alpha}$), the taste for conformity and the network structure. Notwithstanding, whenever the players in a local-average game do not reach the first-best equilibrium, the social planner (tax authority) may try to restore it by *subsidizing* or *taxing* specific individuals in the network.

**Proposition 2.4.** *Continuing from Proposition 2.3, the first-best outcome ($\hat{\boldsymbol{p}}^o$) is restored whenever the social planner endows individuals with the following subsidy/tax per unit of effort:*

$$\boldsymbol{S}^o = \frac{\lambda}{1-\lambda}\boldsymbol{G}^\top(\boldsymbol{I}-\boldsymbol{G})\hat{\boldsymbol{p}}^o,$$

*where the optimal per-effort subsidy for each individual $i$ is:*

$$S_i^o = \frac{\lambda}{1-\lambda}\sum_{j\neq i} g_{ji}(\hat{p}_j^o - \bar{\hat{p}}_j^o).$$

Evidently, the social planner gives a positive subsidy to agents who under-invest in effort and a negative subsidy (taxes) to those who over-invest. Analogous to the first-best outcome, the optimal subsidy/tax values are in function of the taste for conformity and the network structure. Moreover, given that the optimal subsidy/tax is in function of the first-best outcome, which is itself in function of productivity ($\boldsymbol{\alpha}$), then the optimal subsidy/tax is also in function of productivity. Scrutinizing the individual per-effort subsidy from Proposition 2.4, the social planner subsidizes (taxes) individuals whose neighbors' outcomes are above (below) their respective social-norm values; i.e. the tax authority should subsidize (tax) agents who exert outcomes below (above) those of their neighbors.

Notwithstanding, the tax authority is unable to *tax*, i.e. reduce, the subjective audit probability of taxpayers. In fact, the tax authority can only *subsidize*, i.e. augment, taxpayer perceptions by conducting a series of audits on them. Furthermore, the tax authority is constrained to incur on inadequate subsidies, given that optimal subsidies follow a real-valued function while audits are binary variables. Consider a vector $\mathbf{A}_i := (A_{i,t-1}, A_{i,t-2}, ..., A_{i,t-m})^\top \in \{0,1\}^m$ which records taxpayer $i$'s personal history of audits, where $A_{i,t-s} = 1$, if agent $i$ was audited during the period $(t-s)$, and $A_{i,t-s} = 0$, otherwise. The size of vector $\mathbf{A}_i$ is equal to $m$, the fiscal memory length, which denotes the number of periods a taxpayer can recall into the past and it is set exogenous and identical for all agents. For any taxpayer $i$ at an arbitrary time $t$, we have that $S_{i,t}^o \in \mathbb{R}$, but $A_{i,t} \in \{0,1\}$. Not only the plausible subsidy values are limited, but also they are discrete since audits cannot be divided among more than one taxpayer. Although the approach presented in this paper is limited with respect to subsidy flexibility, the results of the optimization problem are analogous from the tax authority's point of view.

Thereafter, if the tax authority decides to attempt to restore the first-best outcome, it must choose how to allocate its limited number of audits among all taxpayers. Namely, the objective of the tax authority at an arbitrary time $t$ is to identify the key set of taxpayers, $\mathcal{M}$, to be audited in order to maximize the global subjective audit probability of the entire set of taxpayers $\mathcal{N}$ for the next period, with $\mathcal{M} \subset \mathcal{N}$, and constrained by a limited number of audits equal to $\lfloor np \rfloor$, where $n$ is the number of taxpayers and $p$ is the true audit rate[6]. Mathematically, the tax authority's problem is given by:

$$\begin{aligned} \max_{\{\mathcal{M}\subset\mathcal{N}\}} \quad & \frac{1}{n}\sum_{i=1}^{n} \hat{p}_{i,t+1}(A_{i,t}, \mathbf{A}_{-i,t}, \cdot) \\ \text{s.t.} \quad & A_{i,t} = 1 \iff i \in \mathcal{M}, \\ & A_{i,t} = 0 \iff i \notin \mathcal{M}, \\ & |\mathcal{M}| \leq \lfloor np \rfloor, \end{aligned} \tag{2.22}$$

where the individual subjective probability for all taxpayers $i \in \{1,2,...n\}$ at time $t+1$ is dependent on whether they have been audited or not ($A_{i,t}$), and dependent on who else was audited or not ($\mathbf{A}_{-i,t}$).

Applying the results from Proposition 2.3 and Proposition 2.4 to Equation 2.22 the solution for the tax authority's maximization problem is straightforward. First, the tax authority is able to compute the vector of optimal individual subsidies ($\boldsymbol{S^O}$). Afterwards, the tax authority's optimal enforcement strategy is to audit the $\lfloor np \rfloor$ taxpayers with the maximal individual subsidy ($S_i^o$) values.

Conclusively, given the presence of social influence and heterogeneous income-productivity levels in the taxpayer network, the tax authority is able to design an optimal enforcement regime adopting the properties of local-average games. It is worth mentioning that the proposed enforcement mechanism is *static* in nature, i.e. it does not depend on time. Nevertheless, the tax authority could simply revise the network structure and update the income-productivity levels next period in order to find the *dynamic* (successive) key target group to audit.

[6]The floor function ($\lfloor np \rfloor$) denotes the greatest integer less than or equal to $np$.

**Taxpayers' optimization problem**

The scope of this paper is to explore the optimal actions from the tax authority's point of view. What is more, the previously introduced enforcement strategy is optimal independently of the taxpayer decision-making process. That is, the optimal audit scheme is heterogeneity-proof with respect to taxpayers' potential expected and non-expected utility theories, biases, intrinsic motives and social interaction effects. Notwithstanding, for the sake of completeness, the taxpayers' optimization problem will be mathematically characterized.

A considerable amount of research has been invested to study the process of self-reported income and tax compliance decision-making. Despite the fact that the first models of tax evasion were based on the expected utility theory, many subsequent theories have challenged the original premise. On the one hand, the seminal idea of Allingham and Sandmo (1972) and modified by Yitzhaki (1974) modeled tax evasion under an expected utility approach. In the original expected utility models, a rational agent receives an exogenous earned income ($I$) and optimizes its expected utility of net income after taxes ($\tau$) and applicable penalties fines ($\phi$). Following, the fraction of declared income $d \in [0, 1]$ is chosen to maximize the following expected utility given a generic von Neumann–Morgenstern utility function $u(\cdot)$:

$$EU = pu(I - \tau dI - \phi\tau[I - dI]) + (1 - p)\ u(I - \tau dI), \tag{2.23}$$

where the taxpayer faces a (perceived) audit probability, ($p$), of being audited and a complementary probability $(1 - p)$ of not being audited. In the first case, the taxpayer's income after taxes and penalty fines would amount to its earned income, minus the taxes paid on declared income, minus the penalty fines applied on undeclared taxes. In the second case, its net income would amount to its earned income minus the taxes paid on declared income. Formally, the necessary and sufficient condition for evasion to take place, i.e. $d > 0$, is:

$$p < \frac{1}{1 + \phi}. \tag{2.24}$$

Nonetheless, this condition is regularly met (Hashimzade et al. (2013)). In this sense, agents should be largely non-compliant. Albeit being a revolutionizing model for public economics, the authors themselves acknowledged that the model considerably overestimated the true tax evasion rates and further research was recommended.

On the other hand, Yaniv (1999) and Bernasconi and Zanardi (2004) proposed non-expected utility theories to attain results which were more consistent with empirical evidence. A commonly accepted representation of non-expected utility theory is given by a value function $V$, defined as:

$$V = \nu_1(p, 1 - p)\upsilon(I - \tau dI - \phi\tau[I - dI]) + \nu_2(p, 1 - p)\upsilon(I - \tau dI), \tag{2.25}$$

where $\nu_1(p, 1 - p)$ and $\nu_2(p, 1 - p)$ are weighting functions that translate the audit and complement probabilities $(p, 1 - p)$ into more general transformations. Further, $\upsilon(\cdot)$ is a payoff-function, which allows for more general representations than the standard utility functions[7]. Notwithstanding, the early non-expected utility models were not able to take into account the effect that other taxpayers may have on one's reference income. From then until now, different theoretical models have been proposed over a wide range of potential utility functions, diverse parameters and novel specifications. An exhaustive survey of tax compliance modeling techniques was gathered by Hashimzade et al. (2013), placing particular interest in models which account for social interaction and non-expected utility theories.

In the current framework, taxpayers optimize with respect to endogenous perceived audit rates. Consider a vector $\mathbf{A}_i := (A_{i,t-1}, A_{i,t-2}, ..., A_{i,t-m})^T \in \{0, 1\}^m$ which records taxpayer $i$'s personal history of audits, where $A_{i,t-s} = 1$, if agent $i$ was audited during the period $(t - s)$, and $A_{i,t-s} = 0$, otherwise. The size of vector $\mathbf{A}_i$ is equal to $m$, the fiscal memory length, which is exogenous and identical for all agents. Individuals compute their own observed frequency of audits, $f$. That is, for each taxpayer $i$ at time $t$, the empirical (historical) probability of being audited is given by:

$$f_{i,t} = \frac{1}{m} \sum_{s=1}^{m} A_{i,t-s}. \tag{2.26}$$

[7] For example, it is commonly assumed that utility functions are concave, i.e. $u'(\cdot) > 0$ and $u''(\cdot) < 0$, which is not a requirement for $\upsilon(\cdot)$ payoff functions.

Gächter and Renner (2018) emphasized that individual belief dynamics in tax compliance are strongly path-dependent with respect to the average past behavior of other players. Taking this remark into consideration, Equation 2.27 defines the updating mechanism of the endogenous subjective audit rate similarly to Pellizzari and Rizzi (2014), while further specifying for a social-norm parameter. Once the social interactions in the network have taken place, each taxpayer updates its heterogeneous, subjective audit rate ($\hat{p}$), which is endogenous and individual-specific. Along these lines, the heterogeneous subjective audit rate *ex post* to the threat-to-audit message for taxpayer $i$ can be expressed as:

$$\hat{p}_{i,t+1} = \frac{1-\omega}{2}\hat{p}_{i,t} + \frac{1-\omega}{2}f_{i,t} + \omega(\alpha_i \bar{\hat{p}}_{i,t}), \tag{2.27}$$

where $\omega \in (0,1)$ is the weight that taxpayers give to the newly acquired information, and $\alpha_i > 0$ is the previously introduced income productivity level. Hence, the subjective audit rate for a given agent $i$ at time $t+1$ may be affected by three different channels. First, taxpayer $i$ takes into consideration its prior belief about its own endogenous audit rate ($\hat{p}_{i,t}$). Second, the taxpayer weighs its own empirical (observed) audit rate ($f_{i,t}$). Third, agent $i$ evaluates the social-norm value of the audit rate in its neighborhood ($\bar{\hat{p}}_{i,t}$) and translates the newly acquired information in terms of its own individual productivity level ($\alpha_i$) by applying the transformation $\alpha_i \bar{\hat{p}}_{i,t}$, where $\alpha_i \bar{\hat{p}}_{i,t} \leq 1$ for all $i \in \{1, 2, ..., n\}$. The weights placed on the first two terms of Equation 2.27 are expressed in terms of $\omega$ for simplicity, given that the results derived in Section 2.4 will depend only on the value of $\omega$[8].

The dynamics of ($\hat{p}_{i,t+1}$) defined in Equation 2.27 describe the post-message (heterogeneous) subjective audit rates of the taxpayers. In the current local-average game context, these heterogeneous subjective audit rates are the probabilities which taxpayers will eventually employ to compute their optimal tax compliance decision. Following, the taxpayer's value function in the current setting is defined by inserting the endogenous subjective probability defined in Equation 2.27 into the generalized model presented in Equation 2.25, as:

$$V = \hat{p}\upsilon(I - \tau dI - \phi\tau[I - dI]) + (1-\hat{p})\upsilon(I - \tau dI). \tag{2.28}$$

Consequently, the agent's optimization problem reduces to maximizing the value function $V$, which is dependent on the endogenous parameter $\hat{p}$, as:

$$\max_{\{d\}} V(\hat{p}, d, I, \tau, \phi, \cdot) \tag{2.29}$$

where agents optimize only over the fraction of declared income $d$, while $I$, $\tau$, $\phi$ and any other given parameters are exogenous to the taxpayer maximization problem. Optimally enhanced audit schemes can directly increase income disclosures (Alm et al., 1993; Slemrod et al., 2001; Kastlunger et al., 2009; Casal and Mittone, 2016). That is, optimal $d$ is monotonically increasing with respect to $\hat{p}$[9]. Since the tax authority is designing a fiscal policy to maximize the subjective audit rate, from the point of view of the tax authority, the optimal audit strategy is independent of the utility (value) function of the taxpayer.

Although this subsection does not fully address the optimal actions from the taxpayer's point of view, further intuition and several explicit solutions to specific models may be found in the literature mentioned below. Some of the non-expected utility theories employed in tax evasion research are: prospect theory (Kahneman and Tversky (1979); Yaniv (1999)), rank-dependent expected utility theory (Quiggin (1982)), Choquet expected utility theory (Chateauneuf (1994)) and cumulative prospect theory (Bernasconi and Zanardi (2004)). Moreover, different explanations have been offered to justify the adherence of expected and non-expected utility models with available empirical evidence: regret and disappointment (Loomes and Sugden (1987)), uncertainty (Kischka and Puppe (1992)), non-additive probabilities (Chateauneuf (1994)), risk aversion (Bernasconi (1998)), ambiguity (Snow and Warren (2005)), over-weighting the detection probability (Arcand and Rota-Graziosi (2005)) and endogenous reference levels (Rablen (2010)). Furthermore, social interaction models have attempted to categorize diverse communal effects such as: psychic costs of tax evasion (Baldry (1986); Gordon (1989)), perception of fairness (Cowell and Gordon (1988)), social customs (Myles and Naylor (1996)), tax morale (Dell'Anno (2009)), and public goods (Pellizzari and Rizzi (2014)). In addition, to mention a few utility functions which have been tested, one may identify: exponential (Hokamp and Pickhardt (2010)), logarithmic (Hashimzade et al. (2013)), and power-law (Pellizzari and Rizzi (2014)) utility functions.

[8]Indeed all the weights in Equation 2.27 may be different from one another, as long as all three weights are between zero and one, not including, and the sum of all three weights adds up to one.

[9]For a specific example of said directly proportional relation, please refer to Chapter 1 of the current dissertation.

## 2.4 Policy implementation and robustness analysis

Computer simulation techniques, such as agent-based models, have been proven to be reliable complements for testing game-theoretic hypothesis. Such techniques encompass four broad components: behavior, occupational variation, geographic characteristics and social influence. Behavior denotes the capability to recreate agents of various types and notorious diversity. Occupational variation differentiates individual income and productivity levels. Geographic characteristics assess the location of an agent inside a network structure. Social influence dynamics keep track of connections, indirect spillover effects and social-norm values. When there are costs of forming a link between two nodes in a network-formation model, individuals try to minimize such connection costs. Although local-average games provide a solid workhorse model to simulate social interactions, it is important not to ignore *homophily* behavior. That is, individuals tend to connect with others who have similar productivity levels, reducing their dis-utility costs of failing to conform with the social norm of their peers. Strictly speaking, individuals want to minimize the difference between their outcomes and those of their neighborhood (social norm). Consequently, this section presents an implementation of the hypothesized optimal audit policy, where agents create links among themselves in a first stage, and where homophily behavior emerges.

The game works as follows. In *Step 1* the initial state of the agents (taxpayers) is delimited by endowing each individual with a set of parameters. At the beginning of *Step 2* the tax authority sends a message to all taxpayers aiming to incentive positive taxpayer behavior and persuade individuals to disclose their income. Once the players have been parameterized and the message has been received, *Step 3* consists in creating links between players to create a connected network. We say a network is connected if there exists at least one path between any two arbitrarily chosen nodes. Moreover, we say two agents are 'neighbors' if they share a direct link between each other. *Step 4* pertains to agent interaction and social influence in the sense of Hokamp and Pickhardt (2010) and Andrei et al. (2014), where taxpayers exchange information with their neighbors and update their subjective audit rate. During *Step 5*, individuals maximize their expected utility by choosing their optimal declared income. In *Step 6* the tax authority, or social planner, applies its optimal audit strategy intending to maximize the global subjective audit rate; which in turn maximizes the aggregate level of income declarations and fiscal revenues. Afterwards, the game loops back to *Step 4*, where individuals share information once more and repeat the process indefinitely. The outline of the game's dynamics is depicted in Table 2.1.

Table 2.1: Outline of the dynamic game on tax evasion

| Step | Description |
|---|---|
| *Step 1* | Agents (taxpayers) are parameterized. |
| *Step 2* | The tax authority emits a threat-to-audit message. |
| *Step 3* | The social network is built. |
| *Step 4* | Agents hold social interactions and share information. |
| *Step 5* | Agents choose their optimal declared income. |
| *Step 6* | The tax authority applies its optimal audit strategy. |
| *Loop* | Go back to *Step 4*. |

### Agent parameters

All taxpayers are endowed with an initial set of parameters as specified in Table 2.2. The gross income ($I$) is exogenous and individual-specific. Tax rates ($\tau$), penalty rates ($\phi$), true audit rates ($p$), number of taxpayers ($n$), fiscal memory length ($m$), a weighting parameter ($\omega$) and a taste for conformity ($\theta$) are exogenous and societal, i.e. they are identical for all agents. Fiscal memory refers to the number of time periods which an agent can recall into the past. The parameter $\omega$ refers to the weight that agents give to new information received from other taxpayers. The taste for conformity measures the preference of an individual to follow the social norm. Subjective audit rates ($\hat{p}$) are endogenously computed and may vary among individuals. The declared income ($d$) is derived endogenously by each individual. Finally, the global subjective audit rate ($q$) is the mean value of the subjective audit rates among all taxpayers $i \in \{1, 2, \ldots, n\}$ in the network.

Table 2.2: Nature and type of employed parameters

| Parameter | Exogenous | Endogenous | Societal | Individual |
|---|---|---|---|---|
| $I$: Earned income | X | | | X |
| $\tau$: Tax rate | X | | X | |
| $\phi$: Penalty rate | X | | X | |
| $m$: Fiscal memory length | X | | X | |
| $n$: Number of taxpayers | X | | X | |
| $\omega$: Weighting parameter | X | | X | |
| $\theta$: Taste for conformity | X | | X | |
| $p$: True audit rate | X | | X | |
| $\hat{p}$: Subjective audit rate | | X | | X |
| $d$: Declared income | | X | | X |
| $q$: Global subjective audit rate | | X | X | |

Formally, the value of $q \in [0,1]$ is computed as $q = \frac{1}{n}\mathbf{e}^\top \hat{\mathbf{p}}$, where $\mathbf{e} := (1,\dots,1)^\top \in \mathbb{R}^n$ is a column-vector of ones with dimension $n$, and $\hat{\mathbf{p}} := (\hat{p}_1, \hat{p}_2, ..., \hat{p}_n)^\top$ is the vector of subjective audit rates of all taxpayers in the network, with $\hat{p}_i \in [0,1]$ for all $i \in \{1,2,\dots,n\}$. From a game-theoretic point of view, the objective of the tax authority in our context is to maximize the global (mean) subjective audit rate ($q$) across the entire network of taxpayers.

### Simulating taxpayer behavior

Once the taxpayers have been parameterized (*Step 1*) and the tax authority has emitted its threat-to-audit message (*Step 2*), then the network formation process takes place (*Step 3*). The goal in *Step 3* is to create a network structure which accounts for group cohesiveness (*homophily*)[10]. Group cohesion may be understood as the force or action of individuals with common attributes to link together and form a social group, subsequently linking the group to other members of society. In the current paper, cohesiveness is based primarily on wealth. That is, linkage probability between two taxpayers is correlated with the similarity of their income levels.

In such a way, the first step is to give each agent a $(x, y)$ node-position in a Cartesian coordinate system. First, taxpayers sample their income from a uniform distribution $I \sim U(\underline{I}, \overline{I})$, where $\underline{I}$ is the lowest possible income and $\overline{I}$ the highest one. Following, agents set their $y$-axis coordinate as $y_i = (I_i - \underline{I})/\overline{I}$, hence $y_i \sim U(0,1)$. Afterwards, the $x$-axis coordinate is set randomly and accordingly to $x_i \sim U(0,1)$. The $x$-axis coordinate accounts for all the non-wealth characteristics of the taxpayer. The second step is to compute all the Euclidean distances between nodes and selecting a threshold such that the total number of links is given by the arbitrarily fixed number of agents ($n$) and the expected node-degree ($\mu$). Following, a link will be formed between two nodes only if their Euclidean distance is smaller than or equal to the aforementioned threshold. Thereafter, the resulting graph includes $n\mu$ links among $n$ nodes. The third step is to connect each isolated node (if any) to its closest neighbor in the Euclidean sense. Lastly, in case the graph is disconnected (more than one isolated cluster exists) a randomly selected node from the largest cluster will form a link with a randomly chosen agent from an isolated cluster; the process will repeat until no isolated cluster remains. In consequence, after row-normalization, the resulting graph corresponds to the network $\mathbf{g}$ and the row-normalized adjacency matrix $\mathbf{G}$.

The intuition behind the *cohesive* geographical distribution of nodes is as follows. Taxpayers are aligned in function of their income in the $y$-axis and according to all other individual characteristics in the $x$-axis. Hence, agents connect to those who are the most similar to them, i.e. their nearest geographical neighbors. Lastly, the minimal amount of additional links are created in order to secure that there are no isolated nodes and that the network graph is connected. The resulting structure is similar to the *preferential-attachment* and *node-fitness* models proposed by Gamannossi degl'Innocenti and Rablen (2020).

**Remark 2.1.** *A taxpayer positioned in a (x, y) plane will link with its peers located inside a circumference centered at itself and of radius equal to a certain threshold. Another aspect to consider is the impact of*

[10] For different types of cohesive and non-cohesive networks employed to model tax evasion refer to Andrei et al. (2014), Garcia Alvarado (2019) and Gamannossi degl'Innocenti and Rablen (2020).

*asymmetry in the taxpayer's awareness space. That is, an agent may attempt to link exclusively with peers of similar wealth (its vision space would be an horizontal ellipse in the plane) or exclusively with peers which share similar x-axis characteristics (its vision space would be a vertical ellipse in the plane). Nonetheless, the outcomes of the audit strategy are invariant of geometrical awareness spaces as long as the expected number of links per node ($\mu$) remains unaltered.*

**Diverse network-based audit strategies**

In the following, denote the optimal enforcement regime derived in Section 2.3 as the *Subsidy* strategy. A natural question to answer would be to compare the efficiency of the proposed *Subsidy* strategy against other network-based strategies. This section examines several alternative well-known centrality measures, commonly employed in game theory. *Betweenness* centrality is related to the connectivity and the level of control a node exerts over the information flow. *Closeness* centrality considers the shortest paths between nodes and measures the efficiency with which information is disseminated through a network. *Degree* centrality refers to the number of links or connections that a certain individual holds inside the network. Eigenvector centrality (*Eigencentrality*) measures a node's importance as a consequence of being linked to other important nodes; sometimes it is associated with the prestige of an individual inside a group. Denote *Intercentrality* as the network-based strategy proposed by Ballester et al. (2006) for local-aggregate games, where nodes are targeted proportionally to their Bonacich centrality. Finally, a *Random* strategy is tested, where a group of randomly selected taxpayers is audited.

Consider a benchmark scenario with parameters fixed to $n = 1000$ individuals, an expected number of links per agent of $\mu = 8$, a weight parameter for new information of $\omega = 0.34$, a taste for conformity of $\theta = 1$, i.e. $\lambda = 0.50$, and a true audit rate of $p = 5\%$. It should be kept in mind that, since individual true audit rates are dependent on the specific audit scheme, the current section understands $p$ as the 'average' true audit rate within the network. Each audit strategy was tested 100 times, and for 40 fiscal periods as in Andrei et al. (2014). The mean time series of the global subjective audit probability ($q$) attained by each audit strategy is presented in Figure 2.1. The proposed *Subsidy* (S, closed dot) audit scheme realized the highest steady state convergence; followed in order by *Degree* (D, open dot), *Random* (R, solid line), *Intercentrality* (I, triangle), *Betweenness* (B, plus), *Closeness* (C, asterisk) and *Eigencentrality* (E, cross). Not only the proposed *Subsidy* strategy obtained the best results, but it was one of the only two network-based strategies that surpassed the naive random audit scheme.

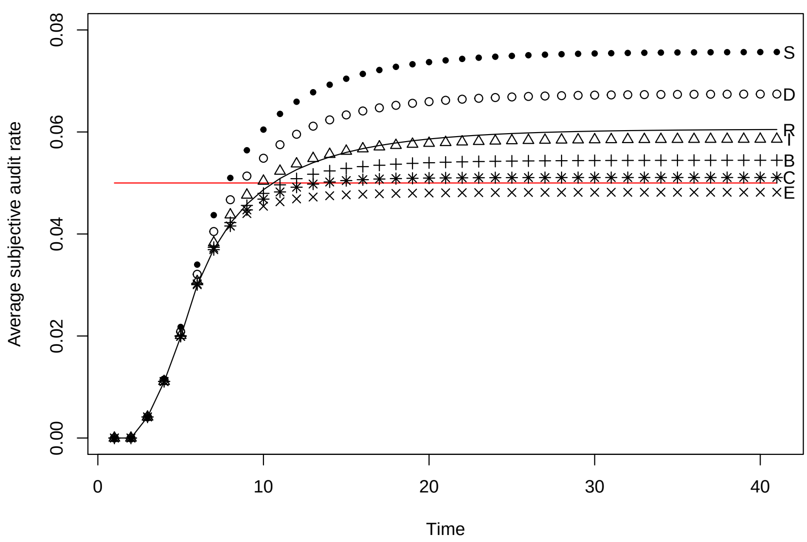



Figure 2.1: Convergence level of the global subjective audit rate ($q$) for different audit strategies: *Subsidy* (S), *Degree* (D), *Random* (R), *Intercentrality* (I), *Betweenness* (B), *Closeness* (C) and *Eigencentrality* (E). The proposed *Subsidy* strategy secured the highest average convergence level.

The violin plots[11] in Figure 2.2 show the distributions of the convergence levels of the global subjective audit rate ($q$) attained by each audit scheme. Once again, it is clear to see that the proposed audit mechanism consistently achieves the best results. Surprisingly, the *Degree*-based mechanism also reached considerably high levels for some runs, albeit inconsistently and with large fluctuations. Nonetheless, the variability of results for the *Degree* scheme is remarkably high. A two-sample *t-test* confirmed that the *Subsidy* strategy outperformed the *Degree* scheme at a 0.001% confidence level. Notwithstanding, the fact that the *Subsidy* strategy could be matched under certain circumstances suggests a plausible limitation of enforcing binary audits instead of real-valued subsidies.

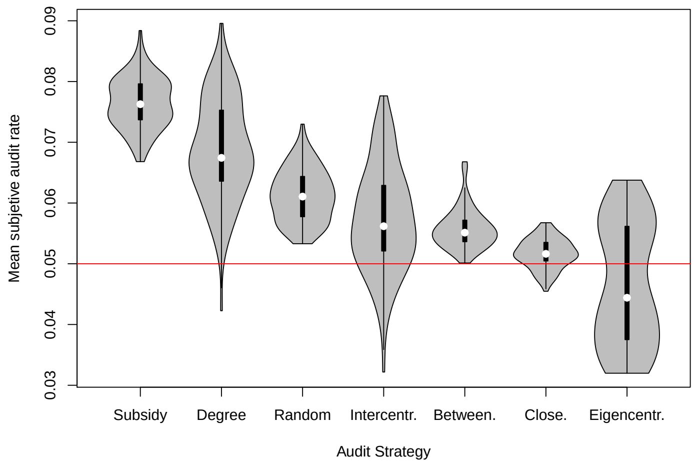


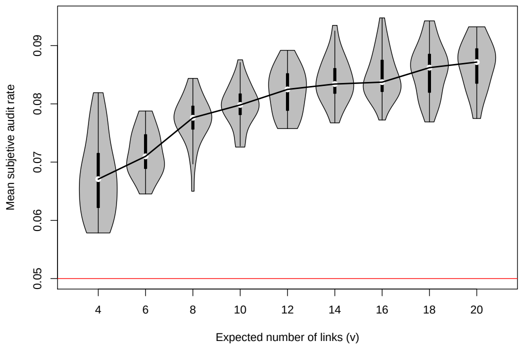

Figure 2.2: Comparison of the convergence level distributions of the mean (global) subjective audit rate ($q$) attained by diverse audit schemes. The proposed *Subsidy* strategy obtained the highest convergence levels. Moreover, the average value of the global subjective audit rate from the *Subsidy* strategy outperformed the average value of the global subjective audit rate of the second-best strategy at a 0.001% confidence level.

### Parameter effects and robustness

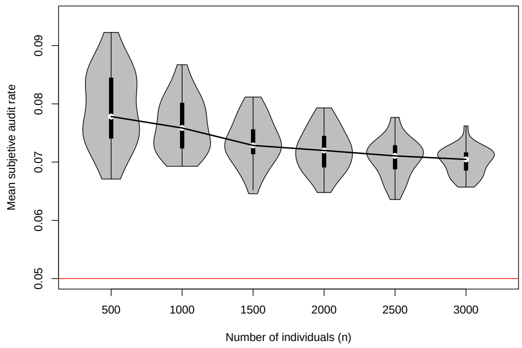
The optimal audit strategy derived in Section 2.3 is robust to individual heterogeneity with respect to potential utility functions and non-expected utility theory decision processes. Notwithstanding, the efficiency of said audit scheme may vary according to the number of individuals ($n$), the average node-degree ($\mu$), the density of the network ($\delta$), the (average) true audit rate ($p$), the attention placed to new information ($\omega$) and the taste for conformity ($\theta := \lambda/(1-\lambda)$). In the interest of assessing the role of each parameter, *ceteris paribus*, consider the original benchmark scenario: $\{n = 1000,\ \mu = 8,\ \omega = 0.34,\ p = 5\%,\ \lambda = 0.50\}$. To determine how the efficiency of the optimal audit strategy is affected by each variable, a series of simulations were reproduced calibrating each parameter one at a time.

The results from six different parameter examinations are presented in Figure 2.3. Figure 2.3a shows how the mean (global) subjective audit rate ($q$) proportionally increases with respect to the expected number of links per node ($\mu$); analogous to considering the total number of links. In contrast to this effect, Figure 2.3b presents how the mean subjective audit probability is inversely proportional to the total number of individuals ($n$). Also, as noted by Galbiati and Zanella (2012), the dispersion of individual heterogeneity is larger in smaller groups of taxpayers. Intuitively, it would be interesting to test the effect of both parameters simultaneously. Controlling for a constant network density, that is $\delta = v/n$, Figure 2.3c illustrates how the convergence level of the global subjective audit rate reaches a steady state for $n \geq 1500$. A series of *t-tests* confirmed that, for all values of $n \in \{1500, 2000, 2500, 3000\}$, the null hypothesis (difference in means equals zero) cannot be rejected. Further analysis in Figure 2.3d shows a non-monotonic effect of the taste for conformity on the convergence level of the global subjective audit probability; nonetheless, the strategy achieves positive outcomes for all tested values of $\lambda \in [0.1, 0.9]$. This

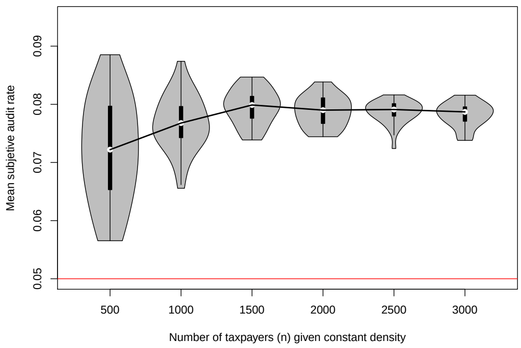
[11] Violin plots are similar to box plots, with the addition of displaying the kernel distribution of the sample.



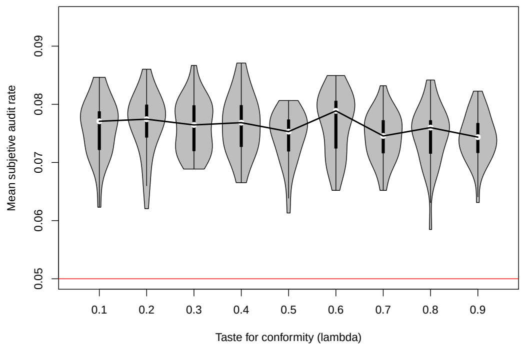

(a) Parameter: Expected node-degree ($\mu$)



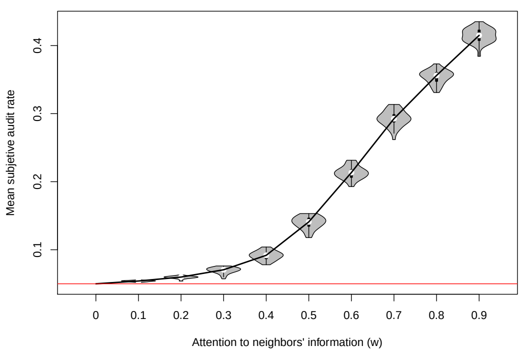

(b) Parameter: Number of individuals ($n$)



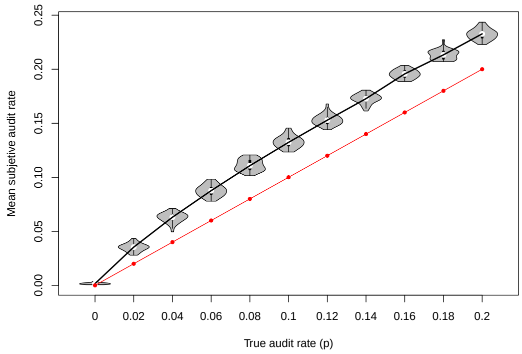

(c) Parameter: Constant density ($\delta$)




(d) Parameter: Taste for conformity ($\lambda$)




(e) Parameter: Attention to neighbors ($\omega$)




(f) Parameter: 'Average' true audit rate ($p$)

Figure 2.3: Testing the effect of key parameters on the mean subjective audit rate, *ceteris paribus*. Parameters considered: (a) number of individuals ($n$), (b) expected node-degree ($\mu$), (c) constant network density ($\delta$), (d) taste for conformity ($\lambda$), (e) attention placed on new information ($\omega$), and (f) 'average' true audit probability ($p$).

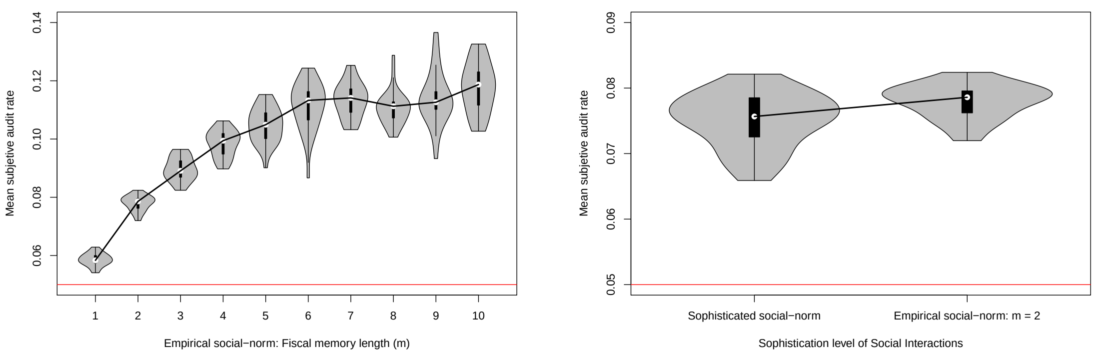
non-monotonic effect follows in line with the results presented by Ushchev and Zenou (2020). Another important parameter is the attention level that agents place on the new information acquired from their neighbors ($\omega$). Figure 2.3e displays a prominent non-linear relation between the attention level and the steady state of the mean subjective audit probability. On the one hand, if agents place no attention on new information, then the proposed optimal audit strategy would be inefficient. On the other hand, if agents place full attention on new information and disregard their own priors and empirical experience, then the tax authority could reach remarkably high steady-state levels of the mean subjective audit rate. At last, Figure 2.3f compares the attained convergence level of the mean subjective audit probability against the (average) true audit rate ($p$) for several values of $p \in [0\%, 20\%]$. Following, the optimal audit scheme manages to realize a global subjective audit rate ($q$) significantly larger than the (average) true audit probability ($p$) for any non-zero audit rate.

**Extension: Unsophisticated social interactions**

Onu and Oats (2015) noted that not always taxpayers are willing or able to share sophisticated information among their peers. Following, the current paper defines a secondary communication channel which limits to simple past observations and abstains from appealing to stronger assumptions. Hence, taxpayers refrain from communicating their expected audit probabilities and only share their empirical frequency of being audited, $f$, during social interactions. The latter is a noisy estimate of the former, yet plausibly it is more realistic to share an observed frequency rather than a computed probability. Consequently, agents learn the social-norm value of the empirical frequency of audits in their neighborhood, i.e. the average $f$-value of their neighbors at time $t$:

$$\bar{f}_{i,t} = \sum_{j=1}^{n} g_{ij} f_{j,t}. \tag{2.30}$$

A comparison between sharing sophisticated social-norm messages and un-sophisticated ones is represented in Figure 2.4. Specifically, Figure 2.4a shows the mean subjective audit rate attained by sharing empirical social-norm messages ($\bar{f}$) and how the fiscal memory length ($m$) plays a positive role in raising the equilibrium levels. The longer the fiscal memory, the wider the window of opportunity for the tax authority to design an optimal audit scheme. In particular, Figure 2.4b demonstrates how, for a memory length $m \geq 2$, the outcomes of sharing un-sophisticated messages are at least as good as the ones achieved by enabling sophisticated communication among taxpayers.



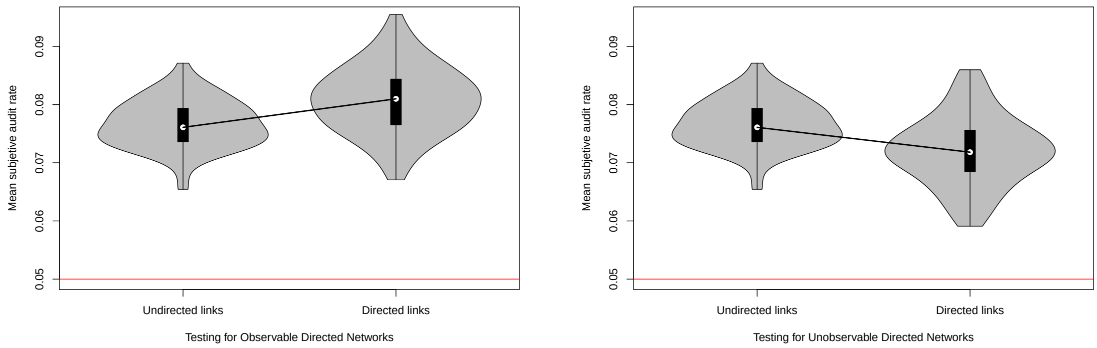

(a) Sharing *empirical* social-norm messages (b) Sophisticated and un-sophisticated messages

Figure 2.4: For $m \geq 2$ the outcome is at least as good as when sophisticated communication is enabled.

**Further extensions and robustness checks**

**Directed and undirected taxpayer links**

A recurrent question in network theory is whether the links between agents are directed or undirected. In the former, information flows in a single direction; while in the latter, information flows bilaterally. The previously introduced network $\mathbb{g}$ is undirected and symmetric, which implies that $g_{i,j} = 1 \iff g_{j,i} = 1$ and $g_{i,j} = 0 \iff g_{j,i} = 0$. Define a directed network $\mathbb{g}'$, $\mathbb{g}' \subset \mathbb{g}$, where all taxpayer links are directed and no link is bilateral. That is, if $g'_{i,j} = 1$ then $g'_{j,i} = 0$ for all $\{i, j\} \in \{1, 2, ..., n\}$, with $g'_{i,i} = 0$ for all $i \in \{1, 2, ..., n\}$. Figure 2.5 illustrates two different scenarios of the directed network: whether the tax authority can distinguish between directed and undirected links, or not. If the social planner can observe the direction of the taxpayer links in network $\mathbb{g}'$, Figure 2.5a shows that the optimal audit strategy would be more effective in the case of directed networks, and a two-sample *t-test* confirmed it at a 0.01% confidence level. However, if the tax authority would not be able to observe the link direction, it would be forced to solve the optimization problem employing the undirected network $\mathbb{g}$. Figure 2.5b shows that, although the strategy still attains large convergence levels of the mean subjective audit rate, the outcome of the audit enforcement scheme is lessened. As a remark for both conditions (Figures 2.5a and 2.5b), in case some links are allowed to be bilateral, the outcome dispersion would take an intermediate position between the two illustrated distributions, respectively.




(a) The tax authority can distinguish the direction of the taxpayer links.

(b) The tax authority can not distinguish the direction of the links and treats them as undirected.

Figure 2.5: Comparison between directed and undirected taxpayer links.

### Initial subjective audit rate

Alm et al. (2009) found that the outcome of certain audit enforcement schemes may be dependent on the initial perception of taxpayers regarding audit frequencies. Notwithstanding, computer simulations suggest that the optimal audit strategy derived in this paper is invariant to the taxpayers' initial subjective audit rate distribution at time $t = 0$. Denote the initial distribution of subjective audit rates as $\hat{p}_{i,t=0} \sim U(0, \rho)$, for all taxpayers $i \in \{1, 2, ..., n\}$, where $\rho$ is the maximal possible value for the initial subjective audit rate. Figure 2.6a shows that the steady state dispersion is invariant for any value of $\rho \in \{0, 0.1, 0.2, \ldots, 0.9, 1\}$. That is, the initial distribution of taxpayer subjective audit rates ($\hat{p}_{i,t=0}$) plays a negligible effect on the convergence level of the mean subjective audit rate. Following, the assumption that taxpayers must know the original (average) true audit rate emitted by the government may be cautiously relaxed.

### Non-cohesive networks

An important remark may be stated regarding the cohesiveness of the taxpayer network structure. Following the precedents by Andrei et al. (2014), Gamannossi degl'Innocenti and Rablen (2020) and Ushchev and Zenou (2020), this paper models social networks of tax evasion considering homophily behavior and cohesive relations among individuals. That is, agents tend to form links with peers who are akin to them and with whom they share similar traits and characteristics. Nonetheless, Figure 2.6b shows the lack of efficiency attained by the *Subisdy* audit scheme tested over an Erdos-Renyi random graph, which is well-known to have no cohesion among nodes. In an Erdos-Renyi random graph model, every pair of nodes has the same probability of forming a link, irrespective of any individual-specific characteristics. The result is a network which has no cohesiveness nor homophily. Consequently, the optimal network-based audit strategy proposed in the current paper would be efficient exclusively for taxpayer networks which retain some cohesive behavior.

Economists and sociologists have long recognized the presence of homophily and segregation in social networks (Schelling, 1969; Diprete et al., 2011). In general, many real-world networks present assortative mixing, clustering, degree correlation, small-world phenomenon and power law degree distributions. That is, network formation is seldom purely random. On the one hand, individuals actively make the choice to befriend others who are like themselves (McPherson et al., 2001). One the other hand, homophily and segregation may emerge as a consequence of linking costs (de Martí and Zenou, 2017). If we assume that two agents from a same community always face a low cost of linking, even if the probability of meeting is random, the probability of forming a link would be greater between two more similar players than between two less similar. Empirically, social networks do not form purely at random (Moody, 2001; Currarini et al., 2009) and social links in the real world are typically driven by homophily and similarity on socially significant attributes (Melamed et al., 2020). Furthermore, in our context, it would be difficult to imagine that players would exchange confidential tax information with other players they met randomly and with whom they do not share social ties. As a consequence, the cohesion assumption is relatively weak in the current framework.

#### Attentiveness to the threat-to-audit message

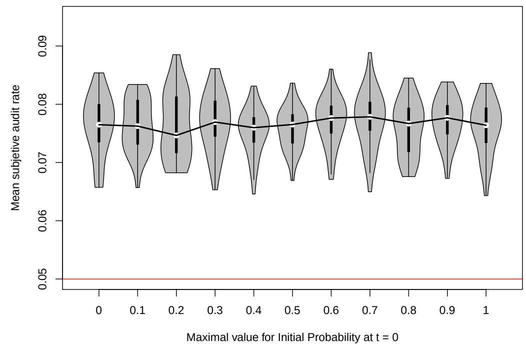
The design and implementation of threat-to-audit messages as a tool to curb income under-reporting is a well-studied topic in public economics (Slemrod et al. (2001); Kleven et al. (2011); Pomeranz (2015); Whillans et al. (2016); Lopez-Luzuriaga and Scartascini (2019)). For this reason, an extension was modeled to measure the performance of the optimal audit strategy whenever taxpayers ignore the threat-to-audit message emitted by the tax authority.

Define $\eta$ as the attentiveness of taxpayers. Following, after the message is sent, a fraction $(1-\eta)$ of agents decide to ignore the message and opt to keep their heterogeneity (income-productivity) levels unchanged. That is, $\alpha_i = 1$ if $i$ belongs to the fraction of agents who ignored the message[12]. Nonetheless, the tax authority does not know who (if any) decided to ignore the message. Therefore, the targeted taxpayers to be audited are derived as usual. Figure 2.6c shows a conclusive relationship between the taxpayers' attentiveness and the efficiency of the audit strategy. Ostensibly, as the fraction of agents who listens to the message decreases, the performance of the optimal audit scheme diminishes as well. This result sheds light on the long-standing assumption that threat-to-audit messages should be credible and binding in order to reinforce taxpayer behavior.

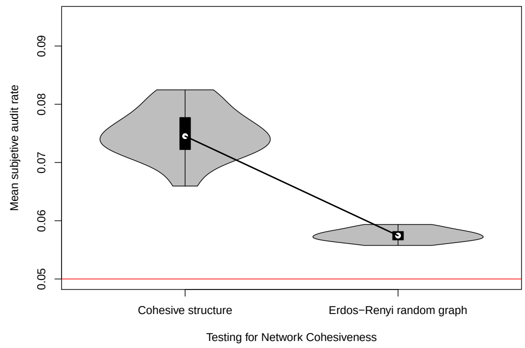
#### Imperfect omniscience by the tax authority

As considered in Gamannossi degl'Innocenti and Rablen (2020), the last extension appraises the value of information about the true taxpayer social network from the tax authority's point of view. So far, the working assumption on the current paper has been that the tax authority is able to observe all the links between taxpayers. To relax this assumption, denote as $\zeta$ the fraction of links that the tax authority can unequivocally learn, while it completely ignores the other $(1-\zeta)$ fraction of links. Hence, for an arbitrary $\zeta$, the tax authority computes the optimal vector of subsidies ($\mathbf{S}^o$) using its partially-known network, albeit taxpayers continue to share information across the true complete network. Figure 2.6d shows a positive and non-linear relation between the tax authority's omniscience level and the efficiency of the proposed audit scheme. Moreover, for a fraction $\zeta > 20\%$ the optimal audit strategy already shows some improvement compared to the true audit rate. Furthermore, if the tax authority unequivocally knows more than 35% of the true links, i.e. $\zeta > 0.35$, the proposed audit scheme outperforms random auditing and most of the alternative network-based policies in the simulations. Consequently, the optimal audit strategy presented in this paper could potentially achieve *better-than-most* outcomes even with just a share of observable taxpayer links. Finally, according to the simulations, the strategy may accomplish its full potential for any value of $\zeta > 0.70$. Hypothetically, if the tax authority could unequivocally observe more than 70% of the true links, it would be in position to devise and enforce the optimal audit strategy proposed in this paper. Notwithstanding, the costs and plausibility of observing either 35% or 70% of the taxpayer links remain open questions.

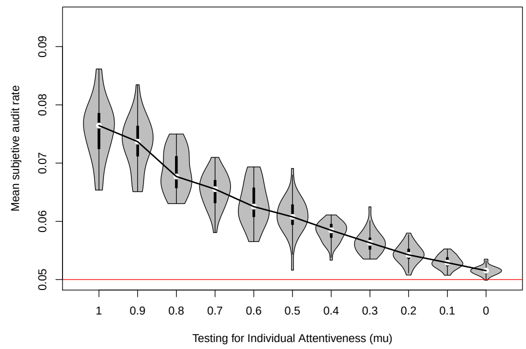
[12] Analogously, $1-\eta$ may be considered as the fraction of taxpayers who, by any reason, cannot compute their own heterogeneity level $\alpha_i$, and opt to keep their initial value of $\alpha_i = 1$.



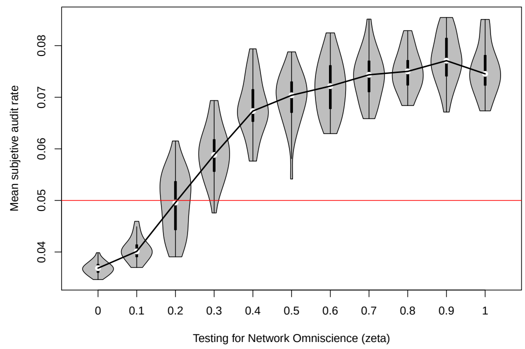

(a) Effect of the initial subjective audit probability




(b) Cohesive and non-cohesive networks




(c) Attention placed to the threat-to-audit message




(d) Tax authority's omniscience of the network

Figure 2.6: Outcomes of the mean (global) subjective audit rate by relaxing several key assumptions: (a) varying initial distributions of the subjective audit rate, (b) the difference between cohesive and non-cohesive networks, (c) the level of attention placed on the tax authority's threat-to-audit message, and (d) the fraction of links that the tax authority can unequivocally observe.

## 2.5 Conclusions

### Policy implications

A number of relevant policy implications may be deduced from the research laid out in this paper. First, there is a sizable room for action for threat-to-audit messages and analogous techniques to curb income under-reporting. The present paper studies how the tax authority may influence taxpayer attitudes as in Whillans et al. (2016), while keeping in close attention the correct manner to emit messages proposed by Alm et al. (2009) and Salmon and Shniderman (2019). As in Scartascini and Castro (2015), the current paper also shows that the effectiveness of these messages is only consolidated after corresponding measures are introduced (i.e. not lying to the citizens and targeting taxpayers according to the emitted threat-to-audit message). The present study considers income levels as the most reliant *observable/estimable* individual-specific predictors of tax payments in money terms, as evidenced in Alm, Jackson and McKee (1992). Nonetheless, there is no need to assume income as the best and only dimension to be treated in the threat-to-audit messages. The tax authority may aim to target any heterogeneous characteristic which is individual-specific. In fact, the tax authority should target the dimension which it believes will encourage taxpayers to increment their income disclosures the most. Additionally, the current study extends the notions of optimal network-based strategies from Hashimzade et al. (2016) and elucidates a plausible manner in which the tax authority may re-establish the path-dependent aggregate tax-compliance level discussed by Gächter and Renner (2018). Moreover, the optimal strategy proposed herein targets taxpayers in function of the network structure as in Drago et al. (2020) and Gamannossi degl'Innocenti and Rablen (2020). Consequently, the present paper sheds light on the potential benefits of investing in tools and techniques in order to acquire further taxpayer information, which could help the tax authority build accurate taxpayer social networks.

**Concluding remarks**

This paper derives an optimal two-step audit strategy, where a threat-to-audit message is emitted by the tax authority in the first step. Said message provides a measurable *ex post* heterogeneous productivity amid taxpayers. In the second step, the heterogeneity condition allows the tax authority to devise an optimal enforcement regime, derived by means of game-theoretic techniques. Consequently, the proposed optimal audit scheme targets the group of taxpayers who, by being audited, triggers a chain reaction of spillover effects which maximizes the global (mean) subjective audit rate across the entire network. Moreover, a unique Nash Equilibrium is characterized in terms of individual productivity levels and the network structure.

This study presents the first game-theoretic optimal audit strategy which is robust to expected and non-expected utility theories, taxpayer heterogeneity and irrespective of any utility function the individuals may attempt to optimize in their decision-making processes. Furthermore, the tax authority may implement the strategy indifferent to whether taxpayers are fully-rational or not. Additionally, a series of computer taxpayer simulations provided supplementary robustness checks for the proposed audit scheme. The optimal strategy is more effective in denser taxpayer networks, invariant to the taste for conformity level, robust to large numbers of taxpayers given a constant network density, and where the outcome efficiency is proportional to the degree of attention that taxpayers place on the new information acquired from their neighbors. Moreover, the audit strategy is robust to un-sophisticated communication during social interactions, and it is applicable for any non-zero (average) true audit rate. Ultimately, the simulation results indicate that, even if only a potentially small fraction of links are observable, the tax authority may still design a *better-than-most* audit strategy.

Despite the substantial robustness of the game-theoretic model, there are a few inherent limitations which should not go unmentioned. The proposed strategy imposes a degree of cohesiveness among taxpayers and assumes that at least some type of social interaction takes place every period among individuals. Further, the model requires at least a fraction of taxpayers to listen and believe the threat-to-audit message, and to take into consideration the new information acquired from their neighbors. Also, taxpayers are expected to be able to get a fair idea of their relative income heterogeneity with respect to their society. Lastly, the tax authority may be unable to accurately estimate income heterogeneity levels, observe links, and it is limited to enforce discrete $\{0, 1\}$ audits instead of allocating real-valued optimal interventions. This paper calls for further research in game-theoretic approaches to tax evasion. It is crucial to delve deeper into the process of social interactions among taxpayers and to investigate the possible incurred costs of acquiring additional information in order to build accurate taxpayer social networks.

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## Appendix of Chapter 2

### Propositions

*Proof of Proposition 2.1.* Employing the definition of Bonacich centrality (Bonacich, 1987) one can reinterpret the $n \times n$ matrix $(1-\lambda)[\mathbf{I}-\lambda\mathbf{G}]^{-1}$ as:

$$(1-\lambda)(\mathbf{I}-\lambda\mathbf{G})^{-1} = (1-\lambda)\sum_{k=0}^{\infty}\lambda^k\mathbf{G}^k, \tag{2.31}$$

where the Bonacich centrality is well-defined only if $\lambda < 1/\mu_1(\mathbf{G})$, where $\mu_1(\mathbf{G})$ is the largest eigenvalue of $\mathbf{G}$. In particular, given that $\mathbf{G}$ is row-normalized and with non-negative entries, the spectral radius of $\mathbf{G}$ is equal to one, and so $\mu_1(\mathbf{G}) = 1$. Following, $(1-\lambda)(\mathbf{I}-\lambda\mathbf{G})^{-1}$ is well-defined for any $\lambda \in [0,1)$.

Moreover, given that $\mathbf{G}$ is row-normalized, then $\mathbf{G}^k$ is also row-normalized for any integer $k$. Define $\mathbf{e} := (1,\ldots,1)^\top \in \mathbb{R}^n$ as a column-vector of ones with dimension $n$. Since $\mathbf{G}^k$ is row-normalized, one has:

$$(1-\lambda)(\mathbf{I}-\lambda\mathbf{G})^{-1}\mathbf{e} = (1-\lambda)\sum_{k=0}^{\infty}\lambda^k\mathbf{G}^k\mathbf{e} = (1-\lambda)\sum_{k=0}^{\infty}\lambda^k\mathbf{e}.$$

Furthermore, applying the properties of geometric series with $\lambda \in [0,1)$, one can obtain:

$$(1-\lambda)(\mathbf{I}-\lambda\mathbf{G})^{-1}\mathbf{e} = (1-\lambda)\frac{1}{(1-\lambda)}\mathbf{e} = \mathbf{e}.$$

Therefore, $(1-\lambda)(\mathbf{I}-\lambda\mathbf{G})^{-1}$ is also row-normalized for any given $\lambda \in [0,1)$.

□

*Proof of Proposition 2.2.* Given that the matrix $\mathbf{G}$ is row-normalized and with non-negative entries, the spectral radius of $\mathbf{G}$ is equal to one. That is, the largest eigenvalue of $\mathbf{G}$ is equal to one. Following, the $n \times n$ matrix $(1-\lambda)[\mathbf{I}-\lambda\mathbf{G}]^{-1}$ is well-defined and row-normalized for any $\lambda \in [0,1)$. Therefore, the existence and uniqueness of the Nash Equilibrium is guaranteed for any $\lambda > 0$ such that $\lambda < 1$, or analogously for any $\lambda$ such that $\frac{\lambda}{1-\lambda} > 0$.

□

*Proof of Proposition 2.3.* Undoubtedly, the proof of Proposition 2.3 is extensive and mathematically sophisticated, to the point that it is practically impossible to replicate it in this paper without falling to the brink of plagiarism. That is why, for the purposes of the current doctoral thesis, we have decided to limit ourselves to referring to the original work where this result was published for the first time.

Proof: Ushchev and Zenou (2020).

□

*Proof of Proposition 2.4. Idem*, the latter comment applies for the proof of Proposition 2.4

Proof: Ushchev and Zenou (2020).

□

**Claims**

*Proof of Claim 2.1.* Substituting the result from *Proposition* 2.3 into the definition of $\hat{\mathbf{p}}^o$ in *Proposition* 2.4 the first-best outcome $\hat{\mathbf{p}}^o$ is restored whenever the social planner endows individuals with the following subsidy/tax per unit of effort:

$$\boldsymbol{S}^o_{\hat{p}} = \frac{\lambda}{1-\lambda}\boldsymbol{G}^\top(\boldsymbol{I}-\boldsymbol{G})\left[\boldsymbol{I}+\frac{\lambda}{1-\lambda}(\boldsymbol{I}-\boldsymbol{G})^\top(\boldsymbol{I}-\boldsymbol{G})\right]^{-1}\boldsymbol{\alpha},$$

where $\boldsymbol{I}$ is a $n \times n$ identity matrix and the optimal subsidy $\boldsymbol{S}^o$ is dependent on the network topology of $\boldsymbol{G}$ and proportional to the heterogeneous income productivity vector $\boldsymbol{\alpha}$.

Analogously, the optimal subsidy/tax per unit of effort to restore the the first-best outcome $\boldsymbol{x}^o$ starting from the utility function specified in Equation 2.5 is given by:

$$\boldsymbol{S}^o_{x} = \frac{\lambda}{1-\lambda}\boldsymbol{G}^\top(\boldsymbol{I}-\boldsymbol{G})\left[\boldsymbol{I}+\frac{\lambda}{1-\lambda}(\boldsymbol{I}-\boldsymbol{G})^\top(\boldsymbol{I}-\boldsymbol{G})\right]^{-1}\boldsymbol{\pi},$$

where $\boldsymbol{\pi} := (\pi_1, \pi_2, ..., \pi_n)^\top \in \mathbb{R}^n_+$ is the productivity vector, which is an exogenous characteristic. As stated in Claim 2.2, all taxpayers are assumed *ex ante* homogeneous with exception of the exogenous earned gross income $I_i > 0$. Recalling that $x_i := \tau d_i I_i$ is defined as the tax payment of player $i$ in monetary terms, where $\tau \in (0,1)$ is a societal level (flat) tax rate, $d_i \in [0,1]$ is the fraction of income disclosed by player $i$ to the tax authorities and $I_i > 0$ is the exogenous given gross earned income of taxpayer $i$, it is clear that the only possible exogenous heterogeneity factor must come from the earned income $I_i$. Hence, by definition of $x_i$ and for otherwise homogeneous taxpayers, tax payments expressed in monetary terms are directly proportional to earned income as in Alm, Jackson and McKee (1992). Define $\mathbf{L} := (I_1, I_2, ..., I_n)^\top \in \mathbb{R}^n_+$ as the exogenous earned (gross) income corresponding to all players in network $\mathrm{g}$. Following, the individual productivity vector $\boldsymbol{\pi}$ is monotonously and directly proportional to $\boldsymbol{L}$. Therefore, given that $\boldsymbol{S}^o_x \propto \boldsymbol{\pi}$ and $\boldsymbol{\pi} \propto \boldsymbol{L}$, one has that $\boldsymbol{S}^o_x \propto \boldsymbol{L}$. Moreover, from Equation 2.12, one has that $\boldsymbol{L}$ and $\boldsymbol{\alpha}$ are monotonously and directly proportional to each other by construction. Indeed, the correlation coefficient $\rho(\boldsymbol{\alpha}, \boldsymbol{L}) = 1$ by definition. Therefore, one has that $\boldsymbol{S}^o_x \propto \boldsymbol{\alpha}$ by construction of $\boldsymbol{\alpha}$.

Furthermore, given that $\boldsymbol{S}^o_{\hat{p}} \propto \boldsymbol{\alpha}$ by Proposition 2.3 and Proposition 2.4, and $\boldsymbol{S}^o_x \propto \boldsymbol{\alpha}$ as specified above, one has that the correlation coefficient $\rho(\boldsymbol{S}^o_{\hat{p}}, \boldsymbol{S}^o_x) = 1$ by definition of $\boldsymbol{\alpha}$. That is, for all taxpayers $i \in \{0, 1, \ldots, n\}$, the rank of the individual value $S^o_{\hat{p},i}$ inside the vector $\boldsymbol{S}^o_{\hat{p}}$ is exactly the same as the rank of the individual value $S^o_{x,i}$ inside the vector $\boldsymbol{S}^o_x$. Lastly, given that the solution from the tax authority's problem specified in Equation 2.22 is to audit the $\lfloor np \rfloor$ taxpayers with the maximal individual subsidy values, one has by the above results that the $\lfloor np \rfloor$ maximal $S^o_{x,i}$ values correspond to the same set of taxpayers whose $S^o_{\hat{p},i}$ subsidies correspond to the $\lfloor np \rfloor$ maximal values of $\boldsymbol{S}^o_{\hat{p}}$. Conclusively, if the tax authority decides to attempt to restore the first-best outcome, one has that the key set of taxpayers $\mathcal{M}_{\hat{p}}$ to be audited in order to maximize the *global subjective audit probability* across the entire set of taxpayers $\mathcal{N}$ for the next period, with $\mathcal{M}_{\hat{p}} \subset \mathcal{N}$ and $|\mathcal{M}_{\hat{p}}| \leq \lfloor np \rfloor$ is constituted by exactly the same elements as the key set of taxpayers $\mathcal{M}_x$ to be audited in order to maximize the *total tax payments* among the entire set of taxpayers $\mathcal{N}$ for the next period, with $\mathcal{M}_x \subset \mathcal{N}$ and $|\mathcal{M}_x| \leq \lfloor np \rfloor$.

□

*Proof of Claim 2.2.* From Equation 2.20, the Nash Equilibrium in the current local-average game is characterized by:

$$\hat{\mathbf{p}}^* = \mathbf{M}\boldsymbol{\alpha}.$$

Moreover, from Equation 2.21 the Nash Equilibrium social norm is given by:

$$\bar{\hat{\mathbf{p}}}^* = \mathbf{G}\mathbf{M}\boldsymbol{\alpha}.$$

It is easy to verify how both the Nash Equilibrium ($\hat{\mathbf{p}}^*$) and the social-norm equilibrium ($\bar{\hat{\mathbf{p}}}^*$) are expressed in terms of the so-called individual *income-productivity* vector ($\boldsymbol{\alpha}$) and the network structure. Following, if all taxpayers would be homogeneous, that is if $\alpha_i = \alpha_j$ for all $\{i, j\} \in \{1, 2, ..., n\}$, then the equilibrium outcome levels would be the same for all taxpayers and independent of the network structure

□

*Proof of Claim 2.3.* Bonacich (1987) mentioned that a discount parameter $\lambda$ can be interpreted as a probability under certain conditions. Indeed, for the row-stochastic adjacency matrix $\mathbf{G}$ with non-negative entries and for $\lambda \in (0, 1/\mu_1(\mathbf{G}))$, the adjacency matrix $\mathbf{G}$ can be interpreted as a transition probability matrix, where $\mu_1(\mathbf{G})$ denotes the largest eigenvalue of matrix $\mathbf{G}$. Following, for $\lambda \in (0, 1)$, the weight $\lambda$ can be interpreted as a probability and the adjacency matrix $\mathbf{G}$ can be seen as a transition probability matrix in the Markovian sense, i.e. the future state of a variable depends only on its current state and the paths followed by the communication channel are independent of their origin.

Suppose each taxpayer chooses its own income productivity stochastically or by tatonnement (trial and error) following a Markovian process, where the universe of states is composed by the $n$ beliefs that each individual has on the state of the world $\Omega \in \{\alpha_1, \alpha_2, \dots, \alpha_n\}$. Instead of rationally computing their own income productivity as specified in Equation 2.12, taxpayers decide to *copy* or *mimic*[13] the income productivity of a fellow taxpayer. Assume that taxpayer $i$ chooses its own income productivity $\alpha_i$ with probability $1 - \lambda$ and mimics or copies the income productivity of a neighbor taxpayer with probability $\lambda$. Following, suppose as well that with probability $1 - \lambda$ taxpayer $i$ decides to mimic taxpayer $j$ and choose $\alpha_j$, and with probability $\lambda$ taxpayer $i$ decides to go on and mimic the income productivity of one of $j$'s neighbors. Sequentially, this process repeats over and over until taxpayer $i$ fixes a neighbor from whom to mimic its effort.

Define $Z_i$ as the random variable which measures the income productivity (bounded rationally) exerted by taxpayer $i$. Recursively, one can define the probability of the effort exerted by taxpayer $i$ to be equal to the income productivity of taxpayer $j$ as:

$$\mathbb{P}(Z_i = \alpha_j) = (1 - \lambda) \sum_{k=0}^{\infty} \lambda^k g_{ij}^{[k]}, \tag{2.32}$$

where $g_{ij}^{[k]}$ denotes the number of paths of length $k$ which start in $i$ and end in $j$ in the transition probability matrix $\mathbf{G}$.

Combining together the definitions from Equation 2.19 and Equation 2.31, one has that the $n \times n$ matrix $\mathbf{M} = [m_{i,j}]$ can be specified as:

$$\mathbf{M} := (1 - \lambda)(\mathbf{I} - \lambda \mathbf{G})^{-1} = (1 - \lambda) \sum_{k=0}^{\infty} \lambda^k \mathbf{G}^k, \tag{2.33}$$

where $\mathbf{I}$ is a $n \times n$ identity matrix and $\lambda \in (0, 1)$.

Moreover, each entry $[m_{i,j}]$ is given by:

$$m_{ij} = (1 - \lambda) \sum_{k=0}^{\infty} \lambda^k g_{ij}^{[k]}, \tag{2.34}$$

which is mathematically equivalent to Equation 2.32.

Therefore, $\mathbb{P}(Z_i = \alpha_j)$ can be rewritten as:

$$\mathbb{P}(Z_i = \alpha_j) = m_{ij}.$$

Computing the expected value of $\mathbb{P}(Z_i = \alpha_j)$ one has:

$$\mathbb{E}[Z_i] = \sum_{j=1}^{n} m_{ij} \alpha_j,$$

or in matrix form:

$$\mathbb{E}[\mathbf{Z}] = \mathbf{M} \boldsymbol{\alpha} = (1 - \lambda) \sum_{k=0}^{\infty} \lambda^k \mathbf{G}^k \boldsymbol{\alpha}. \tag{2.35}$$

Hence, whether agents make decisions fully rationally or bounded rationally, on average, the stochastic Nash Equilibrium and the rationally Nash Equilibrium are equivalent in our context. It is important to remark that Ushchev and Zenou (2020) were the first to prove the equivalence between the Nash Equilibrium in effort of a network static game and the expected effort of a Markov chain.

□

[13] In network games, one usually imitates an effort made, here we are modifying the concept to fit our context.

# Chapter 3

# The network structure of global tax evasion

## – Evidence from the Panama Papers –

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**Abstract**

This paper builds on recent insights from network theory and on the rich dataset made available by the Panama Papers in order to investigate the micro-economic dynamics of tax evasion. We model offshore financial entities documented in the Panama Papers as links between jurisdictions in the global network of tax evasion. A quantitative analysis shows that the resulting network, far from being a random collection of bilateral links, has key features of complex networks such as a core-periphery structure and a fat-tail degree distribution. We argue that these structural features imply that policy must adopt a systemic perspective to mitigate tax evasion. We offer three sets of insights from this perspective. First, we show that the optimal deterrence strategies for a social planner facing a strategic tax evader in a Stackelberg competition can be characterized using the notion of Bonacich centrality. Second, we show that efficient tax treaties must contain exchange information clauses and link tax havens to non-haven jurisdictions. Third, we identify through centrality measures tax havens that ought to be priority policy targets.

**JEL classification:** H26 · H87 · D85 · C54
**Keywords:** Tax Evasion · Socio-economic Networks · Game Theory

### 3.1 Introduction

Curbing tax evasion has been a permanent issue on the policy agenda ever since the advent of taxation systems. In recent decades, the acceleration and liberalization of financial flows has led to a globalization of the issue whereby tax-evaded wealth circulates through complex chains of jurisdictions and legal entities before finding shelter in tax havens (see e.g. Garcia-Bernardo et al. (2017)). According to Johannesen and Zucman (2014), 8% of the global household financial wealth is hence held offshore. This eventually

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led to a 'crackdown' on tax havens: in April 2009, G20 countries urged each tax haven to sign at least 12 tax information exchange treaties (TIEA's) under the threat of economic sanctions. As a consequence, more than 300 treaties were signed before the end of 2009 and another 1000 tax treaties were written or amended shortly afterwards (Johannesen and Zucman (2014)). The efficiency of the crackdown has however been questioned. In particular, Johannesen and Zucman (2014) give evidence, using BIS data on cross-border deposits, that the crackdown has led to a mere reallocation of tax-evaded funds.

In addition to tax information exchange agreements, diverse inter-jurisdictional fiscal policies have been set in motion to deter international tax evasion. The European Union Savings Directive, enforced in 2005, obliges cooperating jurisdictions to disclose the financial information of entities whose owner is a EU resident. The Foreign Account Tax Compliance Act (FATCA), signed in March 2010, requires all non-US financial institutions to report the assets and identities of all U.S. citizens and residents to the U.S. Department of the Treasury. In June 2018, the OECD introduced a multilateral agreement on automatic exchange of information, known as the Common Reporting Standard (CRS). Today, this initiative comprises over 4,000 additional bilateral tax information exchange agreements involving 108 jurisdictions worldwide. Notwithstanding, the existing literature upholds that all previously implemented coordinated fiscal policies have been systematically circumvented by tax evaders (Zucman (2013); Johannesen and Zucman (2014); Caruana-Galizia and Caruana-Galizia (2016); Omartian (2017); Alstadsæter et al. (2018); Casi et al. (2020)).

This paper proposes a novel solution to the pervasive problem of tax evasion by adopting a network perspective of the matter. That is, our study offers a potential methodological solution to the ongoing issue of international tax evasion by modeling this phenomenon as a network game and by applying some well-known properties of network and game theory to address the problem. In order to design more efficient tax evasion mitigation policies, a detailed understanding of the mechanics of tax evasion is required. However, the lack of data and the complex nature of tax-evasion schemes have prevented the use of standard micro-economic and micro-econometric methods in this perspective. In this paper, we build on recent insights from network theory and on the rich dataset made available by the Panama Papers in order to bridge part of this gap. The Panama Papers, a leaked dataset that has been made publicly available by the International Consortium of Investigative Journalists (ICIJ) in early 2016, provide information on a set of 213,634 offshore financial entities created by Mossack-Fonseca, one of the leading providers of offshore financial services. Offshore financial entities allow to conceal wealth from a source country, the one of the owner of the entity, to a host country, the one where the entity is registered, in such a way that the identity of the owner is concealed. These can thus be seen as tax-evasion links in a network of countries. Adopting this perspective, we provide a quantitative analysis of the resulting network. This analysis highlights that the network, far from being a random collection of bilateral links, has a hierarchical organization characterized by a core-periphery structure and a fat-tail degree distribution. We argue that policy ought to account for these structural features in the design of tax evasion mitigation policies.

Our work provides three set of insights in this perspective. First, we develop a theoretical model to deliver normative insights on optimal deterrence strategies for a social planner facing a strategic tax evader in a Stackelberg competition. The objective of the social planner is to maximize the detection probability of tax evasion across the worldwide network. He can enforce a number of tax treaties in this perspective. The tax evader aims to minimize the probability of detection. He faces a cost that is proportional to the intensity of tax evasion. Our main analytical result in this setting is that the social planner ought to choose the global structure of tax-treaties in such a way that the linked countries form a sub-network for which the sum of Bonacich centralities is maximal. At the formal level, this result highlights the need to adopt a systemic perspective on tax evasion as the Bonacich centrality of the network does not depend on local properties of the network but on its global structure. From a more applied perspective, our results imply that the social planner should first form a 'barrier' of tax treaties surrounding the most central tax havens (i.e. form a quasi-star network of treaties) and then systematically extend the set of treaties to eventually cover the whole set of countries (i.e. form a quasi-complete network). In this perspective, our results suggest to target jurisdictions according to a priority order determined by their Bonacich centrality in the network of international tax evasion. Second,we characterize the most central actors in the global tax-evasion network. This characterization can be used to identify tax havens that ought to be priority targets of evasion deterrence policy (e.g. building on Albert et al. (2000)). Finally, we provide an econometric analysis of the determinants of network formation and of the impact of tax treaties thereupon. Our results are consistent with those of Johannesen and Zucman (2014) and

Omartian (2017). In particular, we show that efficient treaties are those that contain an information exchange clause and that link offshore financial centers to 'non-haven' countries. This calls for further refinements of the type of 'treaty policy' implemented during the G20 crackdown.

The remaining of the paper is organized as follows. Section 3.2 reviews the related literature. Section 3.3 provides a formal model of the Stackelberg competition between a representative tax evader and a social planner aiming at deterring tax evasion. Section 3.4 provides an empirical analysis of the global tax-evasion network on the basis of the Panama Papers. Section 3.5 investigates the determinants of network formation and the impact of treaties on cross-country tax evasion. Section 3.6 presents a numerical implementation of our theoretical model, and Section 3.7 concludes.

## 3.2 Literature Review

The features of tax havens have been extensively studied in the recent literature. In an early contribution, Hines Jr. (2007) puts forward a first set of stylized facts. Studying 45 major offshore financial centers, the author mentions that tax havens tend to be small (commonly below 1 million inhabitants), affluent and well-governed. Moreover, such fiscal paradises tend to incentive economic activity in neighboring non-haven countries. Dharmapala (2008) extends this set of stylized facts, noticing that tax havens are more prone to be island countries, poorly endowed with natural resources, and relatively close to major financial capital exporters. Moreover, most tax havens seem to bear a British legal origin and to account for a highly advanced telecommunication infrastructure. Dharmapala and Hines Jr. (2009) perform an econometric study over more than twenty different covariates to define which characteristics make a jurisdiction more or less prone to become a tax haven. The authors find, using probit models, that tax havens tend to have a small population and a large GDP *per capita* as compared to the world average. Moreover, governance has a large and statistical significant impact on the probability of a jurisdiction becoming a tax haven. The authors asseverate that only well-governed countries, which may reasonably be seen as trustworthy, qualify as potential tax havens.

A second strand of literature aims to measure the size of tax havens and thus to evaluate their impact on fiscal policy. Zucman (2013) asserts that at least 50 percent of all deposits held through tax havens belong to households. Hence tax havens are primarily used as a channel of tax evasion (by households) and not simply as a tool for tax avoidance (by firms). Furthermore, Zucman (2013, 2014) estimates that about 8% of the global household financial wealth is held offshore, an amount that surges to about 7.6 trillion USD in 2013. Besides, he mentions these coefficients to be a lower bound, which account only for financial wealth and not all types of assets; other sources estimate the amount to be even higher, between 8.9 and 32 trillion U.S. Dollars (Henry (2012)). Further remarks show an increasing flow of deposits from developing nations, a shrinkage from a large number of small accounts to a reduced amount of affluent 'key-clients' in fiscal paradises and an assumption that about 80% of the wealth held in Switzerland and other tax havens seems to be evading taxes. Alstadsæter et al. (2018) conclude that around 10% of the world's GDP equivalent is concealed offshore.

Another line of research studies the impact of tax policy on tax havens. Slemrod and Wilson (2009) argue that tax havens are freeloaders for large non-haven economies and do not provide the potential financial incentives other studies (such as Hines Jr. and Rice (1994) and Desai et al. (2006)) had implied. The authors suggest that abolishing some, or all, tax havens would increment the welfare in non-haven nations. Moreover, the nullification of even a few large fiscal paradises would leave all other countries better-off, including any of the still remaining tax havens. As mentioned by Hines Jr. (2010), tax havens are generally pass-through financial locations, where neighboring countries are both the largest sources and destinations of the money flow. Picard and Pieretti (2011) discuss how offshore financial centers can be persuaded to comply with strict supervision of their funds and shareholders' identities whenever the pressure placed on them poses a sufficiently high risk of damaging their business operations. Elsayyad and Konrad (2012) conclude that a 'big-bang' multilateral agreement would be less costly than sequential tax information exchange agreements, and that the order of tax treaties would matter for an efficient sequential deactivation of tax havens. Hanlon et al. (2013) argue that small increments of detection risk may be enough to deter cross-country tax-evasive behavior. Moreover, Konrad and Stolper (2016) claim that the success of a policy against offshore financial centers is the outcome of a coordination game between potential investors and tax havens.

The natural experiment induced by the G20 crackdown on tax havens has also generated a substantial literature. Johannesen and Zucman (2014) explore how tax treaties between jurisdictions affected the flow of deposits from sources to host countries. The authors conclude that whenever a country signed a treaty with a tax haven there was a reallocation effect, meaning that evaders would shift their deposits to another jurisdiction where no treaty existed. Moreover, the study suggests that tax treaties signed between two tax havens have no statistically significant effects. Potentially, the success of the G20 policy was undermined due to the lack of a coordinated systemic strategy in the bilateral TIEA-type treaty implementations (evidence of this is found in Bilicka and Fuest (2014) and Johannesen and Zucman (2014)). Braun and Weichenrieder (2015) find that, for German affiliates, TIEA's decreased the number of operations with tax havens by 46 percent. Similarly, Andersson et al. (2019) observe strong announcement effects of TIEA's between Norway and important tax havens for Norwegian tax evaders. Bennedsen and Zeume (2018) evidence how a considerable number of multinational firms actively engage in 'haven hopping'. That is, firms strategically transfer their subsidiaries from offshore financial centers which have signed a TIEA treaty to others who have not. O'Donovan et al. (2019) assess that the occurrence of the Panama Papers leakage erased 135 billion USD in market capitalization among firms directly linked to the Panama Papers. The authors suggest that many offshore financial entities were incorporated for illegal purposes, such as tax evasion or bribe payments, which in turn generated firm value. These results shed light on the importance of secrecy for tax evaders whenever undertaking operations in fiscal paradises.

Tax information exchange agreements, the European Union Savings Directive, the Foreign Account Tax Compliance Act (FATCA), and the OECD-sponsored Common Reporting Standard (CRS) are among the most successfully multilateral fiscal policies designed to deter international tax evasion. Caruana-Galizia and Caruana-Galizia (2016) examine the effects of the 2005 EU Saving Directives. Employing the information leaked in the Panama Papers, the authors find a substitution effect where EU-resident owned entities migrated to non-cooperating jurisdictions; meanwhile, non-EU owned entities remained stable. Exploiting the Panama Papers, Omartian (2017) uncovers that the FATCA induced U.S. investors to downsize their offshore activity by approximately one-third. Similarly, Johannesen et al. (2018) estimate that the U.S. enforcement initiatives on evasive accounts led to the disclosure of 120 billion USD concealed in offshore financial centers. Casi et al. (2020) study the efficiency of the Common Reporting Standard and find a 11.9% reduction in cross-border deposits, followed by a pronounced relocation effect of funds held by tax evaders seeking secrecy offshore. Albeit the CRS resembles a 'big bang' agreement, in the sense of Elsayyad and Konrad (2012), not all jurisdictions signed[1]. Also, some countries agreed to the CRS, but have not enforced any additional measures to facilitate tax information exchange. In particular, the United States have neither signed nor committed to endorse the CRS. This caveat is far from innocuous, since the U.S. holds two empirically confirmed tax havens (Nevada and Wyoming[2]) plus an anecdotal offshore financial center (Delaware). Potentially, a non-universal multilateral agreement might induce non-cooperative offshore financial centers to reclaim the 'tax haven business' at the expense of cooperative jurisdictions (Elsayyad and Konrad (2012)). Indeed, Casi et al. (2020) estimate that cross-border deposits in the United States increased in the post-CRS era between 10.9% (held by non-haven residents) and 17.7% (held by tax haven residents) from 2014 to 2017. These results shed light on the possibility that the United States have emerged as an attractive destination for cross-country deposits. Consequently, instead of putting an end to international tax evasion, the CRS triggered a new relocation effect in the dynamics of wealth concealment similar to that of the G20 2009 crackdown on tax havens.

Despite this growing literature, the issue of international tax evasion has not been investigated from a network perspective. Although tax information exchange mechanisms and previously designed multilateral fiscal policies offer useful tools to deter offshore wealth concealment and tax evasion, they are limited and have plenty of room for improvement. Our work maintains that the still existing problem of global tax evasion can potentially be addressed by applying solutions from network and game theory. Network approaches have been used to model a wide range of financial systems and the interactions between entities. Iori et al. (2005), Vitali et al. (2011), Chinazzi et al. (2013) and Li and Schürhoff (2019) provide various insights about the mechanics of international financial networks, consistently identifying key properties and topological characteristics germane to complex networks. More closely related to our contribution, Garcia-Bernardo et al. (2017) examine corporate tax avoidance networks through corporate ownership relationships in order to identify the jurisdictions that work as conduits or final destinations

[1] The list of countries which did not sign the Common Reporting Standard include several jurisdictions from the EU *black list* of tax havens (American Samoa, Fiji, Guam, Palau, Trinidad and Tobago and U.S. Virgin Islands) and from the EU *grey list* of tax havens (Bosnia and Herzegovina, Botswana, Swaziland, Jordan, Maldives, Mongolia, Namibia and Thailand). Link to EU list of tax havens: https://ec.europa.eu/taxation˙customs/sites/taxation/files/eu˙list˙update˙18˙02˙2020˙en.pdf. Last revised: February 18, 2020.

[2] Nevada and Wyoming were mentioned as recurrent offshore financial centers in the Panama Papers.

of shifted profits.

The design of efficient policies in such network contexts has also induced a large literature (e.g. Ballester et al. (2006), Bramoullé and Kranton (2007), Konig et al. (2008), Konig et al. (2012), Allouch (2015) and Elliott and Golub (2019)). In our context, the problem of the social planner amounts to finding a subgraph maximizing the sum of Bonacich centralities. This problem has been addressed in the economic literature, notably by Konig et al. (2014) and Belhaj et al. (2016) who emphasize its connections with nested-split graphs. The problem is also connected to a well-known problem in graph theory, that of finding the graph with a given number of nodes and vertices that has maximal index (see Corbo et al. (2006), and Chang and Tam (2011)). A long-standing conjecture on that problem is that its solutions are either quasi-complete or quasi-star graphs (see Aouchiche et al. (2008) and Cvetkovic et al. (1997) for solutions in some specific cases).

## 3.3 A formal model of tax evasion deterrence

In June 2018, the OECD introduced the Common Reporting Standard (CRS), a multilateral agreement on automatic exchange of information. This multilateral agreement on automatic exchange of information involves 108 jurisdictions worldwide and accounts for over 4,000 additional bilateral tax information exchange agreements. Although a significant number of countries endorsed the CRS policy, not all jurisdictions signed, including several jurisdictions from the EU *black list* and *grey list* of tax havens. Hence, the Common Reporting Standard seems to have crucial shortcomings comparable to the ones from the G20 crackdown on tax havens (Casi et al., 2020). A non-universal multilateral agreement might induce non-cooperative offshore financial centers to reclaim the 'tax haven business' at the expense of cooperative jurisdictions. There is compelling theoretical (Elsayyad and Konrad (2012)) and factual (Johannesen and Zucman (2014); Caruana-Galizia and Caruana-Galizia (2016); Casi et al. (2020)) evidence to believe that a fraction of these non-compliant jurisdictions may monopolize the 'tax haven business' in the post-CRS era. Consequently, it would be overconfident to assume that the fight against tax evasion and wealth concealment has come to an end. Notwithstanding, the Common Reporting Standard established a new paradigm in the fight against international tax evasion. Although the CRS is still far from universal, and has thus led to reallocation of tax-evaded wealth (Casi et al. (2020)), it provides a framework for global cooperation through which a network of tax treaties can be sequentially completed. The OECD-sponsored Common Reporting Standard, together with the G20 summit in 2009, the EU Savings Directive and the FATCA, provide factual support to the notion of an *international* or *global* social planner who exerts a non-negligible level of influence in all jurisdictions.

The current section presents a theoretical model where an international social planner seeks to maximize the global detection probability of cross-country tax evasion, given a limited number of tax treaties to be implemented. Indeed, existing literature suggests that even a small increment of detection risk may be enough to discourage cross-country tax evasive behavior (Hanlon et al. (2013); Andersson et al. (2019)). In order to do so, the social planner allocates tax information exchange agreements (TIEAS's) between jurisdictions which enable international cooperation and allow for wealth concealment detection. The social planner faces the problem of finding the optimal allocation of a finite number of treaties among country-pairs in the network. By construction, the latter constraint assumes fixed homogeneous costs of enforcing a treaty between any two jurisdictions. Albeit there exists relevant literature on costs of link formation (Konig et al., 2008, 2012), our model assumes no heterogeneous costs. In our context, the existence of a global social planner acting as a single entity of coordinated jurisdictions minimizes costs (Elsayyad and Konrad, 2012), removes frictions and competitions between countries, and renders the link implementation costs homogeneous. These assumptions are well-aligned with recent policy measures such as the development of the Common Reporting Standard by the OECD.

Economic interactions between agents can lead to networks with complex characteristics, such as the widespread diffusion of the influence of individuals throughout the network. The intricate structure of tax-evasion systems raises a number of questions for the design of an efficient anti-tax evasion policy. Where is tax-evaded wealth likely to be located in the network? How does the structure of the network affects tax-evasive behavior in origin countries? What are the efficient policies to deter tax evasion given its networked structure? In order to address these issues, we introduce a simple model of the flow of funds in the tax-evasion network and investigate in this setting the strategic behavior of an optimizing tax-evading agent and of a social planner aiming at deterring tax evasion. On the one hand, the tax evader chooses the optimal fraction of wealth to be concealed. On the other hand, the social planner derives the optimal strategy to deactivate tax havens by maximizing the global detection probability of tax evasion (analogously of wealth concealment).

### 3.3.1 Notation and definitions

We first recall a set of notions and known results related to networks and, in particular, Bonacich centrality. The Bonacich centrality and its proportional measures have been extensively employed to model interactions and optimal actions in network games (Ballester et al., 2006; Ushchev and Zenou, 2020). In particular, the intuition behind the Bonacich centrality is useful to model Nash Equilibrium and optimal strategies to maximize (minimize) aggregate outcome levels in networks of tax evasion (see Gamannossi degl'Innocenti and Rablen (2020) and also Chapter 2 of the current dissertation).

**Definition 3.1.** *Given a network with adjacency matrix $G \in \mathbb{R}_+^{N\times N}$, and a discount factor $\beta \in [0,1]$, the Bonacich centrality (see Bonacich (1987) and Ballester et al. (2006)) of a node $i$ is defined as the discounted sum of the weights of all paths in the network leading to $i$. Namely, the vector of Bonacich centrality is given by:*

$$b(G,\beta) = \sum_{t\in\mathbb{N}} \beta^t G^t \tilde{e} = (I - \beta G)^{-1}\tilde{e}, \tag{3.1}$$

*where $\tilde{e}$ is the vector $(1,\cdots,1) \in \mathbb{R}_+^N$ and the Bonacich centrality is well-defined only if $\beta < 1/\mu_1(G)$, where $\mu_1(G)$ is the largest eigenvalue of $G$ (also referred to as the index or as the spectral radius of $G$).*

This definition can be extended to account for an arbitrary vector of weights on the origins of paths, leading to the definition of the Bonacich centrality of an adjacency matrix $G$ for a discount factor $\beta \in [0,1]$, and a vector of initial weights $x \in \mathbb{R}_+^N$ as:

$$b(G,\beta,x) = \sum_{t\in\mathbb{N}} \beta^t G^t x = (I - \beta G)^{-1}x. \tag{3.2}$$

In the following, we shall be concerned with the determination of the network with a given number of links that maximizes the sum of Bonacich centralities. Following *Remark 1* and *Lemma 1* in Belhaj et al. (2016), such networks necessarily are nested-split graphs in the following sense.

**Definition 3.2.** *An (unweighted) network $G$ is a nested-split graph if:*

$$[G_{i,j} = 1 \text{ and } \deg(G,k) \geq \deg(G,j)] \Rightarrow G_{i,k} = 1,$$

*where $\deg(G,k)$ denotes the degree of node $k$ in the network $G$.*

Such graphs are called nested as it can be shown that they are structured by classes of nodes having the same degree and the same set of incoming links[3]. Some notable classes of nested-split graphs are defined as follows:

**Definition 3.3.** *The quasi-complete network with $N$ nodes and $\nu$ links, denoted by $QC(N,\nu)$, is the graph that contains the complete subgraph $K_p$ with ${}^{p(p-1)}/_2 \leq \nu < {}^{p(p+1)}/_2$ and the remaining $\nu - {}^{p(p-1)}/_2$ links are set between the nodes in $K_p$ and one other node.*

**Definition 3.4.** *The quasi-star graph with $N$ nodes and $\nu$ links, denoted by $QS(N,\nu)$, is the graph with $p$ central nodes, each having $N-1$ links, and the remaining $\nu - p(N-1)$ links being directed towards a specific node, so as to construct another central node.*

### 3.3.2 Centrality and the distribution of tax-evaded wealth

We first consider a simple phenomenological model of the dynamics of wealth in a tax-evasion network. The network is represented by a column-stochastic adjacency matrix $(G_{i,j})_{i,j=1,\cdots,N} \in \mathbb{R}_+^{N\times N}$ where $N$ is the number of countries in the network and $g_{i,j}$ measures the share of wealth outgoing from country $j$ that is directed towards country $i$, i.e. the probability that a unit of tax-evaded wealth, which is outgoing

[3]Further intuition about nested-split structures, namely quasi-star and quasi-complete network formation processes, is provided in the Appendix.

from $j$, is directed towards $i$. Tax-evasive behavior is captured by a single parameter $\beta \in [0,1)$, which measures the intensity of tax evasion, i.e. the share of tax-evaded wealth concealed in $i$ that is rerouted further, while the share of tax-evaded wealth that stays in country $i$ is given by the complement $1-\beta$.

Empirically, $\beta$ likely depends on the host country and on the number of countries through which the funds have transited since the origin country. Considering $\beta$ is constant renders the process homogeneous in space and in time, and thus analytically tractable. From the point of view of a tax evader aiming at avoiding detection, this amounts to considering that the probability of detection is independent of the host country and decreases with each link added to the tax-evasion path, independently of the trajectory followed previously. Furthermore, an homogeneous $1-\beta$ would also imply that there is the same propensity to stop funds in all financial offshore centers, independently of the institutional environment.

In this setting, the dynamics of tax-evaded wealth can be characterized by the distribution of funds in circulation through the network, $x(t) \in \mathbb{R}_+^N$, and the distribution of idle funds in the network, $y(t) \in \mathbb{R}_+^N$. One has:

$$\begin{cases} x(t+1) = \beta G x(t), \\ y(t+1) = (1-\beta)x(t) + y(t). \end{cases} \tag{3.3}$$

The first equation represents the flow of funds actively circulating through the network. The second equation represents the fact that a share $(1-\beta)$ of funds stops circulating in the network at every step. Combining both equations, and assuming that $y(0)=0$, one can determine the distribution of funds in the network at time $t$ as a function of the initial distribution of funds, $x(0)$. Namely, one has:

$$x(t) = \beta^t G^t x(0), \tag{3.4}$$

$$y(t) = (1-\beta)\sum_{s=0}^{t-1} \beta^s G^s x(0). \tag{3.5}$$

As long as $\beta < 1$, Equation 3.4 implies that, asymptotically, all funds become idle in the network. In turn, Equation 3.5 implies that, at time $t$, the (idle) funds in the network are distributed according to the discounted sum of paths of length less than $t$. Accordingly, funds are asymptotically distributed proportionally to the Bonacich centrality of the network. Namely, one has the following proposition.

**Proposition 3.1.** *If tax-evaded wealth follows the dynamics given by Equation 3.3, with $\beta < 1$, one has:*

$$\lim_{t \to +\infty} x(t) = 0,$$

$$\lim_{t \to +\infty} y(t) = (I - \beta G)^{-1} x(0),$$

*where $(I-\beta G)^{-1}x(0)$ is the Bonacich centrality of the network with adjacency matrix $G$, corresponding to the discount factor $\beta$ and the initial vector of weights $x(0)$. Since the adjacency matrix $G$ is column-stochastic and with non-negative entries, its spectral radius is equal to one. Hence, the largest eigenvalue of $G$ is equal to one and the Bonacich centrality $(I-\beta G)^{-1}x(0)$ is well-defined for any $\beta \in [0,1)$.*

Proposition 3.1 can then be used to estimate the distribution of tax-evaded wealth among tax havens on the basis of the structure of the tax-evasion network, the propensity to evade taxes and the distribution of wealth among origin countries.

### 3.3.3 Policy and behavior in tax-evasion networks

As previously emphasized, policymakers in tax-evading countries have tried to curb the flow of tax evasion by pressuring tax havens to sign information exchange treaties that ought to hamper the circulation of tax-evaded money. In other words, they have tried to alter the structure of the network of tax evasion to reduce the share of tax-evaded money. In order to characterize efficient strategies from this perspective, we analyze the interactions between a tax evader, who aims to minimize the probability of being detected by dispersing her funds across a tax-evasion network, and a social planner, who aims at minimizing tax evasion through the implementation of an efficient set of treaties.

Formally, we represent the strategy spaces of the tax evader and of the social planner as follows. On the one hand, the tax evader chooses the intensity of tax evasion $\beta \in [0,1)$. On the other hand, the social planner chooses the set of links $(i, j) \in N \times N$ on which a treaty is implemented and tax evasion can thus be detected. We represent this choice by a vector $(h_{i,j})_{i,j \in N} \in \{0,1\}^{N \times N}$, where $h_{i,j} = 1$ if a treaty is implemented between jurisdiction $i$ and $j$, and $h_{i,j} = 0$ otherwise. These joint choices determine a global probability of detection $\pi(h, \beta)$. Namely, the probability of detecting tax-evaded wealth originating from jurisdiction $i$ is given by:

$$\pi_i(h,\beta) = (1-\beta) + (1-\beta)\beta \sum_{j \in N} h_{j,i} g_{j,i} + (1-\beta)\beta^2 \sum_{j_1, j_2 \in N} h_{j_2,j_1} g_{j_2,j_1} h_{j_1,i} g_{j_1,i} + \cdots + (1-\beta)\beta^m \sum_{j_1,\cdots,j_m \in N} \prod_{\mu=1}^{m} h_{j_{\mu+1},j_\mu} g_{j_{\mu+1},j_\mu} h_{j_1,i} g_{j_1,i} + \cdots \quad (3.6)$$

where the term $(1-\beta)\beta^m$ corresponds to the share of wealth that is stored $m$ steps away from the country of origin and the term $\prod_{\mu=1}^{m} h_{j_{\mu+1},j_\mu} g_{j_{\mu+1},j_\mu} h_{j_1,i} g_{j_1,i}$ corresponds to the probability that the tax evader gets caught along the path $(i, j_1, \cdots, j_m)$.

Denoting by $K(h)$ the matrix with coefficients $(k_{j,i} := g_{j,i} h_{j,i})_{i,j \in N}$, one can write in matrix form the probability of detection of tax-evaded wealth initially distributed according to $x \in \mathbb{R}_+^N$, $\pi_x(h, \beta)$, as:

$$\pi_x(h,\beta) := (1-\beta)\tilde{e}^\top \sum_{m=0}^{+\infty} (\beta K(h))^m x = (1-\beta)\tilde{e}^\top (I - \beta K(h))^{-1} x. \quad (3.7)$$

Hence, the probability for a representative (or aggregate) tax evader with initial distribution of wealth $x \in \mathbb{R}_+^N$ to get detected is proportional to the sum of the Bonacich centralities of the nodes of the network $K(h)$ for the discount factor $\beta$ and the vector of initial weights $x$.

**Proposition 3.2.** *For every $x \in \mathbb{R}_+^N$ and $h \in \{0,1\}^{N \times N}$, $\pi_x(h, \cdot)$ is decreasing and concave in $\beta$.*

In the current context, the tax evader has incentives to increase $\beta$ in order to minimize the probability of detection (see Appendix for the proof of Proposition 3.2). However, these incentives can be mitigated by the cost of tax evasion. This cost has many potential drivers: direct financial costs such as payment of tax-evasion services, liquidity costs related to the reduced availability of evaded versus non-evaded funds, and reputation and psychological costs in case of detection. We shall denote by $c(\beta)$ the cost of choosing an intensity $\beta$ of tax evasion and assume throughout that the cost is a smooth (twice differentiable) and increasing function of the intensity of tax evasion. We then assume that the tax-evading agent chooses a tax-evasion intensity in $[0, \overline{\beta}]$, where $\overline{\beta} < 1$, and arbitrates between the probability of getting detected and the cost of tax evasion. More precisely, we consider that the utility of an agent choosing a tax-evasion intensity $\beta \in [0, \overline{\beta}]$ is given by:

$$u(h,\beta) = -\pi_x(h,\beta) - c(\beta).$$

The optimal behavior of the tax-evading agent thus depends on the properties of the cost function. Yet, one can ensure *à priori* that, given a treaty policy $h$, there exists an optimal level of tax evasion $\phi(h)$. Indeed, $[0, \overline{\beta}]$ is compact and $u$ is continuous, as $c$ and $\pi_x$ both are continuous. Following, the tax-evasion intensity, $\beta$, may be defined as the reaction function, $\phi(\cdot)$, of the tax-evading agent to the treaty policy, $h$, implemented by the social planner:

$$\beta := \phi(h).$$

As for the social planner, we consider that he faces a constraint limiting the actual influence that he can exert on the probability of detection, e.g. on the number of treaties that he can implement. This constraint is assumed to be of the form $\sum_{i,j \in N} h_{i,j} = \nu$, with $\nu \in \mathbb{N}$. This constraint is consistent with the one imposed by the G20 on tax havens, obliging them to sign a given number of TIEA's. Formally, the problem of the social planner, if he takes as given the propensity to evade taxes, $\beta$, is defined as:

$$\mathcal{S}_{\nu,\beta} := \begin{cases} \max & \pi_x(h,\beta) \\ s.t & \sum_{i,j \in N} h_{i,j} = \nu. \end{cases}$$

In other words, the objective of the social planner is to choose a set of treaties $h$, i.e. detection probabilities, so that the sum of Bonacich centralities in the network $K(h)$ is maximal.

We shall further consider that the social planner acts as a Stackelberg leader who foresees the strategic reply of the tax evader to his actions, and thus derives his optimal policy accordingly[4]. Hence, in the following, we focus on the Stackelberg equilibrium of the tax-evasion game defined as follows.

[4]The Stackelberg model is a type of sequential game with leader-follower interactions.

**Definition 3.5.** *A pair $(h^*, \beta^*)$ is a Stackelberg equilibrium of the tax-evasion game if:*

1. *$h^*$ is a solution to* $\mathcal{S}_\nu := \begin{cases} \max & \pi(h, \phi(h)) \\ s.t & \sum_{i,j \in N} h_{i,j} = \nu. \end{cases}$

2. *$\beta^* := \phi(h^*)$ is a solution of the problem* $\begin{cases} \max & -c(\beta) - \pi_x(\beta, h^*) \\ s.t & \beta \in [0, \overline{\beta}]. \end{cases}$

**Remark 3.1.** *In our framework the set of treaties are determined by the social planner, whereas in practice treaties are signed in a decentralized manner. Yet, our objective is normative. We are interested in determining the efficient set of treaties.*

### 3.3.4 Optimal tax-evasion behavior

We first characterize the behavior of a tax evader for a given deterrence policy $h \in \{0,1\}^{N \times N}$, which is considered as fixed throughout this subsection. From the point of view of the tax evader, the strategy of the social planner is predetermined, that is, the tax evader may view it as a constant. In other words, the tax evader acts as a Stackelberg follower. The impact of tax-evasion intensity $\beta$ on the probability of detection is given by Proposition 3.2. That is, for every $x \in \mathbb{R}_+^N$ and $h \in \{0,1\}^{N \times N}$, one has that $\pi_x(h, \cdot)$ is decreasing and concave in $\beta$.

The concavity of $\pi_x$ implies that agents have, *à priori*, very strong incentives to evade taxes. There are increasing marginal returns to tax evasion in terms of probability of non-detection: as $\beta$ increases, the probability of detection decreases more and more rapidly. This non-convexity originates from the fact that an increment in the intensity of tax evasion is amplified, non-linearly, by the network. Yet, these incentives can be mitigated by the cost of tax evasion. Hence, the optimal behavior of a tax-evading agent eventually depends on the properties of the cost function.

One can not analytically characterize the optimal behavior of the tax evader in the general case. In particular, one can not guarantee that the optimum is unique, nor determine whether it is in the interior or on the boundary of the domain. However, one can characterize two polar cases that are of particular interest. First, if the cost of tax evasion is concave, i.e. if the marginal cost of tax evasion is decreasing, there are only two potentially optimal strategies: either the agent does not evade taxes at all, or she fully evades taxes. Namely, letting $\phi(h) = \text{argmax}_{\beta \in [0,\overline{\beta}]}\ u(h, \beta)$, one has the following proposition.

**Proposition 3.3.** *If the cost function $c$ is concave, then the problem $\max_{\beta \in [0,\overline{\beta}]}\ u(h, \beta)$ can not have an interior solution, and one has:*

- *Either $u(h, \overline{\beta}) \geq u(h, 0)$ and $\phi(h) = \overline{\beta}$.*
- *Or $u(h, \overline{\beta}) \leq u(h, 0)$ and $\phi(h) = 0$.*

The second polar case is the one where the cost of tax evasion is more convex than the probability of detection, i.e. the marginal cost of tax evasion is increasing faster than the probability of tax evasion decreases. Then, there exists a unique optimal level of tax evasion. In particular, if the marginal impact of tax evasion on the probability of detection is large enough, then it is optimal to fully evade taxes. Namely, one has the following proposition.

**Proposition 3.4.** *If $c$ is such that $-\pi''_x(h, \beta) < c''(\beta)$ for every $\beta \in [0, \overline{\beta}]$, then there exists a unique solution, $\phi(h)$, to the problem $\max_{\beta \in [0,\overline{\beta}]}\ u(h, \beta)$, and one has:*

- *If $c'(\overline{\beta}) + \pi'_x(\overline{\beta}) \leq 0$, then $\phi(h) = \overline{\beta}$.*
- *If $\pi'_x(0) + c'(0) \geq 0$, then $\phi(h) = 0$.*
- *If $\pi'_x(0) + c'(0) \leq 0$ and $c'(\overline{\beta}) + \pi'_x(\overline{\beta}) \geq 0$, then there exists a unique $\tilde{\beta} \in [0, \overline{\beta}]$ such that $\phi(h) = \tilde{\beta}$.*

### 3.3.5 Strategic deterrence

The social planner is aware that his actions influence the behavior of tax evaders, and thus must derive his optimal strategy accordingly. Building on Proposition 3.3, one can provide a simple characterization of the social planner's equilibrium strategy in the case where $c$ is concave.

**Proposition 3.5.** *Assume that the cost function $c$ is concave. If $h^*$ is a solution to $\mathcal{S}_{\nu,\overline{\beta}}$, then one has that $(h^*, \beta^* := \phi(h^*))$ is a Stackelberg equilibrium of the tax-evasion game.*

Hence, in the case where the cost is concave, it suffices to focus on the behavior of the social planner in a setting where the tax evader fully evades taxes. This will be our focus for the remaining of this section.

**Remark 3.2.** *For an arbitrary cost function, the strategic interactions become more complex and the Stackelberg equilibrium can hardly be analytically characterized. A meaningful proxy of the optimal behavior of the social planner can nevertheless be characterized by taking the propensity to evade taxes as given, i.e. by solving the problem $\mathcal{S}_{\nu,\beta}$ as done below.*

In this setting, a fundamental remark is that the problem $\mathcal{S}_{\nu,\beta}$ is equivalent to finding the subgraph of $G$ with $\nu$ links for which the sum of Bonacich centralities is maximal. This objective function is clearly supermodular because the number of new paths obtained by the addition of a link to a subgraph is an increasing function of the subgraph. Hence, our problem amounts to the maximization of a supermodular function under cardinality constraints, which is known to be NP-hard in general (see e.g Nagano et al. (2011)). Nevertheless, one can analytically characterize the solutions for some particular cases of interest.

If the intensity of tax evasion $\beta$ is small enough and the $\nu$ links with the largest weight in $G$ can be unambiguously identified, then the social planner can focus on the first order connections in the network and simply target the links of $G$ with the largest weight. Namely, one has:

**Proposition 3.6.** *Assume the $\nu$ links with the largest weight in $G$ can be unambiguously identified, i.e. there exists $\mathcal{L}_\nu(G)$ such that $|\mathcal{L}_\nu(G)| = \nu$ and $g_{i,j} > g_{k,l}$ for all $(i,j) \in \mathcal{L}_\nu(G)$ and all $(k,l) \notin \mathcal{L}_\nu(G)$. Then, for $\beta$ small enough, a solution $h^*$ to $\mathcal{S}_{\nu,\beta}$ is such that:*

$$h^*_{i,j} = \begin{cases} 1 & \text{if } (i,j) \in \mathcal{L}_\nu(G), \\ 0 & \text{otherwise.} \end{cases}$$

If the network $G$ is unweighted and complete, i.e. all tax-evasive paths are equally likely *à priori*, the problem of the social planner amounts to finding from the set of networks with $N$ nodes and $\nu$ links, the one for which the sum of Bonacich centralities is maximal. For small $\beta$, this problem is investigated in detail by Belhaj et al. (2016), building on Abrego et al. (2009). Namely, one has:

**Proposition 3.7.** *Assume for all $\{i,j\} \in N \times N$ that $g_{i,j} = 1$. Then, for $\beta$ small enough, a solution $h^*$ to $\mathcal{S}_{\nu,\beta}$ is either a quasi-star or a quasi-complete network. Moreover,*

- *If $\nu \leq \dfrac{N(N-1)}{2} - \dfrac{N}{2}$, then $h^* = QS(N,\nu)$.*
- *If $\nu \geq \dfrac{N(N-1)}{2} + \dfrac{N}{2}$, then $h^* = QC(N,\nu)$.*

The results from Proposition 3.7 evidence that, if $\beta$ is small enough and if the social planner exerts little influence (measured in terms of the number of nodes and links), then the optimal solution is to design a quasi-star graph $h^* = QS(N,\nu)$. On the other hand, if $\beta$ is small enough and if the social planner exerts great influence over the network, then the optimal solution is to form a quasi-complete graph $h^* = QC(N,\nu)$.

If $\beta$ is large (i.e. $\beta$ tends towards $1/\mu_1(G)$) and the network $G$ is unweighted and complete, *Lemma 2* in Corbo et al. (2006) shows that maximizing the sum of Bonacich centralities is equivalent to the well-known problem in graph theory of finding the graph with a given number of nodes and vertices that has maximal index (see for example Chang and Tam (2011)). A long-standing conjecture on that problem is that its solutions are either quasi-complete or quasi-star graphs (see Aouchiche et al. (2008)

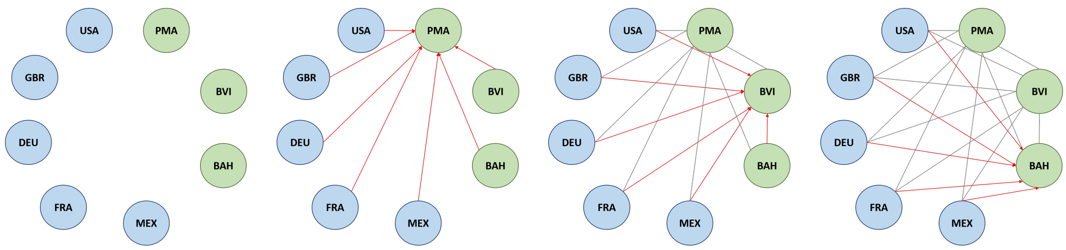
and Cvetkovic et al. (1997) for solutions in some specific cases). In particular, according to *Proposition 1* in Corbo et al. (2006), for $N$ large enough and $N \leq \nu \leq 2N-2$, one has $h^* = QS(N, \nu)$.

The Nash Equilibrium may no longer be unique nor interior if the tax-evasion intensity $\beta$ is 'too large', i.e. $\beta > {}^1/_{\mu_1(G)}$. That is, a subset of nodes would be inactive at equilibrium. These are called partially-cornered equilibria. Nonetheless, since the adjacency matrix of network $G$ is column-stochastic, then its spectral radius is equal to one. This implies that the largest eigenvalue of the adjacency matrix is also equal to one and thus that the Nash Equilibrium is interior and unique for any value of $\beta \in [0, 1)$, which is true by definition of $\beta$. Therefore, this scenario would not affect the optimization problem from the point of view of the social planner and its solution would still be optimal (Corbo et al. (2006)).

This set of results reiterates that the optimal policy for a social planner who aims at deterring tax evasion depends on the structure of the network and on the level of influence that he can exert. If his influence power is low, i.e. he can impact a limited number of links, he shall aim at forming quasi-star structures. That is, to isolate tax havens one after the other. If his level of influence is relatively large, then he shall aim at forming quasi-complete structures, i.e. try to dismantle connections within the core of the network.

### Quasi-star and quasi-complete network structures

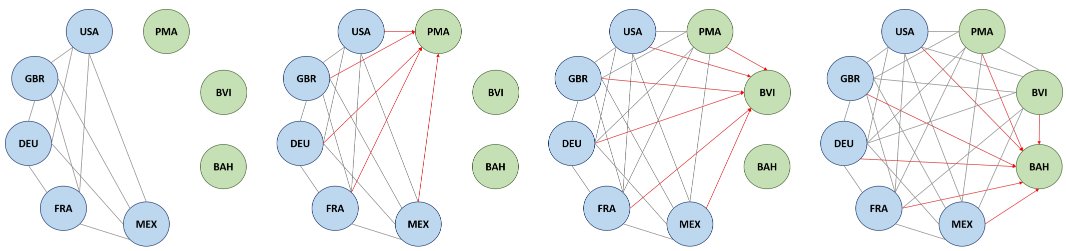
For the sake of further intuition on the interpretation of Proposition 3.6 and Proposition 3.7, Figure 3.1 and Figure 3.2 show the step-by-step formation process of two hub-like structures, where the blue nodes represent a set of generic non-haven countries and the green nodes serve as a group of arbitrary offshore financial centers. Figure 3.1 exhibits the network formation process of a quasi-star graph. The initial condition (Figure 3.1a) is a set of isolated nodes without any existing links. In the first step, all the nodes form a star-graph with the first target (Figure 3.1b). Then, all nodes proceed to the second targeted node (Figure 3.1c). The process repeats recursively (Figure 3.1d), until the network is fully connected.




(a) Step 0 (b) Step 1 (c) Step 2 (d) Step 3

Figure 3.1: Building a complete network by means of quasi-star graphs.

Likewise, Figure 3.2 displays the network formation process of a quasi-complete structure. The initial condition (Figure 3.2a) accounts for a complete cluster of connected nodes and a set of isolated nodes. In the first step, all the nodes from the cluster create a new complete-graph with the first target (Figure 3.2b). Next, the new cluster proceeds to the second targeted node (Figure 3.2c). The process repeats recurrently (Figure 3.2d), until the network is fully connected.




(a) Step 0 (b) Step 1 (c) Step 2 (d) Step 3

Figure 3.2: Building a complete network by means of quasi-complete graphs.

In our context, the optimal strategy is to design a hub-like structure, either a quasi-star or a quasi-complete graph, targeting offshore financial centers according to their Bonacich centrality in the network of international tax evasion. According to Proposition 3.7, if the social planner exerts great influence and possesses an extensive power to establish TIEA treaties between countries, then the optimal strategy would be to link jurisdictions following a quasi-complete network formation process. Following, the social planner should conceive an initial cluster of tax cooperative countries (as the OECD, for example) and recursively expand the tax treaty network by strategically adding new jurisdictions according to their Bonacich centrality in the worldwide network of tax evasion. On the contrary, quasi-star structures for TIEA treaties are optimal for a social planner who exerts little influence. That is, if the number of treaties to be allocated is considerably limited with respect to the number of nodes in the network (see Proposition 3.7), then the budget of links may be depleted before connecting all jurisdictions. Consequently, in the latter case, the social planner should opt to promptly connect the nodes as in a quasi-star network formation processes.

## 3.4 Empirical analysis of the global tax-evasion network

### 3.4.1 Data from the Panama Papers

Our empirical analysis of the global network of tax evasion is based on the Panama Papers, a leaked dataset that has been made publicly available by the International Consortium of Investigative Journalists (ICIJ) in early 2016[5]. The dataset documents the activities of Mossack-Fonseca, a Panamanian firm that was one of the leading providers of offshore financial services (until the leak). A key part of said offshore financial services is the creation of offshore financial entities (shell companies). Our working assumption, throughout the paper, is that the activities of Mossack-Fonseca are representative of these of the offshore financial industry. Evidence to support this claim has been given by Omartian (2017) and Alstadsæter et al. (2018). Omartian (2017) considers the Panama Papers to be potentially representative of the global picture by contrasting them against the Bahamas Leaks; which enlist all entities incorporated in the Bahamas regardless of their offshore service provider. Alstadsæter et al. (2018) find strong similarities between how much each country owns in wealth offshore and the use of tax havens as revealed by the Panama Papers. That is, per country, there is a strong correlation between the amount of wealth held offshore and the number of owners of Mossack-Fonseca offshore financial entities.

The Panama Papers provide 2.6 Terabytes of information on 213,634 offshore financial entities that had been incorporated in different tax havens by Mossack-Fonseca. More precisely, for each entity, the *Entities* file of the Panama Papers discloses the name of the registered financial body, the country of the beneficial owner, the jurisdiction where the entity was created, the incorporation date, the company type and the status of the account[6]. Even though the Mossack law firm began operations in 1977 and joined forces with Fonseca in 1986, the operations leaked in the Panama Papers include information regarding shell companies that date back to 1936[7]. After filtering out the entities for which source country, host country or date of incorporation were missing, we have obtained a consolidated dataset of 212,811 entities ranging from the first entity incorporated in Panama by a Swiss holder in November 1936 to the last offshore account registered for a Chilean resident in Wyoming in December 2015. Each one of these entities potentially allows to conceal wealth from a source country, the one of the owner of the company, to a host country, the one where the company is registered and that generally is a tax haven, in such a way that the identity of the owner is (partly) concealed. Consequently, each offshore financial entity can be seen as a tax-evasion link between two countries.

In the following, the aforementioned offshore financial entities are interpreted as time-stamped links between two countries in the global network of tax evasion. More precisely, we consider networks for which the set of nodes, $N$, is composed by the 161 jurisdictions which appear at least once as a source

[5]The data is available under https://offshoreleaks.icij.org/pages/database.

[6]The dataset in fact comprises 4 other files. The *Addresses* file shows the location where the entity was registered. The *Intermediaries* and *Officers* files show, respectively, the broker and shareholder names assigned to the entity. The *Edges* relate entities, addresses, intermediaries and officers. Moreover, the ICIJ provides three additional datasets on global tax evasion: the *Bahamas Leaks*, the *Offshore Leaks* and the *Paradise Papers*. However, these do not provide enough information to systematically recover the beneficial owner's country of residence, the jurisdiction where the entity was incorporated and the date of incorporation.

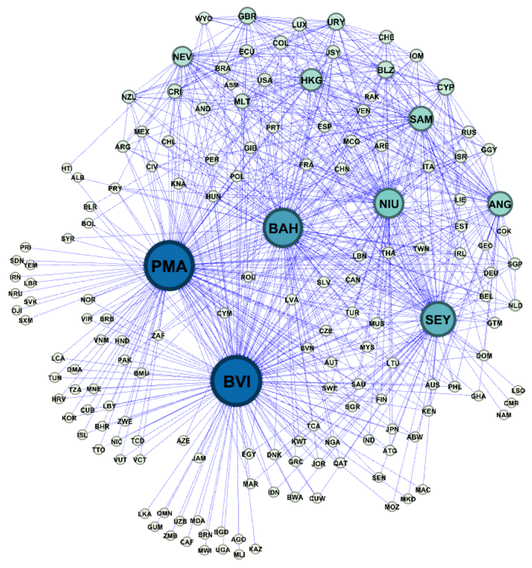
[7]This is due to the fact that registered agents can change over time; so a company may have had a registered agent (a law firm as Mossack-Fonseca) when it was created and years later changed it. We thank the ICIJ and Emilia Diaz Struck for clarifying this question.

or host in the dataset (see Table 3.11 in the Appendix) while the set of links is defined by considering there is a link from country $i \in N$ to country $j \in N$ if and only if there exists an entity incorporated in country $j$ whose owner is located in country $i$.

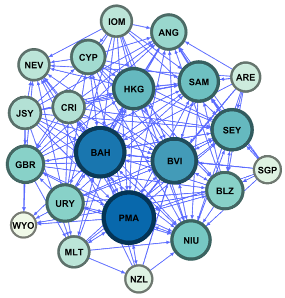
We shall then construct different networks by considering different subsets of links: (i) the cumulative (also referred to as static) network that has all possible links independently of their time stamps, and (ii) dynamic sequences of networks where only links formed within a given year are considered. All the networks treated are directed (from source to host country) but we will study both unweighted and weighted networks, where the weight corresponds to the number of entities incorporated during the period under consideration. Finally, entities where source and host countries happened to be the same country were neglected, which allows us to consider only simple graphs (i.e. without self-loops).

### 3.4.2 Global structure of the tax-evasion network

The existing literature hints at the complex nature of tax-evasion mechanisms. Garcia-Bernardo et al. (2017) highlight the elaborate nature of tax-evasion circuits implemented by multinational companies. The reallocation of funds among offshore centers after the G20 tax haven crackdown, which has been put forward by Johannesen and Zucman (2014), emphasizes the adaptive capacity of the tax-evasion system. In this subsection, we investigate whether these complex adaptive features are reflected in the network structure. We start by representing the structure of the complete network of global tax evasion, where a link is formed from source $i$ to host $j$ if at least one entity was incorporated between the two jurisdictions in the entire registries of the Panama Papers. The inter-temporal tax-evasion network (containing all links independently of their time stamps) is represented in Figure 3.3a. Node size and color are related to the connectivity level of each jurisdiction. It is immediate to see the pronounced heterogeneity among jurisdictions, where Panama (PMA), British Virgin Islands (BVI), Bahamas (BAH), Seychelles (SEY) and Niue (NIU) are highly connected, while more than a hundred nodes are weakly linked.




(a) Complete network.

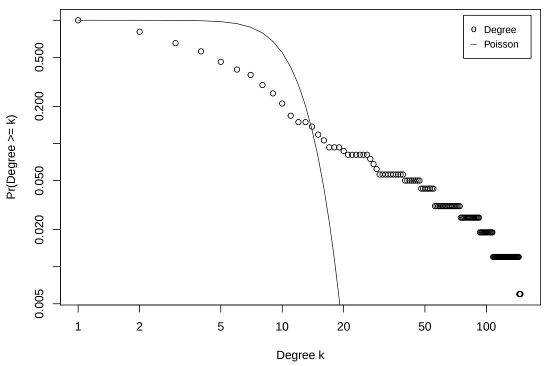



(b) Core of the network.

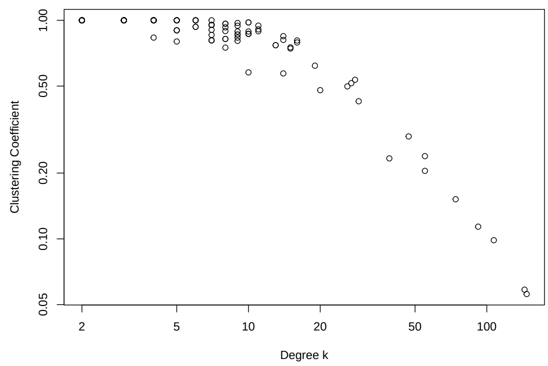
Figure 3.3: Graphical representation of the complete inter-temporal network (left panel) and the empirically observed core of the tax-evasion network evidenced by the Panama Papers (right panel). The size and the color intensity of the nodes are proportional to their degree (i.e. to their number of connections).

In the empirical tax-evasion network, wealth is concealed from source countries towards host offshore financial centers. Intuitively, this network formation process potentially induces a core-periphery structure, where the periphery of the of the network is constituted by the source countries and the core of the network by the host jurisdictions. Hence, *à priori*, the global tax-evasion network plausibly has a core-periphery structure organized around said host jurisdictions. Figure 3.3b exhibits the core of the network as a subgraph of the structure presented in Figure 3.3a. Size and color of nodes are proportional to their connectivity, considering only core jurisdictions. Compared to the complete network, the node heterogeneity inside the core is noticeably less pronounced. Evidently, this is a natural result of considering only 21 nodes out of 161. However, this outcome also exposes the strong relationships inside the core. The core of empirical offshore financial centers is highly connected, and each jurisdiction in the core can be reached via a sequence of directed links from every other jurisdiction in the core. In consequence, this high connectivity sheds light on the use of multi-layered structures (re-wiring) to conceal wealth described by Omartian (2017).

Clearly, the general structure illustrated in Figure 3.3a is complex and hard to discern in plain sight. To formally identify the network topology, we follow the procedures detailed by Li and Schürhoff (2019) and present the results in Figure 3.4. In particular, Figure 3.4a shows how the network's empirical degree distribution is fat-tailed compared to the respective (Poisson) degree distribution of a random network. This log-log scale plot illustrates that about 85% of countries are weakly connected. However, about 5% of nodes have more than 50 partner jurisdictions, and 2% have more than 100. Hence, compared with a Poisson distribution, the network of global tax evasion has a higher level of connectedness heterogeneity among nodes. Figure 3.4b details the local-connectedness of jurisdictions, where the degree distribution across nodes is plotted against the clustering coefficient of each jurisdiction. The clustering coefficient measures the extent to which the connections of a node are linked among themselves. A low clustering coefficient indicates that links are highly specific to a node, and the negative slope of the degree-clustering relationship indicates that high-degree nodes receive links preferentially as in a core-periphery (or nested-split) graph. As illustrated, the high-degree nodes are also privileged connections: the negative slope of the degree-clustering relationship reveals that high degree nodes receive specific links. That is, the neighbors of low-degree nodes are highly connected; while the neighbors of high-degree nodes are mostly isolated. This is indicative of a hierarchical structure in which nodes receive links according to a priority order which is highly correlated with the degree. This hierarchical structure, together with the node heterogeneity and the heavy-tailed degree-distribution, suggest that the empirical tax-evasion network has the topological characteristics of a core-periphery network (Li and Schürhoff (2019)). This finding provides factual and empirical support for the selection of the model presented in Section 3.3.




(a) Comparing the empirical node-degree distribution to that of a random graph (Poisson).




(b) Local connectedness: comparing the clustering coefficients to the node degrees.

Figure 3.4: Analysis of the degree-distribution heterogeneity (log-log plot, left panel) and the relation between node degrees and clustering coefficients (log-log plot, right panel).

One specific feature of the network is that, among the 161 nodes, only 21 have an incoming link (i.e. Mossack-Fonseca incorporated at least one entity). These offshore financial centers compose the core structure of the network. The corresponding core-jurisdictions are listed in Table 3.1. These host jurisdictions correspond, unambiguously, to offshore financial centers. Noticeably, they hold the key features that have been put forward by Dharmapala and Hines Jr. (2009) as characteristic of tax havens. A series of two-sample *t-tests* confirmed that the core jurisdictions have smaller populations, higher GDP *per capita* and higher governance indices than the peripheral jurisdictions, at a 1% significance level.

| Code | Jurisdiction | Pop. | GDP pc | Gov. Ind. | Hub Dist. | Haven | Eng. | Brit. Law |
|---|---|---|---|---|---|---|---|---|
| ANG | Anguilla | 14.61 | 22,596.89 | 0.86 | 3,600 | 1 | 1 | 1 |
| ARE | UAE | 9,154.30 | 39,122.05 | 0.57 | 5,240 | 0 | 0 | 1 |
| BAH | Bahamas | 386.84 | 30,483.82 | 0.86 | 2,125 | 1 | 1 | 1 |
| BLZ | Belize | 359.29 | 4,950.26 | -0.2 | 3,300 | 1 | 1 | 1 |
| BVI | Brit. Virg. Ilds | 30.11 | 31,697.83 | 0.93 | 2,420 | 1 | 1 | 1 |
| CRI | Costa Rica | 4,807.85 | 11,393.02 | 0.69 | 3,575 | 0 | 0 | 0 |
| CYP | Cyprus | 1,160.98 | 23,212.22 | 0.94 | 3,290 | 1 | 0 | 1 |
| GBR | United Kingdom | 65,128.86 | 44,305.55 | 1.45 | 320 | 0 | 1 | 1 |
| HKG | Hong Kong | 7,291.30 | 42,431.89 | 1.39 | 2,940 | 1 | 1 | 1 |
| IOM | Isle Of Man | 83.17 | 81,672.02 | 1.45 | 320 | 1 | 1 | 1 |
| JSY | Jersey | 100.47 | 73,569.64 | 1.45 | 440 | 1 | 1 | 1 |
| MLT | Malta | 445.05 | 23,759.03 | 1.03 | 1,740 | 1 | 1 | 0 |
| NEV | Nevada (US) | 2,883.06 | 44,026.00 | 1.25 | 140 | 0 | 1 | 1 |
| NIU | Niue | 1.63 | 19,025.57 | -0.67 | 9,280 | 0 | 1 | 1 |
| NZL | New Zealand | 4,595.70 | 38,649.38 | 1.85 | 9,280 | 0 | 1 | 1 |
| PMA | Panama | 3,969.25 | 13,684.13 | 0.15 | 3,590 | 1 | 0 | 0 |
| SAM | Samoa | 193.76 | 4,149.41 | 0.68 | 9,280 | 0 | 1 | 1 |
| SEY | Seychelles | 93.42 | 14,725.10 | 0.46 | 8,940 | 0 | 1 | 0 |
| SGP | Singapore | 5,535.00 | 54,940.86 | 1.46 | 5,300 | 1 | 1 | 1 |
| URY | Uruguay | 3,431.55 | 15,524.84 | 0.94 | 8,560 | 0 | 0 | 0 |
| WYO | Wyoming (US) | 586.10 | 57,182.00 | 1.25 | 140 | 0 | 1 | 1 |
| | **Sample Average** | **8,580.26** | **17,555.85** | **0.06** | **3,689** | **0.23** | **0.37** | **0.34** |

Table 3.1: Characteristics of countries in the core of the tax-evasion network. *Pop.* refers to population (2015) expressed in thousands. *GDP pc* indicates GDP *per capita* in USD (2015). *Gov. Ind.* refers to governance index (from the World Bank worldwide governance indicators, ranged from -2.5 to 2.5). *Hub. Dist* measures the distance to the closest major trade hub (Rotterdam, New York City or Tokyo), Haven denotes a 1 if the jurisdiction was labeled as a tax haven by Dharmapala and Hines Jr. (2009) and 0 otherwise, *Eng.* is a dummy variable indicating for English as the main language and *Brit. Law* a dummy variable for British law origins (from the database of Dharmapala and Hines Jr. (2009)).

A node centrality ranking with aggregate data from 1936 to 2015 is featured in Table 3.2. Column (1) confirms the high in-degree connectivity attained by core jurisdictions. More importantly, Column (2), Column (3) and Column (4) show that these financial offshore centers are also characterized by high levels of Bonacich centrality for three different values of arbitrarily chosen $\beta \in \{0.01, 0.05, 0.10\}$. The rankings displayed in Table 3.2 relate to the dynamics of tax-evaded wealth defined in Proposition 3.1.

| Centrality levels of wealth concealers | | | |
|---|---|---|---|
| (1) In-Degree | (2) Bonacich ($\beta = 0.01$) | (3) Bonacich ($\beta = 0.05$) | (4) Bonacich ($\beta = 0.10$) |
| BVI | BVI | BVI | BVI |
| PMA | PMA | PMA | PMA |
| BAH | BAH | BAH | BAH |
| SEY | SEY | SEY | SEY |
| NIU | NIU | NIU | ANG |
| ANG | ANG | ANG | NIU |
| SAM | SAM | SAM | HKG |
| NEV | NEV | HKG | SAM |
| HKG | HKG | NEV | NEV |
| BLZ | BLZ | BLZ | BLZ |
| GBR | CYP | GBR | WYO |

Table 3.2: A centrality ranking with aggregate data from 1936 to 2015 features how the tax havens in the core, which attain a high node-degree, are also characterized by high levels of Bonacich centrality.

The previously introduced core-periphery structure remarks the partition of countries between sources (the periphery) and hosts (the core) of tax evasion. Moreover, it emphasizes the complex structure of tax-evasion circuits. Indeed, the fact that the core is formed by a set of tax havens emphasizes the plausibility that incoming funds are likely to be rerouted towards other offshore financial centers. Table 3.3 demonstrates that this rerouting of funds among tax havens constitutes one of the key activities of the network. In particular, the first two columns show that more than 13% of the entities where incorporated in the British Virgin Islands (BVI) by a Hong Kong (HKG) beneficiary and that the 10 most prominent links account for almost half of the total offshore registries. The second two columns show that BVI holds more than 50% of the listed offshore accounts and that a group of four countries (British Virgin Islands, Panama, Bahamas and Seychelles) holds roughly 90%. The third pair of columns highlight the role of Switzerland (CHE) and Hong Kong (HKG) as major sources of tax–evaded wealth. As a matter of fact, some of the countries with the largest number of incoming links, such as Panama or Hong-Kong, also have large numbers of outgoing links. The activity rates presented in Table 3.3 confirm that funds incoming into a tax haven are rerouted towards other tax havens, most likely to reduce tractability of the funds, as suggested by Johannesen and Zucman (2014) and Omartian (2017). Hence the empirical network is not a collection of random bilateral links that operate independently, but a complex structure.

| Country Pair | Activity % | Host | Activity % | Source | Activity % |
|---|---|---|---|---|---|
| BVI-HKG | 13.30% | BVI | 54.82% | CHE | 18.52% |
| BVI-CHE | 9.60% | PMA | 20.62% | HKG | 18.50% |
| PMA-CHE | 5.66% | BAH | 7.56% | JSY | 6.98% |
| BVI-JSY | 5.11% | SEY | 7.23% | LUX | 5.29% |
| PMA-LUX | 2.73% | NIU | 4.62% | PMA | 4.75% |
| BVI-GBR | 2.65% | SAM | 2.52% | GBR | 4.67% |
| BVI-PMA | 2.34% | ANG | 1.57% | GGY | 3.58% |
| BVI-GGY | 2.30% | NEV | 0.62% | ARE | 3.55% |
| SEY-HKG | 1.83% | HKG | 0.20% | URY | 2.39% |
| BVI-SGP | 1.77% | BLZ | 0.06% | IOM | 2.39% |
| Other 800: | 52.70% | Other 11: | 0.19% | Other 149: | 29.37% |

Table 3.3: Activity rates for the 10 most prominent country pairs, 10 most active host jurisdictions and 10 most active source countries, measured by the share of offshore entities created.

From a conceptual point of view, our results uncover that the global network of tax evasion genuinely is a complex network, characterized by a core-periphery structure and a fat-tail degree distribution. This suggests that the process of network formation is not random but rather driven by a process in which network characteristics matter for link formation, as in Barabasi and Albert (1999) and Jackson and Rogers (2007). In other words, tax-evasion links (offshore financial entities) are created in a systemic perspective that accounts not only for the individual characteristics of the tax havens but also for their position in the tax-evasion network, e.g. in contemplation of further routing possibilities for tax-evaded wealth as emphasized above.

**Dynamics of network formation**

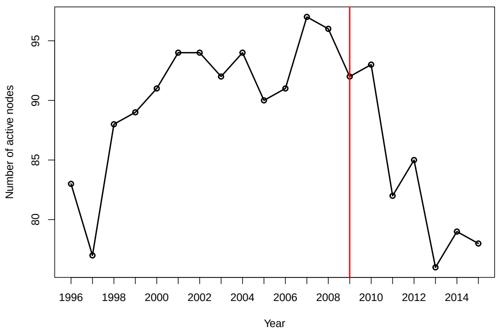
In order to determine the robustness of the preceding results, and to gain a better understanding of the dynamics of network formation, we investigate the properties of the time series derived from the networks obtained by restricting our attention to links formed within an annual time-window. In other words, the network of period $t$ contains a link between country $i$ and country $j$ if an offshore entity was created in country $j$ by an agent of country $i$ during period $t$. Our dynamic analysis focuses on the last twenty years of the database, from January 1996 to December 2015, which account for over 80% of the available registries.

The key features of the network dynamics over this period are displayed in Figure 3.5. First, Figure 3.5a shows that the number of active jurisdictions grew relatively steadily from 1996 until 2008, and then faced a steep negative trend after 2009. Likely, the downturn was caused by the tax information exchange obligations imposed by the G20 on offshore financial centers and not only as a collateral effect of the 2007–2008 financial crisis. Moreover, Figure 3.5b presents a rapidly increasing number of links from 1996 to 2007, followed by an abrupt decline in 2008 and 2009, possibly induced by the financial crisis. After 2009, the number of links formed annually continuously decreased, albeit inconsistently. It is important to note in this respect that entities can be created by anticipation by a provider of offshore financial services in order to furnish future tax-evading offshore entities with some historical legitimacy[8]. Hence, the empirical network observed in year $t$ partly accounts for the demand of tax-evasion channels anticipated by the provider of offshore financial services. Moreover, the decrease in the number of nodes is

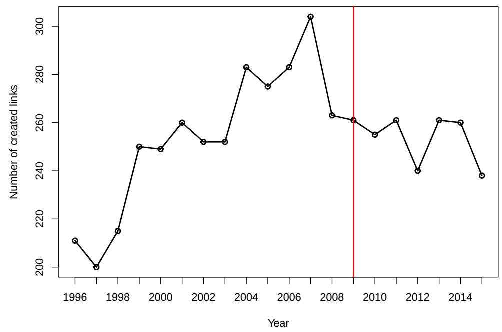
[8]These are also known as 'shelf' companies, see Carr and Grow (2011) and Alvarez and Marsal (2017).

larger in magnitude and in duration than that of the number of links, implying that the shock incidentally caused an increase in the density of the network.

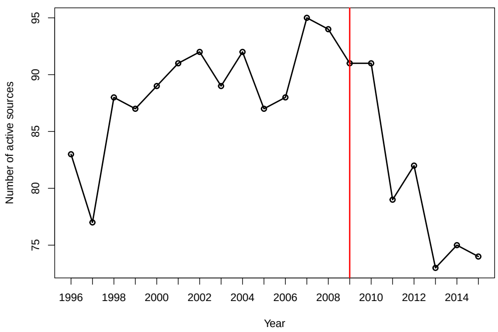
The annual evolution of the number of jurisdictions actively involved in operations with Mossack-Fonseca is dissected in Figure 3.5c and Figure 3.5d. On the one hand, Figure 3.5c illustrates a clear-cut drop in the number of source countries involved with Mossack-Fonseca after 2009. Reasonably, the G20 crackdown on tax evasion prevented further wealth concealment from several sources. Thus, TIEA's may have produced a deterrence effect for some non-haven countries as suggested by Johannesen and Zucman (2014). On the other hand, Figure 3.5d delineates a persistent increment in the number of host jurisdictions employed as offshore financial centers. Conceivably, the G20 policy enforced in 2009 urged providers of offshore financial services to 'get creative' and lure new jurisdictions into adopting wealth concealment operations. This result sheds light on the hypothesis of Elsayyad and Konrad (2012) in which new jurisdictions become fiscal paradises seeking to profit from new or additional 'tax haven business'.



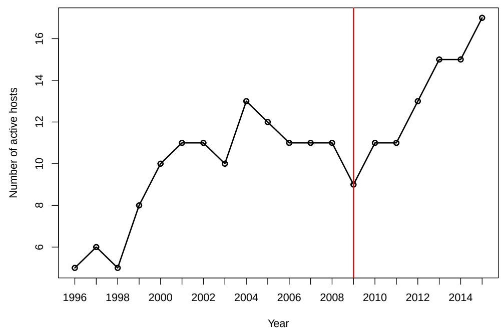

(a) Number of active nodes per year.




(b) Number of links created per year.



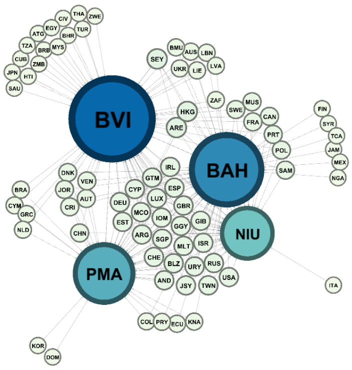

(c) Number of active sources per year.



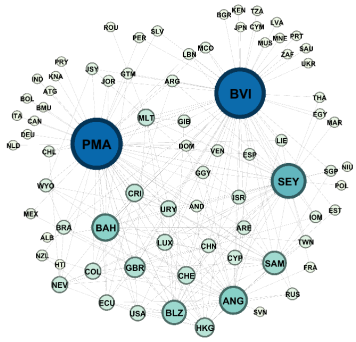

(d) Number of active hosts per year.

Figure 3.5: Dynamic evolution of the tax-evasion network, with annual data from 1996 to 2015. Observed number of active (a) nodes, (b) links, (c) sources and (d) hosts in the network.

In Figure 3.6, the structure of the tax-evasion network is represented at the start (1996, Figure 3.6a) and at the end (2014, Figure 3.6b) of the considered time period. Although the structural features of the network remained stable over time, the roles of individual jurisdictions evolved significantly. For example, Niue and Bahamas lost preference while Seychelles or Anguilla gained centrality over time. Also, Panama and the British Virgin Islands have consistently maintained a very high centrality. Additionally, several new offshore financial centers came into view between 1996 and 2014.



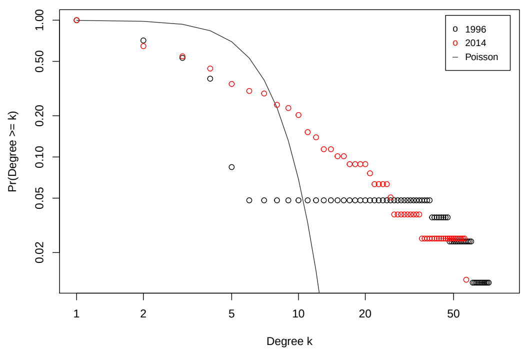

(a) Tax-evasion network in 1996.



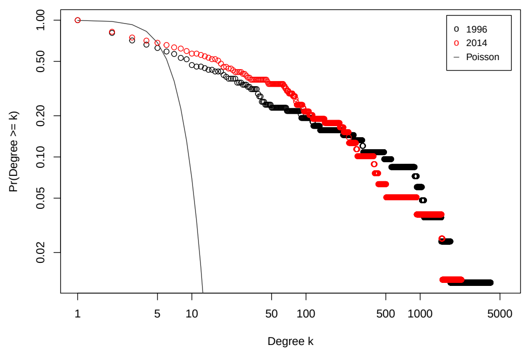

(b) Tax-evasion network in 2014.

Figure 3.6: Structure of the tax-evasion network at the start and at the end of the considered time period.

The temporal evolution of the unweighted and weighted degree distributions of the global tax-evasion network are shown in Figure 3.7. The unweighted degree distributions in Figure 3.7a show a slight increment in the fattening of the body from 1996 to 2014. Nonetheless, such fattening of the body does not restore the fat tails phenomenon. Likewise, Figure 3.7b exhibits a steady presence of heavy tails in the weighted degree distributions. Conclusively, the existence of fat tails has persisted along different time periods. From a structural perspective, Figure 3.6 and Figure 3.7 feature the persistence of a core-periphery structure and of fat-tails.




(a) Unweighted degree distributions.




(b) Weighted degree distributions.

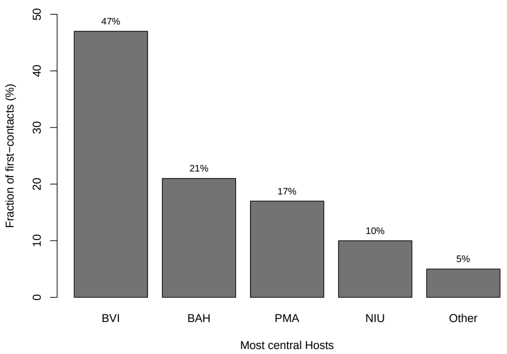
Figure 3.7: Temporal evolution of the unweighted and weighted degree distributions of the network.

This persistence of the core-periphery structure may also be explained by the stability of tax-evasion links. Indeed, as detailed in Table 3.4, 75% of inter-jurisdictional links remain stable on a year-to-year basis, and this figure increases to 85% if considering only core jurisdictions.

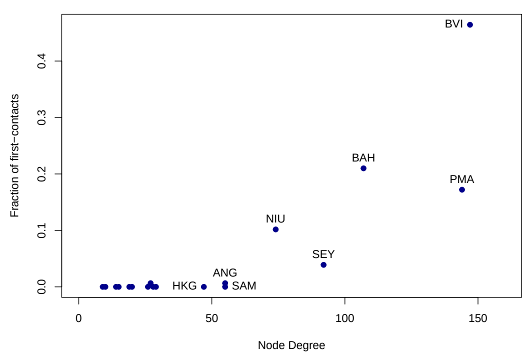
| | Link next year | | | |
|---|---|---|---|---|
| | All nodes | | Core nodes | |
| Link this year | =0 | =1 | =0 | =1 |
| =0 | 88% | 12% | 87% | 13% |
| =1 | 25% | 75% | 15% | 85% |

Table 3.4: Stability of node centrality: from 1996 to 2015

The intuition behind the presence of fat tails can be further explained by an analysis of the micro-level dynamics of the network. Source countries may conceal their wealth offshore by forming links with more than one jurisdiction. Naturally, one of such offshore financial centers must be the first node with which a link is formed from a given source country. Denote this offshore financial center as the 'first-contact' destination of concealed wealth from said source country. Figure 3.8 gives evidence that newly formed offshore financial entities are directed preferentially towards high-degree jurisdictions. Figure 3.8a shows the hegemony sustained by a few jurisdictions which act as prominent 'first-contact' destinations for concealed wealth. Namely, 47% of offshore financial entities were created in the British Virgin Islands, 21 % in the Bahamas, 17% in Panama and 10% in Niue. Figure 3.8b presents a noticeable correlation between the node-degree of tax havens and the fraction of 'first-contacts'. This correlation between degree and linkage probability is consistent with the preferential attachment process, which is well-known to lead to scale-free degree distributions, as discussed in detail by Barabasi and Albert (1999). Indeed, for the years 2010 to 2015, the null hypothesis that the degree distribution of the network follows a power-law distribution is not rejected by a goodness-of-fit test following the bootstrap procedure of Clauset et al. (2009). Indirectly, the presence of fat tails and an apparent preferential-attachment behavior may provide empirical support to the theoretical model of Konrad and Stolper (2016), in which investors obtain strategic complementarities by investing in the same tax haven.




(a) Fraction of 'first-contacts' held by the most central host jurisdictions.




(b) Relationship between node degree and the fraction of 'first-contacts'.

Figure 3.8: Newly formed financial offshore entities are directed preferentially towards high-degree nodes.

## 3.5 Determinants of network formation

The theoretical model introduced in Section 3.3 characterizes an optimal strategy from the point of view of a global or international social planner. Factual proofs to support the notion of a global (inter-jurisdictional) tax authority include the European Union Savings Directive (EU-SD) in 2005, the G20 crackdown on tax havens in 2009, the FATCA federal law approved by the U.S. in 2010 and the more recent Common Reporting Standards published by the OECD's Global Forum on transparency and exchange of information for tax purposes in 2018. Another working assumption of our model is the deterrence effect of tax information regulations (TIEA's, EU-SD, FATCA, etc.) on tax-evasive behavior. Substantial evidence to support this claim is available in the literature (Zucman (2013); Johannesen and Zucman (2014); Braun and Weichenrieder (2015); Caruana-Galizia and Caruana-Galizia (2016); Omartian (2017); Bennedsen and Zeume (2018); Johannesen et al. (2018); Andersson et al. (2019)). Nonetheless, the current section deals with confirming the deterrence effect of TIEA's in our context.

In order to gain further insights on the economic drivers of network formation and on the impact of the G20 tax haven crackdown on the structure of the network, we perform an econometric analysis of the determinants of bilateral link formation. As noted by Braun and Weichenrieder (2015), Caruana-Galizia and Caruana-Galizia (2016) and Omartian (2017), the information presented in the Panama Papers does not include the amount of bilateral deposits, nor any other monetary variable. In order to overcome this caveat in the data, we interpret the sequence of annual networks inferred in the preceding sections as a panel dataset of bilateral links. More precisely, we use a linear probability panel data model to estimate the determinants of the binary link formation variable $L_{i,j,t}$, which assumes a value of 1 if there was at least one offshore financial entity incorporation from source jurisdiction $i$ to host jurisdiction $j$ in year

$t$, and a value of 0 otherwise. The data covers 20 years, from 1996 to 2015, and accounts for 178,163 registered offshore financial entities. Building on the results of the previous sections, the set of host jurisdictions is restricted to those that have at least one incoming link, i.e. those that were explicitly documented as offshore financial centers by the Panama Papers. Following Johannesen and Zucman (2014), we consider the existence of a tax treaty between countries as the key policy determinant of link formation. We thus examine the complete set of endorsed tax agreements as in Johannesen and Zucman (2014). A fundamental remark in this respect is that the authors distinguish among different types of tax treaties: tax information exchange agreements, double taxation conventions, whether treaties followed the OECD standard, and whether treaties included Article 26 (which provides for information exchange on request). Hence, our analysis aims to estimate the impacts of these bilateral tax agreements distinguishing between two different categories: considering all tax treaties versus only considering TIEA's. Hence, we adopt the following linear probability panel data model specification.

$$L_{i,j,t} = \alpha + \beta \text{Treaty}_{i,j,t-1} + \theta_{i,j} + \xi_t + \epsilon_{i,j,t}. \tag{3.8}$$

Here, the outcome variable $L_{i,j,t}$ equals 1 if there is a link (at least one offshore financial entity incorporation) from jurisdiction $i$ to jurisdiction $j$ in period $t$, and 0 otherwise. Analogous binary transformations have been employed in panel data regressions by Braun and Weichenrieder (2015) and Omartian (2017). The dummy variable $\text{Treaty}_{i,j,t-1}$ indicates the presence or absence of a tax treaty between countries $i$ and $j$ in period $t-1$ (see details below). Moreover, pairwise fixed effects $\theta_{i,j}$ and time fixed effects $\xi_t$ were employed to take into account any other external means of influence in the panel data setup, such as distance between jurisdictions, same legal origins, same language, commonalities and time trends (analogous to Johannesen and Zucman (2014); Braun and Weichenrieder (2015); Omartian (2017)). Lastly, $\epsilon_{i,j,t}$ is the error term[9]. Furthermore, we consider two variants of the explanatory variable $\text{Treaty}_{i,j,t-1}$ in the regression defined in Equation 3.8: (i) the existence of any treaty and (ii) the existence of a tax information exchange agreement (TIEA). In this context, the main element of interest is the coefficient $\beta$, which measures the effect of an existing tax treaty (either *Any* or *TIEA*) between source $i$ and host $j$ at time $t$. Our results are reported in Table 3.5. All regressions consider annual observations from 1996 to 2015 and have double-clustered robust standard errors at the pairwise and time levels.

The efficiency of the G20 approach has also been questioned on the basis of the fact that a large number of TIEA's have been signed among tax havens, raising doubts about their actual enforcement (Johannesen and Zucman (2014); Bilicka and Fuest (2014)). In order to investigate this issue, we have further specialized our econometric analysis by distinguishing three types of jurisdictional sources: all sources; non-haven countries, as defined by Dharmapala and Hines Jr. (2009)); and core jurisdictions, explicitly identified as tax havens in the Panama Papers. In our analysis, we estimate separately the regression model introduced in Equation 3.8 for each treaty-type and source-type combination. Hence, Columns 1, 3 and 5 deal with regressions which consider all types of tax treaties between country pairs; while Columns 2, 4 and 6 restrict the independent variable to account for TIEA-type tax treaties only. Moreover, Columns 1 and 2 consider all types of sources, Columns 3 and 4 limit sources to non-haven countries, and Columns 5 and 6 restrict sources to core jurisdictions. Row (i) shows the estimated coefficients for unspecified (any) tax treaties, while row (ii) shows the estimated coefficients considering only TIEA-type treaties. All specifications indicate that tax treaties deter the probability of link formation between two jurisdictions; thus giving support to our working assumption.

On the one hand, Columns 1, 3 and 5 show a negative yet not statistically significant coefficient for all three specifications. Likely, these results suggest a high variability among treaty types. On the other hand, Columns 2, 4 and 6 offer evidence of a statistically significant deterrence effect of TIEA's on link formation probability. An advantage of linear probability models is that the coefficients are directly interpretative. For all jurisdictions, a TIEA would diminish the probability of link formation by 6% at a 10% significance level. This magnitude would increase to 10% at a 5% significance level if the source would be a non-haven country. Lastly, the deterrence effect would amount to 12% at a 1% significance level if the source would be a core-jurisdiction. Further robustness checks were performed on the regression results. The coefficients shown in Table 3.5 are robust to double-clustering, Newey-West and White standard errors, probit and logit link functions, and remain statistically significant after controlling for source and host specific covariates: GDP, population and Governance Index (see Appendix). In addition, the

[9]As a remark, although it would have been interesting to include a measure of centrality as an explanatory variable in Equation 3.8, it is almost certain that this would have generated endogeneity problems with respect to the interpretation of the network coefficients, particularly since the attractiveness of a tax haven can change over time.

Table 3.5: Panel regressions of link formation probability on treaty signature

| Variables | Hosts: All | | | | | |
|---|---|---|---|---|---|---|
| | Source: All jurisdictions | | Source: Non-haven jurisd. | | Source: Core jurisdictions | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| (i) $Treaty = Any$ | -0.0042 | | -0.0250 | | -0.0363 | |
| | (0.0361) | | (0.0386) | | (0.0380) | |
| (ii) $Treaty = TIEA$ | | -0.0637* | | -0.1035** | | -0.1248*** |
| | | (0.0360) | | (0.0404) | | (0.0394) |
| Observations | 16,060 | 16,060 | 11,020 | 11,020 | 12,880 | 12,880 |
| No. of country pairs | 803 | 803 | 551 | 551 | 644 | 644 |
| Number of years | 20 | 20 | 20 | 20 | 20 | 20 |
| Pairwise fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Time fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |

Signif. codes: '***' 0.01 '**' 0.05 '*' 0.10 ' ' 1

Notes: Panel data regressions with linear probability function, where the $p$-values are based on double-clustered robust standard errors. The dependent dichotomous variable measures the existence or non-existence of a link formation between source $i$ and host $j$ at time $t$. The sample period considers annual data from 1996 to 2015. The variable of interest is $Treaty_{i,j,t-1}$, and it is split in two dummy variables: (i) *Treaty* = *Any* if any tax treaty exists between source $i$ and host $j$ at time $t-1$, and (ii) *Treaty* = *TIEA* if a tax information exchange agreement treaty (as defined by Johannesen and Zucman (2014)) exists between source $i$ and host $j$ at time $t-1$.

negative coefficients for TIEA treaties in Columns 2, 4 and 6 remain statistically significant considering monthly data at 10%, 10% and 5% significance levels, respectively.

Our results are consistent with the existing literature. Moreover, Johannesen and Zucman (2014), Bilicka and Fuest (2014), Braun and Weichenrieder (2015) and O'Donovan et al. (2019) find that economic activity between jurisdictions is not a reliable predictor of treaty signature. That is, reverse causality is unlikely, and tax treaties may be seen as orthogonal to the dependent variable in our context. Indeed, Braun and Weichenrieder (2015) fit a two-stage regression-based endogeneity test and conclude that there are no endogenous issues between tax treaty signatures and the binomial transformation of the number of incorporated entities, as $L_{i,j,t}$ in our context. Consequently, we find that tax information exchange agreements (TIEA's) have a negative and statistically significant impact on link formation, whereas non-specific treaties do not have a statistically significant impact. This suggests that coordinated policies, such as the G20 crackdown on tax havens, may have an impact on tax evasion but that the type of treaties enforced is crucial. Also, we find that TIEA's between source and host jurisdictions have a curbing effect on the annual probability of link formation, where both magnitude and statistical significance are conditional on the nature of the source. Moreover, given that not all bilateral transactions are related to tax evasion, and presumably only illegal activities are affected by TIEA's, we may assume that the coefficients presented in Table 3.5 delimit a lower bound and could be even more pronounced for tax-evaded wealth (Johannesen and Zucman (2014)).

For robustness, we propose a complementary analysis of link activity levels, i.e. the number of newly incorporated entities on treaty signature. Similar to Omartian (2017), we consider a logarithmic transformation of the total number of incorporated entities[10] between source $i$ and host $j$ at time $t$:

$$A_{i,j,t} = \ln(1 + Incorporations_{i,j,t}).$$

Thus, we employ the corresponding standard OLS panel data model specification.

$$A_{i,j,t} = \alpha + \beta \text{Treaty}_{i,j,t-1} + \theta_{i,j} + \xi_t + \epsilon_{i,j,t}, \tag{3.9}$$

where the dependent variable $A_{i,j,t}$ measures the logarithmic activity level of newly incorporated entities between source $i$ and host $j$ at time $t$. Analogous to Equation 3.8, the binary variable $\text{Treaty}_{i,j,t-1}$

[10]Number of incorporations plus one, to avoid ln(0).

indicates the presence of a tax treaty between countries $i$ and $j$ in period $t-1$. Pairwise fixed effects $\theta_{i,j}$ and time fixed effects $\xi_t$ are employed to control for external factors of influence, and $\epsilon_{i,j,t}$ is the error term. Once again, separate regressions were estimated by treaty and source types. These complementary results are reported in Table 3.6. All specifications employ annual observations from 1996 to 2015 and account for double-clustered robust standard errors at the pairwise and time levels.

The link incorporation activity levels presented in Table 3.6 respond to tax treaties equivalently to the previously discussed probabilities of link formation. For unspecified tax treaties, Columns 1, 3 and 5 show negative and not statistically significant coefficients for all three regressions. Albeit unspecified tax treaties may deter link activity levels, there are reasons to believe that the variability is high among treaty types. Accordingly, Columns 2, 4 and 6 exhibit a statistically significant deterrence effect of TIEA tax treaties on link activity levels. Applying an exponential transformation, one can recover the estimated impact of a TIEA signed between source $i$ and host $j$ conditional on the source's type. For all (unspecified) sources, a TIEA would deter link activity levels by 16% at a 5% significance level. Restricting for non-haven countries, the impact would increase to 18% at a 5% significance level. Inside the core, however, a TIEA would curb link incorporation activity by 22% at a 1% significance level[11]. Analogously, further robustness checks were implemented: the estimated coefficients shown in Table 3.6 are robust to double-clustering, Newey-West and White standard errors, probit and logit link functions, and remain statistically significant after controlling for source and host specific covariates: GDP, population and Governance Index (see Appendix). Additionally, there are no incidental parameter problems whenever using an OLS function. Once more, there are no indications of endogenous issues nor reverse causality between TIEA's and link activity levels reported in related literature (Johannesen and Zucman (2014); Bilicka and Fuest (2014); Braun and Weichenrieder (2015); Caruana-Galizia and Caruana-Galizia (2016); Omartian (2017)).

Table 3.6: Panel regressions of link incorporation activity on treaty signature

| Variables | Hosts: All | | | | | |
|---|---|---|---|---|---|---|
| | Source: All jurisdictions | | Source: Non-haven jurisd. | | Source: Core jurisdictions | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| (i) $Treaty = Any$ | -0.0442 | | -0.0206 | | -0.1006 | |
| | (0.0798) | | (0.0795) | | (0.0734) | |
| (ii) $Treaty = TIEA$ | | -0.1727** | | -0.2022** | | -0.2452*** |
| | | (0.0807) | | (0.0824) | | (0.0802) |
| Observations | 16,060 | 16,060 | 11,020 | 11,020 | 12,880 | 12,880 |
| No. of country pairs | 803 | 803 | 551 | 551 | 644 | 644 |
| Number of years | 20 | 20 | 20 | 20 | 20 | 20 |
| Pairwise fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Time fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |

Signif. codes: '***' 0.01 '**' 0.05 '*' 0.10 ' ' 1

Notes: Panel data regressions with standard OLS function, where the $p$-values are based on double-clustered robust standard errors. The dependent variable measures entity incorporation activity (as defined by Omartian (2017)) between source $i$ and host $j$ at time $t$. The sample period considers annual data from 1996 to 2015. The variable of interest is $Treaty_{i,j,t-1}$, and it is split in two dummy variables: (i) *Treaty = Any* if any tax treaty exists between source $i$ and host $j$ at time $t-1$, and (ii) *Treaty = TIEA* if a tax information exchange agreement treaty (as defined by Johannesen and Zucman (2014)) exists between source $i$ and host $j$ at time $t-1$.

The persistent effect of TIEA treaties is reiterated by additional robustness checks available in the Appendix. Nonetheless, one particular regression specification suggests that TIEA treaties signed between *non-core* tax haven sources and core financial offshore centers do not have a statistically significant deterrence impact on link formation probability (see Table 3.10 in the Appendix). A similar finding was reported by Johannesen and Zucman (2014). Non-core tax haven sources are jurisdictions that do not

[11] The corresponding transformations are: $e^{-0.1727}-1=-0.1586$; $e^{-0.2022}-1=-0.1830$; $e^{-0.2452}-1=-0.2174$.

belong to the core of the global tax-evasion network in our context, but are identified as tax havens by Dharmapala and Hines Jr. (2009). This category includes jurisdictions such as Switzerland (CHE) and Hong Kong (HKG), which are generally considered as intermediaries in tax-evasion circuits and that, in our network analysis, retain very large out-degrees both in absolute terms and relatively to their GDP. The flow of funds between these jurisdictions is presumed to unfold as follows. Non-haven sources may evade directly towards core jurisdictions or towards non-core tax havens. In the latter case, non-core tax havens may subsequently rewire a substantial share of funds towards core jurisdictions. In turn, said core jurisdictions may further transfer these funds to other nodes inside the core. However, this type of dynamics are not covered by the information revealed in the Panama Papers, and there is no possibility for us to empirically test the deterrence effect of TIEA's whenever wealth is concealed in this manner. Notwithstanding, even if an intermediate layer of wealth concealment would be applied, the current 'anti-money laundering' (AML) and 'know your customer' (KYC) laws implemented to fight terrorism and illegal activities oblige banks and financial institutions to always know the ultimate beneficiary of each account (Omartian (2017)). That is, if a resident of country $i$ uses an intermediate layer in tax haven $k$ to incorporate an offshore financial entity in host $j$, the tax evader may be detected if there is a TIEA between countries $i$ and $j$ (Johannesen and Zucman (2014)). Given the AML and KYC policies, this double-layer mechanism is potentially immaterial for the results presented in Table 3.5 and Table 3.6, as the (nominal) entity holder located in each core jurisdiction is obliged to know the ultimate beneficiary of the incorporation back at the non-haven country of residence. Following, non-core tax havens which engage in additional TIEA treaty signatures should also see their wealth concealment activity hampered (as evidenced by Johannesen and Zucman (2014)).

The results of the fundamental and the complementary analysis are consistent with previous findings (Johannesen and Zucman (2014); Braun and Weichenrieder (2015); Omartian (2017)). Likewise, we find robust empirical evidence to support our working assumptions. The signature of a TIEA between non-haven countries and core jurisdictions plays a significant deterrence effect on the probability of link formation, and on the link activity level. In case funds are rewired, or multi-layered wealth concealment mechanisms are implemented, we find that a TIEA between two core jurisdictions would also significantly curb link formation probability and link incorporation activity. From a public policy point of view, the results of this section first show that tax treaties can have an impact on tax evasion. Second, they emphasize the importance of adding information exchange clauses to ensure an effective deterrent impact. Third, they question the relevance of treaties signed between tax havens, and thus suggest to revisit the definition of the treaty quota imposed by the G20 guidelines.

## 3.6 Implementation of the model

The current section presents a numerical implementation of the model developed in Section 3.3 employing the global (inter-temporal) tax-evasion network constructed in Section 3.4. Moreover, the significant deterrent effect of tax information exchange agreements on international tax evasion has been properly established in Section 3.5. For the numerical implementation one has that, in the case of arbitrary networks and propensity to evade $\beta$, the problem of the social planner is NP-hard (Nagano et al., 2011). Nevertheless, one can obtain (weak) approximations of the optimal policy through a greedy algorithm which sequentially adds to the social planner's strategy the links with the largest marginal contribution (see Kempe et al. (2003) for a detailed description of a similar algorithm and Sviridenko et al. (2017) for approximation bounds). Applying this approach to the global tax-evasion network, one can obtain an approximation of the optimal strategy of the social planner through numerical simulations. The results are reported in Table 3.7. The simulations first show that the optimal strategy is independent of $\beta$ in our context. Moreover, the optimal strategy closely approximates a quasi-star centered around Panama (PMA), which is the node with the largest Bonacich and eigenvector centrality in our framework (when accounting for both incoming and outgoing links). The strategy targets in priority: (i) links with core tax havens, notably Bahamas (BAH) and British Virgin Islands (BVI); (ii) links with non-core tax havens, notably Switzerland (CHE), Luxembourg (LUX) and United Arab Emirates (ARE); (iii) links with large tax-evading jurisdictions, such as USA and Brazil (BRA). These numerical results are consistent with the analytical ones reported in Section 3.3. In particular, these results confirm numerically that the optimal strategy from the point of view of the social planner is to first form a quasi-star surrounding the most central tax haven. This key target is Panama according to our results. However, this finding might be biased by our usage of the Panama Papers.

| Rank | Link | Rank | Link |
|---|---|---|---|
| 1 | (PMA,BAH) | 11 | (PMA,GTM) |
| 2 | (PMA,BVI) | 12 | (PMA,USA) |
| 3 | (PMA,SEY) | 13 | (PMA,COL) |
| 4 | (SEY,SAM) | 14 | (PMA,ARE) |
| 5 | (NIU,BAH) | 15 | (PMA,VEN) |
| 6 | (SEY,NIU) | 16 | (ANG,SAM) |
| 7 | (BVI,ANG) | 17 | (BAH,NEV) |
| 8 | (PMA,CHE) | 18 | (BAH,CHE) |
| 9 | (PMA,LUX) | 19 | (PMA,MCO) |
| 10 | (PMA,ECU) | 20 | (PMA,BRA) |

Table 3.7: Top target links for the social planner inferred from a greedy algorithm for the maximization of the global detection probability $\pi_{\tilde{e}}(\beta, \cdot)$ over the inter-temporal weighted network. The weights have been assigned proportionally to the number of months, within the period 1996-2015, in which at least one offshore entity was created on the corresponding link. The results are identical for every value of $\beta$ in $\{0.05, 0.1, 0.15, 0.25\}$.

The outcome of the model implementation confirms the hub-like nature of the optimal TIEA treaty allocation strategy, where the social planner sequentially deactivates tax havens according to their Bonacich centrality. Acknowledging that our results are built on the Panama Papers, and thus are biased to overstate the centrality of Panama in the network, we offer an example solution to the problem. We suspect that this issue could be directly solved by a social planner with access to more accurate and recent information about bilateral cross-country deposits. Therefore, our theoretical model potentially delivers the *methodology* to identify the optimal sequence of TIEA treaties to be implemented in order to strategically deactivate the remaining tax havens.

A key limitation of this paper is that it studies leaked customer data from a single provider of incorporation services. Undoubtedly, our numerical simulations are biased to overestimate the importance of Panama on the network. Although the Panama Papers may be representative of the global picture (Omartian (2017); Alstadsæter et al. (2018)), our simulations could be easily improved by implementing our theoretical model on more comprehensive international databases. Since the Panama Papers do not permit a proper identification of multi-layered concealment schemes, i.e. rewiring of funds, we must rely on the assumption that tax evasion is 'Markovian'. That is, the paths followed by funds leaving a country are independent of their origin. However, current international regulations regarding 'anti-money laundering' and 'know your customer' oblige banks and financial institutions to know the ultimate beneficiary of every account. Additionally, the newly imposed automatic exchange mechanism, which has replaced the 'on-request' system, facilitates the availability of tax information. Both conditions relax the firmness of our 'Markovian' assumption. Likewise, one could suspect that the impact of TIEA treaties could vary according to the pressure exerted by the non-haven jurisdiction on the tax haven. However, in a world where information is exchanged automatically, this suspicion may be no longer binding. Also, since the exchange of information is now automatic and no longer by request, the impact of TIEA's on the global detection probability presumably has augmented. Furthermore, our model employs a common tax evasion intensity $\beta$ for simplicity, yet the rate of offshore wealth concealment could potentially vary according to the tax evader's country of residence (Alstadsæter et al. (2018)). Notwithstanding, our analytical simulations confirmed that the social planner's strategy is optimal for any coherent level of $\beta$. Finally, in order to take the Common Reporting Standard into account in our model, we could potentially model each pair of CRS-jurisdictions as a TIEA implemented in the network of tax treaties. Regrettably, given that the Panama Papers are restricted to information prior to the start of the Common Reporting Standard, we cannot determine the effect of this multilateral agreement in our model implementation.

## 3.7 Conclusions

In this paper, we investigate optimal deterrence strategies for a social planner facing a strategic tax evader in a Stackelberg competition. The problem turns out to be mathematically equivalent to that of finding the subgraph of a network with maximal Bonacich centrality. This problem has recently received a lot of attention in network and graph theory. We provide both analytical and numerical results that show that an efficient strategy for the social planner is to first form a 'barrier' of tax treaties surrounding the most central tax havens (i.e. form a quasi-star network of treaties) and then systematically extend the set of treaties to eventually cover the whole set of countries (i.e. form a quasi-complete network).

On top of that, we build upon the 'Panama Papers' dataset to provide a network analysis of global tax evasion. Our analysis first establishes that the global tax-evasion network, far from being a random collection of bilateral links, has a hierarchical organization characterized by a core-periphery structure and a fat-tail degree distribution. Moreover, the dynamics of network formation are consistent with a preferential-attachment process, which is characteristic of complex networks. Hence, policy aiming to deter cross-country tax evasion must adopt a systemic approach on the matter. Our paper highlights how policymakers should take these structural features into account to mitigate international tax evasion.

Taking advantage of the natural experiment induced by the G20 2009 crackdown on tax havens, we also study the impacts of fiscal treaties on the formation of tax-evasion links. Our results show that efficient treaties are those that contain an information exchange clause and that link tax havens to non-haven countries, and *core* tax havens among themselves.

The Panama Papers provide a unique opportunity to gain a better understanding of the mechanics of tax evasion. Their usage nevertheless implies some limitations to our analysis. First, we must assume that the activities of Mossack-Fonseca are representative of those of the offshore financial industry. Second, the Panama Papers do not allow to track ownership chains across multiple jurisdictions. Our analysis thus relies on the assumption that tax evasion is 'Markovian', i.e. the paths followed by funds leaving a country are independent of their origin.

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## Appendix of Chapter 3

### Appendix A. Proofs of Propositions

*Proof of Proposition 3.2.* We compute the successive derivatives of $\pi_x$ with respect to $\beta$ (we omit the variable $h$ to simplify notations).

Basic calculus shows that the first derivative is given by:

$$\pi_x'(\beta) = (1-\beta)\tilde{e}^\top (I-\beta K(h))^{-1} K\xi - \tilde{e}^\top \xi,$$

where $\xi := (I-\beta K(h))^{-1}x \geq 0$.
This yields successively:

$$\pi_x'(\beta) = \tilde{e}^\top [(1-\beta)(I-\beta K(h))^{-1}K(h) - I]\xi.$$
$$\Rightarrow \pi_x'(\beta) = \tilde{e}^\top [(1-\beta)(I-\beta K(h))^{-1}K(h) - I]\xi.$$
$$\Rightarrow \pi_x'(\beta) = (1-\beta)(\sum_{m=0}^{+\infty} \beta^m \tilde{e}^\top K(h)^{m+1}\xi) - \tilde{e}^\top \xi.$$

Now, given that $G$ is column-stochastic and $h_{i,j} \leq 1$ for all $i,j \in N$, one clearly has for all $m \in \mathbb{N}$, that:

$$\tilde{e}^\top K^{m+1}\xi \leq \tilde{e}^\top \xi.$$

Thus, one has:

$$\pi_x'(\beta) \leq (1-\beta)(\sum_{m=0}^{+\infty} \beta^m \tilde{e}^\top \xi) - \tilde{e}^\top \xi = [(1-\beta)\sum_{m=0}^{+\infty} \beta^m - 1]\tilde{e}^\top \xi \leq 0.$$

Hence, $\pi_x$ is decreasing with respect to $\beta$.

Basic calculus then shows that the second derivative of $\pi_x$ is given by:

$$\pi_x''(\beta) = 2(1-\beta)\tilde{e}^\top (I-tK(h))^{-1}K(h)\zeta - 2\tilde{e}^\top \zeta,$$

where $\zeta := (I-\beta K(h))^{-1}K(h)(I-\beta K(h))^{-1} \cdot x \geq 0$.
Hence, similar arguments as above imply that $\pi_x''(\beta) \leq 0$ and thus that $\pi_x$ is concave.

□

*Proof of Proposition 3.3.* The proof is straightforward given the convexity of $u$.

□

*Proof of Proposition 3.4.* If $c$ is such that $-\pi_x''(\beta) < c''(\beta)$ for every $\beta \in [0,\overline{\beta}]$, then $u$ is strictly concave and thus $\max_{\beta\in[0,\overline{\beta}]} u(\beta)$ clearly has a unique solution. Then:

- If $c'(\overline{\beta}) + \pi_x'(\overline{\beta}) \leq 0$, then $u'(\overline{\beta}) \geq 0$ and since $u'$ is decreasing, one has $u'(\beta) \geq 0$ for all $\beta \in [0,\overline{\beta}]$. Thus $u$ is increasing over $[0,\overline{\beta}]$ and $\overline{\beta} = \hat{E}\text{argmax}_{\beta\in[0,\overline{\beta}]} u(\beta)$.

- If $\pi_x'(0) + c'(0) \geq 0$, then $u'(0) \leq 0$ and since $u'$ is decreasing, one has $u'(\beta) \leq 0$ for all $\beta \in [0,\overline{\beta}]$. Thus $u$ is decreasing over $[0,\overline{\beta}]$ and $0 = \hat{E}\text{argmax}_{\beta\in[0,\overline{\beta}]} u(\beta)$.

- If If $\pi_x'(0) + c'(0) < 0$ and $c'(\overline{\beta}) + \pi_x'(\overline{\beta}) > 0$, then $u'(0) > 0$ and $u'(\overline{\beta}) < 0$, thus the strict concavity of $u$ implies that there exists a unique $\tilde{\beta} \in [0,\overline{\beta}]$ such that $u'(\tilde{\beta}) = 0$ and $\tilde{\beta} = \hat{E}\text{argmax}_{\beta\in[0,\overline{\beta}]} u(\beta)$.

□

*Proof of Proposition 3.5.* Assume that $h^*$ is a solution to $\mathcal{S}_{\nu,\overline{\beta}}$.

On the one hand, one has $u(0,h) = -1 - c(0)$, which is independent of $h$.

On the other hand, one has $u(\overline{\beta},h) = -\pi(\overline{\beta},h) - c(\overline{\beta})$.

Thus $u(\overline{\beta},h)$ is clearly minimal for $h = h^*$.

Recalling that $\beta^* := \phi(h^*)$, one then has according to Proposition 3.3:

- Either $\phi(h^*) = \overline{\beta}$ and $u(\overline{\beta},h^*) \geq u(0)$. Then, for every $h \neq h^*$, one has that $u(\overline{\beta},h) \geq u(0)$ and thus $\phi(h) = \overline{\beta}$. The fact that $h^*$ is a solution to $\mathcal{S}_{\nu,\overline{\beta}}$ then implies that $h^*$ is a solution to $\mathcal{S}'_k$ and hence that $(\phi(h^*), h^*)$ is a Stackelberg equilibrium of the tax-evasion game.
- Otherwise, $\phi(h^*) = 0$ and thus $\pi(\phi(h^*), h^*) = 1$. As for all $h$, one has by construction $\pi(\phi(h), h) \leq 1$, $h^*$ then is a solution to $\mathcal{S}'_k$ and $(\phi(h^*), h^*)$ is a Stackelberg equilibrium of the tax-evasion game.

□

## Appendix B. Panel Data Robustness Check

Table 3.8: Panel regressions of link formation probability on treaty signature

| Variables | Hosts: All | | | | | |
|---|---|---|---|---|---|---|
| | Source: All jurisdictions | | Source: Non-haven jurisd. | | Source: Core jurisdictions | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| $Treaty = Any$ | -0.0630* | | -0.0756** | | -0.0798** | |
| | (0.0321) | | (0.0368) | | (0.0348) | |
| $Treaty = TIEA$ | | -0.1131*** | | -0.1495*** | | -0.1588*** |
| | | (0.0338) | | (0.0408) | | (0.0398) |
| Host: ln GDP pp | 0.0824** | 0.0769** | 0.0787** | 0.0707** | 0.0681* | 0.0601 |
| | (0.0356) | (0.0357) | (0.0360) | (0.0358) | (0.0373) | (0.0370) |
| Host: Population | 0.6187*** | 0.6351*** | 0.5428*** | 0.5714*** | 0.4974*** | 0.5210*** |
| | (0.1073) | (0.1077) | (0.1202) | (0.1203) | (0.1061) | (0.1066) |
| Host: Gov. Index | 0.3216*** | 0.3162*** | 0.2754*** | 0.2695*** | 0.2933*** | 0.2857*** |
| | (0.0683) | (0.0683) | (0.0705) | (0.0707) | (0.0717) | (0.0714) |
| Source: ln GDP pp | -0.0600** | -0.0595** | -0.0574** | -0.0571** | -0.0438* | -0.0427 |
| | (0.0247) | (0.0248) | (0.0250) | (0.0249) | (0.0261) | (0.0261) |
| Source: Population | -0.0351 | -0.0424 | 0.0098 | -0.0013 | -0.0612 | -0.0730 |
| | (0.0622) | (0.0620) | (0.0693) | (0.0687) | (0.0609) | (0.0606) |
| Source: Gov. Index | 0.0487 | 0.0439 | 0.0346 | 0.0311 | 0.0329 | 0.0275 |
| | (0.0395) | (0.0397) | (0.0439) | (0.0442) | (0.0408) | (0.0408) |
| Observations | 16,060 | 16,060 | 11,020 | 11,020 | 12,880 | 12,880 |
| No. of country pairs | 803 | 803 | 551 | 551 | 644 | 644 |
| Number of years | 20 | 20 | 20 | 20 | 20 | 20 |
| Pairwise fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Time fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |

Signif. codes: '***' 0.01 '**' 0.05 '*' 0.10 ' ' 1

Notes: Panel data regressions with linear probability function, where the $p$-values are based on double-clustered robust standard errors. The dependent dichotomous variable measures the existence or non-existence of a link formation between source $i$ and host $j$ at time $t$. The sample period considers annual data from 1996 to 2015. The variable of interest is $Treaty_{i,j,t-1}$, and it is split in two dummy variables: *Treaty = Any* if any tax treaty exists between source $i$ and host $j$ at time $t-1$, and *Treaty = TIEA* if a tax information exchange agreement treaty (as defined by Johannesen and Zucman (2014)) exists between source $i$ and host $j$ at time $t-1$. *GDP per person* was obtained from the Federal Reserve Economic Data (FRED), *Population* was retrieved from the World Bank and *Governance Indices* were collected from the biannual World Bank's Worldwide governance indicators.

Table 3.9: Panel regressions of link incorporation activity on treaty signature

| Variables | Hosts: All | | | | | |
|---|---|---|---|---|---|---|
| | Source: All jurisdictions | | Source: Non-haven jurisd. | | Source: Core jurisdictions | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| $Treaty = Any$ | -0.1475** | | -0.1306* | | -0.1673** | |
| | (0.0708) | | (0.0737) | | (0.0692) | |
| $Treaty = TIEA$ | | -0.2547*** | | -0.2950*** | | -0.2954*** |
| | | (0.0813) | | (0.0891) | | (0.0851) |
| Host: ln GDP pp | 0.1735** | 0.1610* | 0.1387* | 0.1234* | 0.1198* | 0.1041 |
| | (0.0878) | (0.0881) | (0.0719) | (0.0715) | (0.0760) | (0.0756) |
| Host: Population | 1.1424*** | 1.1780*** | 0.8927*** | 0.9548*** | 0.8161*** | 0.8549*** |
| | (0.2952) | (0.2978) | (0.2816) | (0.2824) | (0.2753) | (0.2784) |
| Host: Gov. Index | 0.5481*** | 0.5363*** | 0.4681*** | 0.4555*** | 0.4729*** | 0.4595*** |
| | (0.1600) | (0.1591) | (0.1392) | (0.1394) | (0.1467) | (0.1454) |
| Source: ln GDP pp | -0.1565** | -0.1555** | -0.0974 | -0.0968 | -0.0830 | -0.0808 |
| | (0.0699) | (0.0700) | (0.0616) | (0.0613) | (0.0672) | (0.0671) |
| Source: Population | 0.0396 | 0.0227 | 0.2722 | 0.2515 | -0.1114 | -0.1346 |
| | (0.1920) | (0.1911) | (0.2119) | (0.2109) | (0.1421) | (0.1410) |
| Source: Gov. Index | 0.2096* | 0.1991* | 0.0881 | 0.0803 | 0.0779 | 0.0683 |
| | (0.1118) | (0.1116) | (0.0959) | (0.0961) | (0.0874) | (0.0872) |
| Observations | 16,060 | 16,060 | 11,020 | 11,020 | 12,880 | 12,880 |
| No. of country pairs | 803 | 803 | 551 | 551 | 644 | 644 |
| Number of years | 20 | 20 | 20 | 20 | 20 | 20 |
| Pairwise fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Time fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |

Signif. codes: '***' 0.01 '**' 0.05 '*' 0.10 ' ' 1

Notes: Panel data regressions with standard OLS function, where the $p$-values are based on double-clustered robust standard errors. The dependent variable measures entity incorporation activity (as defined by Omartian (2017)) between source $i$ and host $j$ at time $t$. The sample period considers annual data from 1996 to 2015. The variable of interest is $Treaty_{i,j,t-1}$, and it is split in two dummy variables: *Treaty = Any* if any tax treaty exists between source $i$ and host $j$ at time $t-1$, and *Treaty = TIEA* if a tax information exchange agreement treaty (as defined by Johannesen and Zucman (2014)) exists between source $i$ and host $j$ at time $t-1$. *GDP per person* was obtained from the Federal Reserve Economic Data (FRED), *Population* was retrieved from the World Bank and *Governance Indices* were collected from the biannual World Bank's Worldwide governance indicators.

Table 3.10: Panel regressions of link formation probability and link activity on treaty signature, restricting sources to non-core tax havens as defined by Dharmapala and Hines Jr. (2009).

| | Hosts: All | | | |
|---|---|---|---|---|
| | Source: Non-core tax havens | | | |
| Dependent variable: | Link Probability $L_{i,j,t}$ | | Link Activity $A_{i,j,t}$ | |
| Predictors | (1) | (2) | (3) | (4) |
| $Treaty = TIEA$ | -0.1017 | -0.0215 | -0.1014 | -0.1131 |
| | (0.1681) | (0.0709) | (0.1990) | (0.1885) |
| Host: ln GDP pp | | 0.1085* | | 0.3419* |
| | | (0.0629) | | (0.1842) |
| Host: Population | | 0.7541*** | | 1.6302*** |
| | | (0.1784) | | (0.5438) |
| Host: Gov. Index | | 0.4003*** | | 0.6926*** |
| | | (0.0907) | | (0.2552) |
| Source: ln GDP pp | | -0.0554 | | -0.4043** |
| | | (0.0526) | | (0.1810) |
| Source: Population | | -0.2185* | | -0.5023 |
| | | (0.1292) | | (0.3755) |
| Source: Gov. Index | | 0.0469 | | 0.3581 |
| | | (0.0787) | | (0.3253) |
| Observations | 4,980 | 4,980 | 4,980 | 4,980 |
| No. of country pairs | 249 | 249 | 249 | 249 |
| Number of years | 20 | 20 | 20 | 20 |
| Pairwise fixed effects | Yes | Yes | Yes | Yes |
| Time fixed effects | Yes | Yes | Yes | Yes |

Signif. codes: '***' 0.01 '**' 0.05 '*' 0.10 ' ' 1

Notes for all specifications: Panel data regressions, where the $p$-values are based on double-clustered robust standard errors. The sample period considers annual data from 1996 to 2015. The variable of interest is $Treaty_{i,j,t-1}$, and it is split in two dummy variables: *Treaty = Any* if any tax treaty exists between source $i$ and host $j$ at time $t-1$, and *Treaty = TIEA* if a tax information exchange agreement treaty (as defined by Johannesen and Zucman (2014)) exists between source $i$ and host $j$ at time $t-1$. The classification of tax havens is determined as in Dharmapala and Hines Jr. (2009). *GDP per person* was obtained from the Federal Reserve Economic Data (FRED), *Population* was retrieved from the World Bank and *Governance Indices* were collected from the biannual World Bank's Worldwide governance indicators.

Notes for Columns 1 and 2: Panel data regressions with linear probability function. The dependent dichotomous variable measures the existence or non-existence of a link formation between source $i$ and host $j$ at time $t$.

Notes for Columns 3 and 4: Panel data regressions with standard OLS function. The dependent variable measures entity incorporation activity (as defined by Omartian (2017)) between source $i$ and host $j$ at time $t$.

**Appendix C. Summary of jurisdictions**

Table 3.11: Classification of jurisdictions

| **Code** | **Jurisdiction** | **Status** |
|---|---|---|
| ALB | Albania | |
| ASM | American Samoa | |
| AND | Andorra | H |
| AGO | Angola | |
| ANG | Anguilla | H |
| ATG | Antigua and Barbuda | H |
| ARG | Argentina | |
| ABW | Aruba | |
| AUS | Australia | |
| AUT | Austria | |
| AZE | Azerbaijan | |
| BAH | Bahamas | H |
| BHR | Bahrain | H |
| BGD | Bangladesh | |
| BRB | Barbados | H |
| BLR | Belarus | |
| BEL | Belgium | |
| BLZ | Belize | H |
| BMU | Bermuda | H |
| BOL | Bolivia | |
| BWA | Botswana | |
| BRA | Brazil | |
| BVI | British Virgin Islands | H |
| BRN | Brunei | |
| BGR | Bulgaria | |
| CMR | Cameroon | |
| CAN | Canada | |
| CYM | Cayman Islands | H |
| CAF | Central African Republic | |
| TCD | Chad | |
| CHL | Chile | |
| CHN | China | |
| COL | Colombia | |
| COK | Cook Islands | H |
| CRI | Costa Rica | |
| CIV | Cote d'Ivoire | |
| HRV | Croatia | |
| CUB | Cuba | |

| **Code** | **Jurisdiction** | **Status** |
|---|---|---|
| CUW | Curacao | H |
| CYP | Cyprus | H |
| CZE | Czech Republic | |
| DNK | Denmark | |
| DJI | Djibouti | |
| DMA | Dominica | H |
| DOM | Dominican Republic | |
| ECU | Ecuador | |
| EGY | Egypt | |
| SLV | El Salvador | |
| EST | Estonia | |
| FIN | Finland | |
| FRA | France | |
| GEO | Georgia | |
| DEU | Germany | |
| GHA | Ghana | |
| GIB | Gibraltar | H |
| GRC | Greece | |
| GUM | Guam | |
| GTM | Guatemala | |
| GGY | Guernsey | H |
| HTI | Haiti | |
| HND | Honduras | |
| HKG | Hong Kong | H |
| HUN | Hungary | |
| ISL | Iceland | |
| IND | India | |
| IDN | Indonesia | |
| IRN | Iran | |
| IRL | Ireland | H |
| IOM | Isle Of Man | H |
| ISR | Israel | |
| ITA | Italy | |
| JAM | Jamaica | |
| JPN | Japan | |
| JSY | Jersey | H |
| JOR | Jordan | H |
| KAZ | Kazakhstan | |

Note 1: Jurisdictions ordered alphabetically by name, part 1 of 2.
Note 2: The status of 'haven' (H) is defined in the sense of Dharmapala and Hines Jr. (2009).

| Code | Jurisdiction | Status |
|---|---|---|
| KEN | Kenya | |
| KWT | Kuwait | |
| LVA | Latvia | |
| LBN | Lebanon | H |
| LSO | Lesotho | |
| LBY | Libya | |
| LIE | Liechtenstein | H |
| LTU | Lithuania | |
| LUX | Luxembourg | H |
| MAC | Macao | H |
| MKD | Macedonia | |
| MYS | Malaysia | |
| MLI | Mali | |
| MLT | Malta | H |
| MUS | Mauritius | |
| MEX | Mexico | |
| MDA | Moldova | |
| MCO | Monaco | H |
| MAR | Morocco | |
| MOZ | Mozambique | |
| NAM | Namibia | |
| NLD | Netherlands | |
| NEV | Nevada | |
| NZL | New Zealand | |
| NIC | Nicaragua | |
| NGA | Nigeria | |
| NIU | Niue | |
| NOR | Norway | |
| OMN | Oman | |
| PMA | Panama | H |
| PRY | Paraguay | |
| PER | Peru | |
| PHL | Philippines | |
| POL | Poland | |
| PRT | Portugal | |
| PRI | Puerto Rico | |
| QAT | Qatar | |
| ROU | Romania | |
| RUS | Russia | |

| Code | Jurisdiction | Status |
|---|---|---|
| KNA | Saint Kitts and Nevis | H |
| LCA | Saint Lucia | H |
| VCT | Saint Vincent & Grenadines | H |
| SAM | Samoa | |
| SAU | Saudi Arabia | |
| SEN | Senegal | |
| SEY | Seychelles | |
| SGP | Singapore | H |
| SXM | Sint Maarten (Dutch part) | H |
| SVK | Slovakia | |
| SVN | Slovenia | |
| ZAF | South Africa | |
| KOR | South Korea | |
| ESP | Spain | |
| LKA | Sri Lanka | |
| SWE | Sweden | |
| CHE | Switzerland | H |
| SYR | Syria | |
| TWN | Taiwan | |
| TZA | Tanzania | |
| THA | Thailand | |
| TTO | Trinidad and Tobago | |
| TUN | Tunisia | |
| TUR | Turkey | |
| TCA | Turks and Caicos Islands | H |
| VIR | U.S. Virgin Islands | |
| UKR | Ukraine | |
| ARE | United Arab Emirates | |
| GBR | United Kingdom | |
| USA | United States | |
| URY | Uruguay | |
| UZB | Uzbekistan | |
| VUT | Vanuatu | H |
| VEN | Venezuela | |
| VNM | Viet Nam | |
| WYO | Wyoming | |
| YEM | Yemen | |
| ZMB | Zambia | |
| ZWE | Zimbabwe | |

Note 1: Jurisdictions ordered alphabetically by name, part 2 of 2.
Note 2: The status of 'haven' (H) is defined in the sense of Dharmapala and Hines Jr. (2009).

**Appendix E. Key characteristics of tax havens**

Tax havens may be understood as countries or jurisdictions that have either no-tax or very low tax regimes, particularly for corporate revenues and personal income. Moreover, such nations tend not to comply with international authorities regarding the exchange of tax information. Also, they account for a lack of transparency and a heightened sense of protectionism for the financial information of the people registered inside their jurisdiction. Fiscal paradises benefit directly from having companies registered inside their domains even if the tax levied on them is low; fees are collected upon registration, upon licensing and at the time of annual renewals.

The current paper deals with the incorporation of offshore financial entities. An example of the latter is an International Business Corporation. An International Business Corporation (IBC) may be considered an offshore legal entity registered as a company in a jurisdiction where it is exempted of paying local corporate taxes and stamp duties (taxes levied on legal documents), not required to appoint local directors, and is allowed to preserve the confidentiality of the beneficial proprietor of the company. Some jurisdictions, as the case for Luxembourg, waive the withholding tax, or retention tax, levied by government to the payer of employment income, dividends and interests.

The purpose of the current appendix is to briefly explore the characteristics of the most prominent offshore financial centers, many of them employed by Mossack-Fonseca, and to understand why these jurisdictions are usually considered fiscal paradises. The list of offshore financial centers includes:

Andorra: Landlocked nation with 77,000 persons and a GDP of 3.3 billion USD; this country does not tax wealth, capital gains, inheritance nor gifts. Prior to 2015, there was no income tax, however a minor levy on income was installed in 2015.

Anguilla: An island with a 311 million USD annual GDP economy and a population shy of 15,000. The island does not tax individual or corporate profits, capital gains nor estate. However, in 2011 they installed a temporary 3% income tax to stabilize the nation's deficit.

Bahamas: This collection of islands with its own currency, Bahamian dollar, are inhabited by 372 thousand people and possess an annual GDP of 7.4 billion USD. The islands does not levies corporate taxes, capital gains, income tax nor wealth tax; however, there are license fees, stamp duties and property taxes.

Bahrain: Arabic-speaking country with 1.4 million persons and a 48.5 billion USD annual GDP. This jurisdiction does not have any tax system at all, meaning that there is no legislation, no auditors and no tax reports. Therefore, Bahrain does not tax inheritances, corporate profits, income from renting real estate nor capital gains.

Barbados: It is an English-speaking, British legal system, Barbadian dollar user, Caribbean island of 277,821 people and a 4.6 billion USD GDP. Barbados is a well regulated tax haven with very low taxes on profits of less than 2.5%; however, capital gains and dividends are exempt from taxes.

Belize: A Caribbean country with 387,000 inhabitants, 1.8 billion USD annual GDP, Belize dollar, English-speaking, non-island and with British legal origins. A license to operate in Belize without any reporting duties may be registered in matter of hours. Belize does not charge taxes on earning from abroad, including dividends, capital gains, revenues and interests.

Bermuda: An island with a GDP of 5.6 billion USD per year and a population of 65 thousand citizens. This jurisdiction, which employs minimal standards of regulations and business laws, hosts 400 international insurance companies and is a popular tax destination. Moreover, there are no income nor corporate taxes in this island.

British Virgin Islands: With 28,000 inhabitants and an annual GDP of 853 million USD, this jurisdiction holds a nominal tax rate of 0% over income. Moreover, no tax is levied on capital gains, sales, value added, profit, inheritance, estate, gifts nor corporate tax.

Cayman Islands: An island nation with a 3.3 billion USD annual GDP and a population of 56 thousand people, yet manages over 36 billion USD on assets. Regarded as one of the most popular tax havens, hosting offices for 40 of the 50 largest banks in the world. The Cayman Islands do not collect taxes on income, capital gains, nor on wealth. Over 10 thousand hedge funds have been registered inside this jurisdiction.

Costa Rica: It is a Spanish speaking, non-island, country with 4.9 million inhabitants, a 57 billion USD annual GDP and its own currency (Colon). Costa Rica offers a 100% exemption of corporate income tax for eight-years on newly registered companies.

Cyprus: This Mediterranean island of 1.1 million people and a GDP of 30 billion USD commenced to tax corporations at a rate of 2.5% since 2013 and joined the OECD Automatic Exchange of Financial Information in Tax Matters in 2017, which took away the island's tax haven status.

Gibraltar: With 32,000 inhabitants and a 2 billion USD of annual GDP, Gibraltar is a low tax haven which also benefits from tourism. Invariant to whether income is domestic or foreign, corporations are taxed at a 10% rate, whereas capital gains, inheritance, wealth, sales and estates are not taxed. Estimates sustain Gibraltar earns more than 100 million pounds each year for concept of corporate taxation. Moreover, Gibraltar is very jealous of its secrecy and places itself as a well-reputed tax destination.

Hong Kong: A small country with a 412 billion USD annual GDP and a population of 7.3 million. Hong Kong taxes income source-based and not residential-based, therefore they would only tax income generated in Hong Kong and not the one produced elsewhere. The country itself is then an ideal node for profit shifting and re-wiring financial activities. This attribute might have placed Hong Kong as the middle-man of a large fraction of financial transactions.

Isle of Man: A self-governing Crown dependency with 85,000 persons and a 4.5 billion USD annual economy. This island has no wealth, capital gains not inheritance taxes. Individual income tax is capped and never higher than 20%, there are no stamp duties and there is a zero percent nominal corporate tax rate (except for rental income and domestic banking profits, which are taxed at a 10% rate).

Jersey: A UK Crown dependency with a 6 billion USD annual GDP and 100 thousand people, Jersey has zero corporate tax on all non-financial institutions and a 10% tax rate on the former; utilities are taxed a 20% rate. Recently, Jersey agreed to share information about financial activity with the US, UK and the EU.

Liechtenstein: Recurring to the Swiss franc, this landlocked European country with less than 38,000 inhabitants and a 5.3 billion USD annual GDP is one of the richest countries *per capita* in the world. Entities incorporated in this jurisdiction pay no income taxes, so long they carry their commercial and economic enterprises elsewhere; limiting the domestic activities of institutions to manage assets and investments. A nominal annual tax of 0.1% is levied on the capital reserves of companies domiciled in the country.

Luxembourg and Switzerland: Holding companies are worldwide known financial institutions incorporated in Luxembourg and Switzerland with subsidiaries in other jurisdictions. Such corporations are allowed to carry on offshore activities exempted from paying taxes on capital gains and on dividends. Moreover, there are no withholding taxes applied whenever the beneficiary is incorporated inside the European Union. Lastly, the names of these corporate beneficiary owners are not required to be declared.

New Zealand (Cook Islands): Cook Islands are in a free association with New Zealand. Fifteen islands with a GDP of 292 million USD and a population of about 13,000 people. Cook Islands are known for generally disregarding international courts, no taxes on offshore profits and very strict laws restricting international authorities to gain access to any type of financial information. Moreover, no registry on any company may be obtained by international law enforces without the consent of the company itself (unless there is a criminal offense pending). The requirements to open an account are one director and one shareholder which may have their meetings anywhere in the world, without submitting any reports and simply paying an annual fee of 300 USD.

Niue: A small island in the Pacific with 1,470 inhabitants, a GDP of 15 million USD per year, and which employs the New Zealand Dollar. This country has a good political stability and a British legal system. International Business Companies located here have no tax duties and do not need to pay for offshore profits. IBC's are not required to file annual reports, require a single director (which may well be overseas) and demand in return a simple yearly fee of 150 USD. Nonetheless, Niue is not a 'credible' fiscal paradise as it is currently a nation that receives aid from New Zealand.

Panama: This Latin American country with 4 million inhabitants, its own currency (Balboa) and an annual GDP of 63 billion USD, jumped to fame after the leak of 11.5 million very sensible financial documents in 2015. Panama has a corporate tax of 25% for local enterprises, while it offers a full tax exemption for offshore entities that carry out the entirety of their economic activities outside Panama. This jurisdiction has a strict financial secrecy, with no limits on currency exchanges and no requirement for corporate shareholders to publicly record their identities.

Seychelles: This is an island in the Indian Ocean with 92,000 inhabitants and a GDP of 2.6 billion USD. Seychelles does not tax income nor profits from financial entities. Corporations may be established in less than 24 hours while paying only an annual fee of 100 USD, regardless of the corporation's size.

Identities and personal details of the beneficial owners are not recorded publicly and companies are exempt from stamp duties on all transactions.

United Arab Emirates (Dubai): With a population of 2.8 million and a GDP of 360 billion USD, this jurisdiction does not account for any type of taxes: corporate, withholding or personal. Income is taxed nominally at a zero percent tax rate.

United Kingdom (Bermuda, Cayman Islands, Gibraltar, Isle of Man, Jersey, Anguilla and British Virgin Islands): All the following are either Crown dependencies or British Overseas Territories, English-speaking, with British legal origins, with very small population and a considerably high GDP *per capita*.

United States (Delaware, Wyoming and Nevada): Delaware has no state taxes on income, corporate or sales profits. Any person, American or not, may operate anonymously through a listing agent in Delaware, paying about 350 USD on annual license and fees, without having to pay taxes on any earnings, inheritance nor capital gains. Nevada does not have an IRS information sharing agreement, does not levy state taxes, accounts for extreme secrecy, and asks for minimal reporting and disclosing, where stockholders' names are not on public record. Similar case for Wyoming.

Uruguay: Employing the Uruguayan peso, this Latin American country of 3.5 million inhabitants accounts for an annual GDP of 78 billion USD. Although there is 25% corporate tax, it is only levied on income generated inside the country, while all the financial flows brought from abroad are not taxed. Moreover, the jurisdiction holds several free trade zones where entities are exempted to pay local taxes as well. Lastly, Uruguay holds a high standard of bank secrecy.

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# Conclusion

A growing theoretical and empirical literature has evidenced the prominent roles played by taxpayer heterogeneity, expectations and social influence dynamics in the success or failure of fiscal policies. In that respect, the present doctoral thesis attempts to address important matters which have so far been overlooked in the economic literature. First, we pursue a parsimonious representation of individual and aggregate taxpayer behavior without neglecting prevalent behavioral insights. Also, we investigate the effectiveness of fiscal policy implementations given the ability of taxpayers and tax evaders to endogenize the information they acquire from their peers and from the tax authority. Furthermore, the optimal fiscal policies presented in this dissertation take into consideration the presence of heterogeneous, adaptive taxpayers who react against the enforcement measures placed in action by the social planner.

Our work aims to integrate recent findings and methodologies from diverse academic fields. We model taxpayer behavior in a fiscal framework where intrinsic and extrinsic taxpayer attributes and characteristics are considered. Moreover, we develop computational models of adaptive agents, to be used as simulation test beds, to perform stylized policy experiments, explore the effects of innovative enforcement measures and assess the time scales over which actions are expected to manifest results.

In the current dissertation, we aim to contribute to the policy-oriented literature by deriving analytical solutions to recurring problems in fiscal policy. Hence, we study the roles played by taxpayer heterogeneity and social influence on the efficacy of fiscal policy enforcement. In particular, our research is innovative in providing intuitions from behavioral economics and psychological research, combining these with relevant methods from network theory and game theory, and allowing for the inclusion of state-of-the-art computational models.

Our research aims to design optimal fiscal policies in scenarios where a social planner faces strategic tax evaders who are able to observe and react against the implemented enforcement measures. Given the inherent mathematical complexity of the analytical models, we propose a combination of numerical methods and computer simulations which allows to accurately test the effectiveness and robustness of diverse fiscal policies. This combination of analytical and computational techniques yields an important advantage to competently deal with complex models emerging from the inclusion of taxpayer expectations and social influence dynamics inherent in economic models of tax evasion.

Conclusively, the present thesis comprehends the foundations of different policy models, the optimality of fiscal policies under taxpayer heterogeneity and the robustness of these policies under diverse economic scenarios. Our findings call for further research on the design and implementation of optimal fiscal policies aimed at deterring tax evasion, both in domestic and international environments.

### A synopsis of the current doctoral thesis

There are two broad research lines dealing with tax evasion and the decision-making process of taxpayers. On the one hand, economic literature has attempted to explain this phenomenon through expected utility models, where rational agents choose the optimal amount or fraction of income to disclose to the tax authorities. On the other hand, behavioral and psychological approaches have discovered many interesting findings about how people differently perceive enforcement parameters and display heterogeneous levels of trust in authorities. Chapter 1 attempts to reconcile both strands of research by introducing a micro-founded model which can replicate and explain many of the stylized facts of individual and collective tax evasion. Several key properties of the model can be analytically derived, and we show conditions under which agents fully comply even in the (known) absence of audits.

The main results of Chapter 1 can be characterized in terms of the *willingness-to-pay taxes*, which may be interpreted as a taxpayer's measure of tax morale corrected for risk aversion. Following, individual tax compliance is predominantly driven by this metric. To further understand the conditions under which differing fiscal policies would be deemed more effective, we computationally replicate taxpayer behavior. Relying on agent-based simulations, we investigate the two main compliance motives: trust (tax morale) and power (risk-aversion to being audited). We identify a complex relationship between trust, power and tax compliance. Specifically, the outcome of our taxpayer simulations hints at a concave impact of trust on compliance, while power manifests convexly. As a consequence, for societies where trust in government is low and enforcement power is also low, we conclude that the social planner should give high priority to finding ways to boost voluntary tax compliance. Hence, our results shed light on the advantages of adopting a 'service and clients' approach, which promotes trust-enhancing measures, over the classical 'cops and robbers' system, which is commonly associated with increased deterrence measures such as harsher fines and more audits.

Chapter 2 builds on the behavioral and empirical insights from the first chapter to develop a game-theoretic model to estimate the cost-effectiveness of different fiscal policies. That is, the second chapter offers a direct comparison between the efficacy levels of diverse audit policies, based on their deterrence effect given a set of initial costs or constraints. Also, we study how the tax authority may influence taxpayer behavior through optimal fiscal policies which take into consideration individual heterogeneity and endogenous expectations. Indeed, a unique Nash Equilibrium is characterized in terms of individual heterogeneity levels and the network structure. Building on this result, the game-theoretic optimal strategy weighs taxpayer salience in function of their individual (heterogeneous) productivity and their position inside the network. Our research extends the notions of optimal network-based strategies and elucidates a plausible way in which the tax authority may re-establish the path-dependent aggregate tax compliance level.

In particular, Chapter 2 proposes an optimal two-step audit strategy, where a threat-to-audit message is emitted by the tax authority in the first step. Said message provides a measurable *ex post* heterogeneous productivity amid taxpayers. In the second step, the heterogeneity condition allows the tax authority to devise an optimal enforcement strategy, derived by means of game-theoretic techniques. Consequently, the optimal audit scheme targets the group of taxpayers who, by being audited, induce a succession of social interactions which eventually leads to the maximization of the mean subjective audit rate across the entire taxpayer network. Our research presents the first network-based optimal audit strategy which is robust to expected and non-expected utility theories, taxpayer heterogeneity and irrespective of any utility function the individuals may attempt to optimize in their decision-making processes. Furthermore, the tax authority may implement the strategy indifferently whether taxpayers are fully rational or not. Additionally, a series of computer taxpayer simulations provided complementary robustness checks for the proposed audit strategy. Our findings shed light on the potential benefits of investing in tools and techniques in order to acquire further taxpayer information, which could help the tax authority to build accurate taxpayer social networks.

Chapter 3 extends the notion of tax evasion to an international setting, while keeping a strong methodological connection with the previous chapters. In recent years, international tax evasion and offshore wealth concealment have become globalized issues for policymakers. Albeit several inter-jurisdictional fiscal policies have attempted to put an end to these problems, offshore financial service providers have circumvented these enforcement measures by relocating funds and deposits to alternative financial offshore centers. There is compelling evidence to believe that previous policy implementations did not put an end to international tax evasion, but induced a change in the relocation dynamics of wealth concealment. Based on this evidence, Chapter 3 builds upon the Panama Papers dataset to provide a network analysis of global tax evasion. Our findings first uncover that the international network of tax evasion, far from being a random collection of bilateral links, has a hierarchical organization characterized by a core-periphery structure and a fat-tail degree distribution. Moreover, the dynamics of network formation are consistent with a preferential-attachment process, which is characteristic of complex networks. These structural features indicate that global tax evasion is, in fact, a complex system. Therefore, we highlight that fiscal policies aiming to deter cross-country tax evasion must adopt a systemic approach on the matter.

In Chapter 3, we present a theoretical model where a representative tax evader chooses the optimal fraction of wealth to conceal offshore, while a social planner seeks to maximize the global detection probability of cross-country tax evasion. In this perspective, we investigate the optimal deterrence strategy for a social planner facing a strategic tax evader in a Stackelberg competition. In order to do so, the social planner establishes tax treaties between jurisdictions which enable tax information exchange and allow for wealth concealment detection. Given a limited number of treaties to be implemented, the social planner faces the problem of finding the optimal allocation of treaties among country-pairs in the network. The problem turns out to be mathematically equivalent to that of finding the subgraph of the network with maximal Bonacich centrality. In our context, we provide both mathematical and numerical results that show that the optimal strategy is to design a hub-like structure, either a quasi-star or a quasi-complete graph, targeting offshore financial centers according to their Bonacich centrality in the network of international tax evasion. Additionally, taking advantage of the natural experiment induced by the G20 2009 crackdown on tax havens, we investigate the impacts of fiscal treaties on the formation probabilities of tax-evasion links and on the offshore financial activity levels of said links. Our results show statistically significant deterrence effects of tax information exchange agreements on link formation probabilities and on link offshore financial activity levels of tax evasion between non-havens and tax havens, and between jurisdictions located in the core of the network. Since a share of cross-country transactions are not related to illegal activities, our estimates present lower bounds for the deterrence effects of tax information exchange agreements on international tax evasion.

There are a few inherent limitations which should not go unmentioned regarding the methodologies and results presented in this dissertation. The mathematical model of taxpayer behavior in Chapter 1 becomes too complex to be completely characterized analytically. Therefore, only a number of fundamental properties may be derived analytically. To address this question, we rely on state-of-the-art computational models and employ calibrated agent-based simulations to exhaustively investigate taxpayer behavior. In Chapter 2, the proposed strategy imposes a degree of cohesiveness among taxpayers. Despite the substantial robustness of the game-theoretic model, the success of the policy requires that at least a non-negligible fraction of taxpayers listens to the threat-to-audit message. Moreover, it is still an open question which could be the possible incurred costs of acquiring additional information in order to build accurate taxpayer social networks. In Chapter 3, the Panama Papers provide a unique opportunity to gain a better understanding of the dynamics of international tax evasion. Nevertheless, their usage implies some limitations to our analysis. First, we must assume that the activities of Mossack-Fonseca are representative of those of the offshore financial industry. Second, the Panama Papers do not allow to track ownership chains across multiple jurisdictions. Our analysis thus relies on the assumption that the tax evasion paths followed by funds leaving a country are independent of their origin.

### Technical summary

The current doctoral thesis aims to examine the dynamics of income tax evasion and taxpayer behavior from all available perspectives. First, we take into consideration literature from both economic and behavioral backgrounds. Particularly, this allows us to contemplate both theoretical research and experimental work in order to bridge part of the gap in the existing literature. Further, we consolidate our mathematical models with insights from psychological and behavioral research, which allows us to derive more accurate representations of taxpayer behavior.

The prevalent academic literature recognizes a broad range of factors and characteristics that may affect taxpayer behavior and tax compliance, both intrinsic and extrinsic of taxpayers. Specifically, taxpayer behavior may be either voluntary or enforced. Following, we study voluntary compliance as a consequence of intrinsic motives such as trust in the government, social norms and peer effects. Also, we investigate enforced tax compliance as a result of increased (perceived) governmental power as an outcome of reinforced audit schemes and fiscal measures.

The research questions studied in the current dissertation address both individual and collective taxpayer behavior and compare our analytical and numerical results with those prevalent in the existing literature. Furthermore, the derived models have strong micro-foundations and are also helpful to study the emergence of macroeconomic behavioral patterns. Consequentially, we perform our simulations both under domestic and international environments to offer a more holistic view about the possible tax-evasion mechanisms which are available for evasive-minded taxpayers.

Acknowledging that tax evasion is the result of a coordination game between taxpayers and tax authorities, we study the optimal actions and strategies from both points of view. Moreover, the normative insights and the optimal fiscal policies derived in the current thesis are robust from the point of view of the tax authority. In particular, our research takes into consideration diverse decision-making processes, such as rational and non-rational taxpayer behavior. Hence, the game-theoretic approaches employed in our research ensure optimal results whether taxpayers are rational or not. Additionally, the analytical solutions derived by means of game-theoretic approaches and applied network analysis were confirmed by a sequence of computational models, simulations and algorithms.

Namely, the current thesis offers a comprehensive technical revision of tax evasion from diverse literary backgrounds, behavioral insights, mathematical models, empirical work, modeling techniques, taxpayer characteristics and decision-making processes, compliance motivations, tax authority's reach, microeconomic and macroeconomic scopes, and both analytical results and computational models.

**Methodological summary**

An exhaustive list of methods is considered in the current work. Chapter 1 and Chapter 2 look at *passive* tax evasion from the point of view of a taxpayer who decides whether to disclose or not a fraction of her income in a domestic environment with no pecuniary evasion costs. Chapter 3, however, considers an *active* tax evasion environment where a taxpayer must explicitly conceal a fraction of her income offshore, which incurs in extra financial costs and deals with an international setting.

Another methodological aspect considered is the different solutions obtained according to the point of view of who is optimizing. On the one hand, Chapter 1 and Chapter 3 compute the optimal strategies from the taxpayer's point of view and obtain the optimal actions for a representative (aggregate) tax evader. On the other hand, Chapter 2 and Chapter 3 also provide normative insights by deriving the optimal strategies from the social planner's point view. Moreover, given that the social planner takes into consideration the optimal actions from the taxpayers' point of view as in a Stackelberg competition, the social planner is able to derive a robust strategy which is optimal invariably of the reactions exerted by the taxpayers. Specifically, both chapters employ recent insights from network theory and game-theoretic techniques to solve the optimization problem from the social planner's point of view.

Furthermore, micro-founded models that help to represent individual taxpayer behavior are defined in Chapter 1 and Chapter 3. Applying statistical techniques such as censored regression and panel data models, we are able to derive important implications from these representations. However, given that said mathematical models tend to be *too complex* to be fully characterized analytically, only some polar cases are thoroughly investigated from the taxpayers' point of view. To overcome this caveat, computational models are employed in every chapter to study the macroeconomic behavioral patterns which emerge from the aggregation of individual taxpayer decisions. Said computational approaches provide additional robustness validations to the analytical results derived in each chapter of the current dissertation.

There are strong methodological links among all three chapters, providing a comprehensive coverage of recent insights from social sciences, game theory and applied network theory, while allowing for the implementation of state-of-the-art computational techniques such as agent-based models and analogous computer simulations. Conclusively, combining the aforementioned methodologies in an economic environment gives us the necessary tools to thoroughly study tax evasion from multiple facets, and allows us to derive robust normative insights for future fiscal policy research.

**Revisiting the research questions**

**Research question 1:** How to design a parsimonious model of individual tax compliance on self-reported income considering both intrinsic and extrinsic motivations for tax compliance?

In Chapter 1, we derive a micro-founded parsimonious mathematical model in line with the 'slippery slope' framework of Kirchler et al. (2008). In particular, our model employs a tax morale parameter (in the sense of Wenzel (2003); Kirchler et al. (2008); Luttmer and Singhal (2014)) and a constant relative risk aversion level (as in Hashimzade et al. (2016)). Given the inherent complexity of the model, we resort to computer simulations (Mittone and Patelli (2000); Davis et al. (2003); Mittone (2006); Korobow et al. (2007); Hokamp and Pickhardt (2010); Calimani and Pellizzari (2014); Hokamp (2014); Hashimzade et al. (2014); Andrei et al. (2014); Pellizzari and Rizzi (2014)). On the one hand, our results are able to replicate individual taxpayer behavior. Namely, we find a dichotomous response of taxpayer disclosures as in Alm, McClelland and Schulze (1992) and Dwenger et al. (2016), where taxpayer behavior 'bunches' at either full evasion or full compliance. Further, we present analytical and computational arguments to explain under which circumstances taxpayers would be willing to fully comply with their tax obligations even in the (known) absence of audits. Our results provide a mathematical justification to the findings of Alm, McClelland and Schulze (1992) and Dwenger et al. (2016). A statistical regression technique shows that our model is consistent with the seminal empirical findings of Alm, Jackson and McKee (1992). On the other hand, our mathematical model is also able to characterize macroeconomic taxpayer behavioral patterns as in Prinz et al. (2014), Pellizzari and Rizzi (2014) and Kogler et al. (2015). Conclusively, we are able to answer the first research question by introducing a mathematical model which is able to replicate individual and aggregate taxpayer behavior, while remaining in line with the 'slippery slope' framework. Furthermore, our work sheds light on the hypothesis by Kirchler et al. (2008) about the appropriateness of adopting a 'service and clients' approach instead of the classical 'cops and robbers' enforcement system whenever taxpayers have a low trust in their government and the tax authority accounts for low enforcement power.

**Research question 2:** Given a finite budget (number) of audits to be enforced during each period, which is the optimal way to target taxpayers such that the mean subjective probability of being audited is maximized across the entire taxpayer network?

Chapter 2 deals with this question by first acknowledging the power of *threat-to-audit* messages (Slemrod et al. (2001); Alm et al. (2009); Kleven et al. (2011); Pomeranz (2015); Boning et al. (2018); Lopez-Luzuriaga and Scartascini (2019); Drago et al. (2020)) and by following the suggestions by Alm et al. (2009), Whillans et al. (2016) and Salmon and Shniderman (2019) about how to devise an appropriate communication channel between the tax authority and the taxpayers.

Accordingly, the social planner sends the following message to all taxpayers: *'Dear citizen, a new audit regime is in place. Last year the societal audit probability was of 'p' and equal for all taxpayers. As of now, the probability of being audited will be proportional to the income level of each taxpayer'.*

In our context, said message assures *ex-post* income-productivity heterogeneity among taxpayers (Patacchini and Zenou (2012)). Immediately afterwards, the tax authority devises an optimal audit strategy taking into consideration the direct effects it may inflict by auditing taxpayers (Calimani and Pellizzari (2014); Hashimzade et al. (2016); Gamannossi degl'Innocenti and Rablen (2020)), taxpayer social interactions (Hokamp and Pickhardt (2010); Andrei et al. (2014)), endogenous social effects (Galbiati and Zanella (2012); Alm et al. (2017); Gächter and Renner (2018)) and spillover effects (Scartascini and Castro (2015); Boning et al. (2018); Lopez-Luzuriaga and Scartascini (2019); Riedel et al. (2019); Drago et al. (2020)). We design an optimal audit strategy by building on the notions of local-*average* games (Ushchev and Zenou (2020)). The proposed audit scheme targets taxpayers in function of their *post-message* individual productivity and their position inside the network. Our results are in line with the existing literature (Scartascini and Castro (2015); Drago et al. (2020); Gamannossi degl'Innocenti and Rablen (2020)). Moreover, the optimal audit strategy is robust to expected and non-expected utility theories, taxpayer heterogeneity, rational and (bounded) non-rational decision-making processes, and it is invariant for any taxpayer utility function.

**Research question 3:** Given a limited number of tax information exchange agreements (TIEA's) to be implemented between countries, which would be the optimal allocation of treaties among country-pairs such that the global probability of tax-evasion detection is maximized?

Chapter 3 builds on the 'Panama Papers' and on recent insights from network theory to address this question. We first study the Panama Papers and the natural experiment induced by the G20 2009 crackdown on tax havens and we confirm the deterrence effect of TIEA-type treaties on tax evasion (similarly to Zucman (2013); Johannesen and Zucman (2014); Braun and Weichenrieder (2015); Caruana-Galizia and Caruana-Galizia (2016); Omartian (2017); Bennedsen and Zeume (2018); Johannesen et al. (2018); Andersson et al. (2019)). In particular, our results are in line with Johannesen and Zucman (2014) and Omartian (2017). Following, we adopt our perspective from a Stackelberg competition in which the social planner takes into consideration the possible reactions that the representative (aggregate) tax evader exerts as a response to the TIEA-type treaty implementations. We formally characterize the equivalence between the social planner's objective and that of finding the subgraph of a network with maximal Bonacich centrality (Corbo et al. (2006); Abrego et al. (2009); Belhaj et al. (2016)). The optimal fiscal policy is thus to enforce tax information exchange agreements between country-pairs following a hub-like structure, targeting offshore financial centers according to their Bonacich centrality in the global network of tax evasion. The specific features of the graph are dependent on the influence that the social planner may exert over the network (Corbo et al. (2006)). Specifically, the social planner should opt to design a *quasi-star* treaty structure if he exerts little influence, and opt for a *quasi-complete* graph if he exerts great influence (Cvetkovic et al. (1997); Corbo et al. (2006); Aouchiche et al. (2008); Chang and Tam (2011)). Additionally, we provide computer simulations to confirm our analytical results and find that the proposed fiscal policy is optimal from the social planner's point of view invariably of the action that the representative (aggregate) taxpayer may exert. Albeit our computer simulations give insights about the most central tax havens which ought to be priority targets for the social planner, we acknowledge that these results may be biased given our employment of the Panama Papers.

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# Part II

# Appendices

# Appendix A

# Network effects in an agent-based model of tax evasion with social influence

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**Abstract**

An Agent-Based Model (ABM) accounting for tax-morale and loss-aversion was implemented over different network systems with social interactions at the local level to study the phenomenon of tax evasion. This ABM is an innovative model which integrates endogenous characteristics of heterogeneous agents and proposes a more relaxed assumption on the information exchanged between agents as compared to previous social models. The current study gives an insight on the possibility that choosing specific network structures may yield to more realistic outcomes. Moreover, this ABM manages to replicate both individual and aggregate results from previous experimental and computational models of tax evasion. A clearcut novelty might be the non-linear channel through which the network centrality enhances a positive effect on the aggregated level of tax compliance. There is a large area of action for public policy makers to further research the presented results about how audit rates, fines and tax morale non-linearly increase income disclosure, whereas tax rates have a non-linear negative impact on tax compliance.

**Keywords:** Agent-Based Models · Tax Evasion · Complex Networks

## A.1 Introduction

Following the influential paper published by Allingham and Sandmo (1972) exploring the rationale behind tax evasion phenomenon, a vast literature has congregated around the modeling of tax compliance. A non-negligible portion of income tax research has explored the mechanisms surrounding social interaction

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among the agents, particularly in agent-based modeling. Mittone and Patelli (2000) delved into the psychological motives of tax compliance inherent to a society composed by three heterogeneous types of agents: full-compliers, imitators, and full-evaders (free-riders). The objective of their endeavor was bound to the analysis of aggregate tax behavior in function of the initial composition of the taxpaying population under two different audit schemes; uniform and tail auditing.

A comprehensive compilation of literature may include Davis et al. (2003) who find stable equilibria both under low and high enforcement schemes, linked by a non-linear and asymmetric transition; Hokamp and Pickhardt (2010) introduced an exponential utility function for agents in order to induce more realistic results; and Korobow et al. (2007) introduced a network structure but also considered individuals who possessed heterogeneous characteristics and intrinsic perceptions about the enforcement regime.

Stepping forward into a more contemporary literature review, Andrei et al. (2014) contributed an additional aspect to be taken into account for agent-based models of income tax evasion. The authors found that the network structure underlying the societal arrangement has a significant impact in the decision process dynamics; principally, individuals tended to disclose a larger fraction of their income whenever they embodied networks with higher levels of centrality. Amongst the number of social structures tested, the Erdos-Renyi random network and the Power Law networks may incentive agents to comply the most given their larger capacity of propagating information and influence dissemination. The usage of network structures in models with 'social pressure' are everyday more frequent. A convenient example is the one by Billari et al. (2007) in which agents must choose a partner based on the mutual proximity with respect to age and social status in a dynamic framework; this approach will be particularly handy for the model implementation in Section A.3.

Alm et al. (2017) conducted a social experiment intended to learn about the burden of peer effects and social pressure in the context of tax compliance. The conclusions reached by the authors discuss how agents have a statistically significant positive effect in the tax disclosures of their 'neighbors' or 'people with whom they frequently share information'; when an agent is surrounded by honest (cheating) individuals, the agent itself starts to behave in a more honest (cheating) manner.

## A.2 A taxpayer's decision to evade

Tax compliance decision-making is ordinarily modeled as a gamble or an investment opportunity involving one risky asset (undisclosed income) and a risk-free asset (disclosed income), the micro-founded expected utility to be optimized with respect to the fraction of income declared $d$ may well be defined as:

$$EU[d] = p \cdot U(X) + (1-p) \cdot U(Y), \tag{A.1}$$

where $X$ is the net income after taxes and penalties in case an audit takes place, and $Y$ is the net income after taxes in case no audit takes place.

Promptly substituting $X$ and $Y$ in terms of the gross earned income $I$, the penalty rate $\theta$ applied to the undisclosed fraction of income in case an audit occurs, and the applicable tax rate $\tau$, reformulates Equation A.1 to:

$$EU = (1-p) \cdot U[I - \tau(d \cdot I)] + p \cdot U[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)] \tag{A.2}$$

Solving for optimality conditions, the rational taxpayer will declare less than its actual income if the expected tax payment on undeclared income is less than the regular rate, that is, whenever $p \cdot \theta < 1$; moreover, the fine rate must be larger than 1. There is a widely known substantial drawback for this model in the sense that it highly overestimates the tax evasion rate.

Akin to the adjustment outlined by Hokamp and Pickhardt (2010), a power utility function is imputed into the model outlined in Equation A.2. Discarding for simplicity the subindex, yet considering for each agent $i$ and each time $t$, the utility function of every single agent is characterized in Equation A.3.

$$U(d, W) = (1+d)^{\kappa} W^{(1-\rho)} \tag{A.3}$$

where the variables are denoted as: period-wealth $W = \{X, Y\}$, the fraction of declared income $d \in [0, 1]$, loss-aversion $\rho \in (0, 1)$, and tax-morale $\kappa \in [0, 1]$. In this sense, a higher the tax morale yields a larger utility of complying; while a higher loss-aversion would yield a lower utility on wealth.

Tax morale has been a recurring matter in the models of tax compliance ever since Myles and Naylor (1996) asserted a social conformity framework in which agents attained an additional utility from conforming to the established social norms. Despite the complications to accurately define tax morale, hereafter tax morale will be understood as an umbrella term, in the sense of Luttmer and Singhal (2014), enclosing intrinsic motivation, reciprocity, culture, biases and social influences. Next in order, loss aversion will be understood as the well-known wealth effect described by Tversky and Kahneman (1973).

A remark for the current tax decision model is the non-matchable income assumption, meaning that an auditor from the Tax Agency does not know beforehand the individuals' incomes. If a society would happen to account for a non-negligible matching system for its labor market, the assumption may be relaxed to take into consideration only the non-matchable portion of the agents' stipends without sacrificing any of the models' intuitions and results.

### A.2.1 Subjective audit rate

The individuals' subjective probability of being audited is updated based on their past experience. Moreover, their audit beliefs are likewise updated by the behaviors of their 'neighbors', defined as the agents with whom they frequently exchange information, as in Alm et al. (2017). Hereafter, the subjective audit probability perceived by agent $i$ at time $t$ can be defined as a weighted average of the agent's prior experience (temporal updating) and the signals from its neighboring individuals (geographical updating) last period.

The universe of agents coexists in a predefined network structure with (local) social interactions and each period agents exchange information with their neighbors, however they never get to know the entire situation nor the composition of the society in which they inhabit. Afterwards, agents update their own perceived audit probability by means of a weighted average of three possible channels: their subjective audit rate in the previous period (prior), their own recalling of past audits (memory), and the signals they received from their neighbors (social influence).

$$\hat{p}_{i,t+1} = \lambda_1 \hat{p}_{i,t} + \lambda_2 \sum_{s=1}^{S_i} \frac{A_{i,t-s}}{S_i} + (1 - \lambda_1 - \lambda_2) \sum_{j \neq i}^{N_{i,t}} \frac{1}{N_{i,t}} \sum_{s=1}^{S_j} \frac{A_{j,t-s}}{S_j} \tag{A.4}$$

where $\lambda_1$ and $\lambda_2$ are convex averaging weights, $A_{i,t-s}$ is valued one if the agent $i$ was audited in the period $(t-s)$ and zero otherwise, $S_j$ is the memory or number of audit periods that agent $j$ can recall in the past, and $N_{i,t-1}$ is the number of neighbors of agent $i$ at time $t$.

## A.3 Implementation of the agent-based model

There are key distinctions that difference ABM's from mathematical models. Arguably one the most germane attributes of any Agent-Based Model is its intrinsic capability of embodying plentiful heterogeneous agents, all possessing unique aspects and personalities. Accordingly, each agent is heterogeneous by acquiring specific built-in characteristics. Secondly, individuals base their decision process in their own subjective probabilities of being audited and not in the true audit rates. Lastly, agents coexist in neighborhoods inside a larger societal structure which allows for information exchange at a local level.

Similarly to Korobow et al. (2007), this model includes the three listed attributes, however there is a key difference in the assumptions about shared information. Korobow et al. (2007), for example, implemented their model under the hypothesis that individuals shared their own, personal 'payoffs' for tax evasion among their neighborhoods, however, they acknowledged the unlikelihood of such delicate information becoming public in real-life scenarios. In order to outplay this limitation, now agents communicate solely their memory about previous audits and update their subjective probability of being audited in conjunction with the frequency of audits perceived by themselves and their immediate neighbors.

Stepping into the realm of the current work, agents are constituted as individuals embroidered by personal traits: tax-morale, loss-aversion, income, age and an initial subjective probability of being caught evading taxes. Moreover, the tax-morale and loss-aversion parameters are dynamic, increasing stochastically with respect to age. On any occasion in which an agent would happen to grow into an age above 65, it would be removed from the network analogous to a retired individual would exit the labor market; to replace the empty node left inside the network, a new individual, aged 18 and with its own particularities, would replace the available position.

Tax morale is initialized from a society-level parameter for the entire network, whereas loss-aversion is entirely endogenous for each individual. For a society level tax-morale of $\kappa_S \leq 0.5$, individual morale is modeled as $\kappa \sim U(0, 2\kappa_S)$. Endorsing the notion of loss-aversion as the preference of avoiding a loss over attaining a win, coupled by the endowment effect in which an individual would rather pay a higher rate to retain something it owns (net income) than to receive another thing it does not own (taxes), it follows that a local and endogenous loss-aversion parameter ($\rho$) may well be defined as the relative income position held by the individual with respect to its neighbors divided by the neighborhood size $|N_i|$ (including the agent) plus one, where the highest loss-aversion measures pertain the most affluent agents.

$$\rho_i = \frac{\text{rank}(I_i)}{|N_i|+1} \tag{A.5}$$

This definition allows the global distribution of individual loss-aversion of $\rho$ to be symmetric around 0.50. The distribution of ($\rho$) resembles a bell-shape tendency, at least when contrasted against the original Uniform$\sim U(0,1)$.

Enhancing audits to shift from random to endogenous and regarding the income effect on tax compliance, a modification was made on the Tax Agency's audit strategy. It would not be a surprise that a Tax Agency would be more inclined into targeting individuals whose eye-catching income stands out from the sample. Ergo, proceeding for each agent, the endogenous probability of being audited is set in accordance to its income level, where individuals with higher salaries have larger probabilities of being audited. Following, the endogenous audit rate $q$ for agent $i$ is the true audit rate $p$ multiplied by the ratio of the agent's income over the average income of the population, shown in Equation A.6.

$$q_i = \frac{I_i}{\sum_{j=1}^{N} I_j} \cdot Np \tag{A.6}$$

Notwithstanding the adjustment implemented for the endogenous audit rates, the mean value of $q$ remains equal to the true audit rate $p$; allowing for consistent testing of parameters. To see this it suffices to sum over all agents $i$ and divide by $N$ in both sides of Equation A.6.

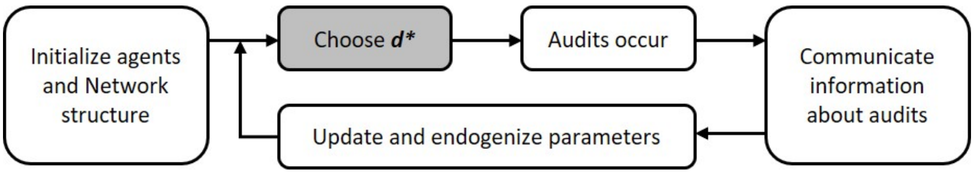


Figure A.1: Simplified process flowchart

Figure A.1 depicts the decision process mechanism in a rather simplified manner. An artificial society is structured as a network, where each agent is initialized with exogenous parameters $\{\kappa_0, \rho_0, q_0, \hat{p_0}, I_0, age_0\}$ and chooses an optimal fraction of income to declare $d^*$. Afterwards, audits take place and agents communicate 'signals' or information regarding the audit process. Next, agents update and endogenize parameters $\{\kappa_t, \rho_t, q_t, \hat{p_t}, I_t, age_t\}$ and repeat the decision process. Every agent repeats the cycle until it is retired from the labor market.

### A.3.1 Network structure

Immediately upon the parameter booting, whether endogenous or not, lies the second cornerstone of the ongoing Agent-Based model with social pressure: the network formation process. Embracing the methodology followed by Andrei et al. (2014), a selection of nine different underlying network structures where tested ensuing comparisons and contrasts among one another: two types of random graphs, small words, large world, Watts-Strogatz, ring, wheel and two types of scale-free networks.

Figure A.2 and Figure A.3 display an Erdos-Renyi random graph and a random geometric graph, respectively, in a toroidal world which 'wraps up' both vertically and horizontally. Albeit both graphs having the exact number of agents, links and degree distribution, its interesting how the physical arrangement appears to be strikingly different. The ABM simulations where implemented in the *Netlogo* software, where the default ordering of agents follows the random geometric structure of Figure A.3. All

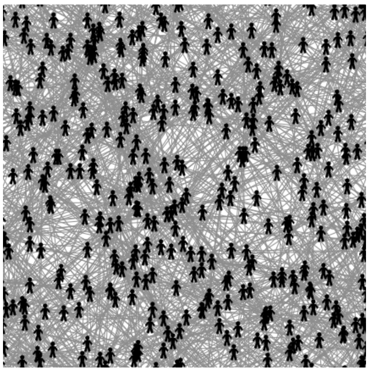

Figure A.2: Erdos-Renyi

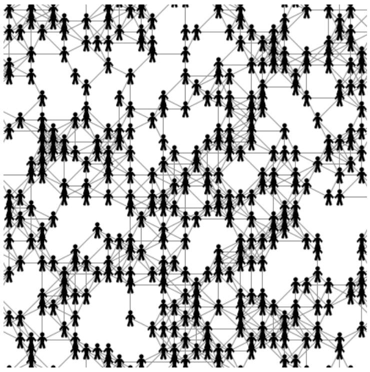

Figure A.3: Random Geom.

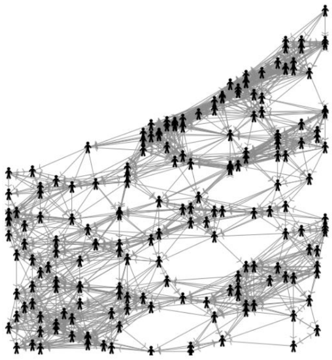

Figure A.4: Fitness Model

network structures, except for the fitness function model, where implemented using the 'nw' extension of *Netlogo*.

Figure A.4 presents a fitness function network in a Cartesian environment without 'wrapping'. This is a specific type of scale-free networks, following a mathematical specification to determine or not an association between any two given individuals. Inspired on the social interaction Agent-Based model with spatial components devised by Billari et al. (2007), individuals are constrained to link only with 'relevant others' within their reach in terms of age and social position. Attending to this notion, an artificial society was emulated on a Cartesian plane where the $x$-axis features the agents' age whilst the $y$-axis represents the individuals' income. First, a newly created set of agents is randomly assigned individual age and salaries and positioned in their corresponding coordinates inside the plane. Then, each time-step, agents advance one unit horizontally, and, stochastically increase their income, shifting north in the plane on the long-run. The procedure continues for each agent until they reach a sufficiently advanced age, in which case they 'retire' from the labor market and are replaced by an offspring endowed with a fraction (two-thirds) of the exiting agent's wealth and being positioned at the left edge, starting their own working life.

Figure A.4 depicts a pyramidal society after 60 timestamps where the top-right corner positions are occupied by old, wealthy individuals, the top-left corner is void (juvenile millionaires) and a dense bottom-left edge reveals a large amount of young agents with low or middle incomes. Evidently, it would be plausible to speculate that in the real world a person would discuss his or her fiscal matters rather exclusively with people of their own age and income level (social status).

## A.4 Results

The main objective of the following section is understanding the effects of different regressors on the fraction of income declared at the society level. The Behavior Space tool incorporated in the *Netlogo* software allowed for a simulation of 21,890 simulations ran over 729 different possible parameter combinations: $\tau = \{25\%, 35\%, 45\%\}$, $p = \{2\%, 6\%, 10\%\}$, $\kappa = \{10\%, 25\%, 40\%\}$, $\theta = \{2, 4, 10\}$, and nine different network structures; each simulation accounted for 350 agents and fixing the probability updating weights to $\lambda_1 = \lambda_2 = \lambda_3 = 1/3$.

The analysis of the parameters is specified in Table A.1 along with their respective significance codes. Keeping in mind the nature of the outcome variable $d$ to be bounded between zero and one, a specific statistical model must be applied for data analysis. The results produced by the simulation were tested under a Tobit model censored for minimum and maximum values of zero and one, respectively, boundaries included. Moreover, quadratic coefficients where added to study the non-linear interactions of each parameter.

Table A.1 delineates the different linear and non-linear effects that each parameter imposes in the fraction of income disclosed. Column (1) and Column (2) both deal with the effects of tax rates, audit rates, fines and tax-morale. The last regressors in Column (1) take into consideration the average closeness-centrality of all individuals in the underlying network where agents coexist; the closeness-centrality is interpreted as 'how easily a node may be reached from all other nodes'. Hereby and after closeness will be understood as the inverse of the average distance of a node to all other nodes; where the distance

Table A.1: Dependent variable: Aggregate $[d]$

| Tobit Model | Closeness | | Dummy variables | |
|---|---|---|---|---|
| Regressors | (1) | | (2) | |
| Intercept | -2.143 | *** | -2.146 | *** |
| $\tau$: tax_rate | -3.392 | *** | -3.392 | *** |
| $\tau^2$: tax_rate$^2$ | 2.348 | *** | 2.347 | *** |
| $p$: audit_rate | 4.060 | *** | 4.060 | *** |
| $p^2$: audit_rate$^2$ | -12.550 | *** | -12.550 | *** |
| $\theta$: fines | 0.055 | *** | 0.055 | *** |
| $\theta^2$: fines$^2$ | -0.003 | *** | -0.003 | *** |
| $\kappa$: tax_morale | 1.841 | *** | 1.841 | *** |
| $\kappa^2$: tax_morale$^2$ | -1.503 | *** | -1.503 | *** |
| closeness | 0.577 | *** | | |
| closeness$^2$ | -0.971 | *** | | |
| Random_Geom | | | -0.002 | |
| Lattice | | | -0.045 | *** |
| Pref_Attach | | | 0.001 | |
| Fitness_Model | | | 0.004 | * |
| Ring | | | -0.081 | *** |
| Small_Worlds | | | -0.022 | *** |
| Watts_Strogatz | | | -0.006 | ** |
| Wheel | | | -0.045 | *** |

Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05

between two nodes is the shortest path in which one node may reach the other. Consequently, a node who requires few steps to reach other nodes will have a lower average distance, implying a larger closeness within the network. On the other hand, Column (2) controls for each network structure by adding one dummy variable for each type while keeping the Erdos-Renyi random-graph as the baseline case, allowing for comparisons with the results by Andrei et al. (2014).

Opening the analysis of the Tobit model, tax rates seem to impose a negative effect on tax compliance, yet such impact seems to marginally increase for very large levels of tax duties. This effect, which can be interpreted from a positive estimated coefficient for $\tau$ and a negative estimated coefficient for $\tau^2$, as seen in Table A.1, is represented in Figure A.5 where tax compliance decreases non-linearly with respect to the tax rate. A basal development of any taxation model is the understanding of how tax rates behavior reflect an impact on the collected revenues from the Tax Agency's point of view. The Laffer Curve is the representation of tax revenues as a function of the tax rate. Governments cannot over-raise the tax rate as it would incentive agents to evade taxes, reducing the governmental revenue. Figure A.6 details the corresponding Laffer Curve for the simulated society.

An outcome from Table A.1 that falls in line with common sense is the positive coefficient for audit rates; as the true probability of being audited increases, a larger proportion of agents experience audits, which in turn communicate the event to their neighbors and the information about a harsher enforcement environment becomes public knowledge, ensuing higher tax compliance among individuals. The quadratic term of the audit rate suggests that, despite the notion of larger audit rates implying higher tax compliance, this policy tool will tend to lose effect as the audit probabilities start turning 'too high'. Fines (or penalties), represented by the parameter $\theta$ in this model, retain a somewhat secondary role at inhibiting tax evasion. Analogous to findings in the tax policy literature, see for example Alm, Jackson and McKee (1992), fine rates have statistically significant effects to deter evasion even though their estimated coefficients are rather low. Fines help deter evasion only up to some degree given that in the model specification they only appear interactively with the true audit rate $p$ forming the enforcement criterion $\theta p$. Ergo, for relatively high values of $p$, parameter $\theta$ loses its strength. The resulting non-linear effects of audit rates on tax evasion have relevance for public policy, shedding light on a possibility that raising audit rates and strengthening enforcement schemes may have marginally decreasing effects. Side by side with these results, Kirchler et al. (2008) point out that policy makers should concentrate less in penalties and enforcement, and instead, focus on policies aiming to heighten voluntary compliance.

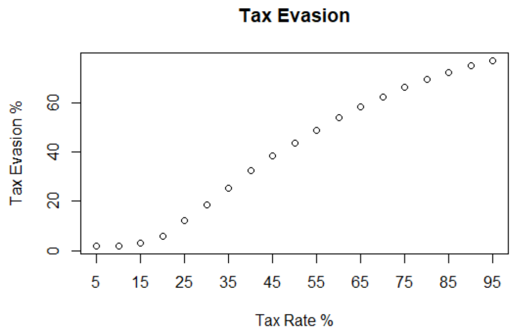


Figure A.5: Tax evasion as a function of $\tau$

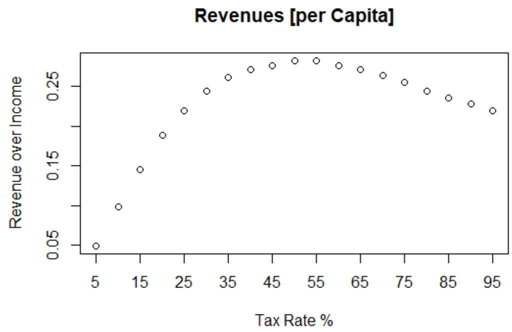


Figure A.6: Laffer Curve

It may be wise to commence the discernment of tax morale by acknowledging how fundamentally difficult it is to measure a society's morale. However, miscellaneous interpretations could typify a government's control over a society's tax morale through a larger participation and political inclusion of citizens or even by generating a feeling over how well the budget is being spent. Relying on citizen's perception of their trust on institutional authorities may be, as well, a proxy conjecture about societal morale. Adopting the assumption, however, that tax-morale is not only measurable but mutable, it has a positive, non-linear, and statistically significant effect on tax compliance, that is, individuals endowed with a higher tax-morale would be more inclined to disclose their true incomes and thus diminish their fiscal evasion. Consequently, societies whose citizen's tax-morale is low should be more concerned in establishing an agenda which would encourage taxpayers' involvement within the society and policies targeting the promotion of how resources are being 'well spent'.

The concluding parameter in Column (1), the closeness centrality of the network, previously defined, yielded a statistically significant positive effect in the aggregate tax compliance and a negative coefficient on its squared transformation. There exists, therefore, a non-linear channel through which closeness in a network may stimulate tax compliance at the aggregate level. Perhaps these peer-effects gain their impetus from the spread of information and the availability of knowledge regarding the audit frequency.

Column (2) provides a deeper look into the dynamics of closeness centrality by recurring to dummy variables in the Tobit model. Even more, the closeness centrality for each structure may be seen in Table A.2 to serve as reference.

Table A.2: Closeness centrality measures

| Network | Closeness | Network | Closeness | Network | Closeness |
|---|---|---|---|---|---|
| Erdos_Renyi | 0.3734 | Pref_Attach | 0.3806 | Ring | 0.0113 |
| Random_Geom | 0.1714 | Small_worlds | 0.2362 | Lattice | 0.0808 |
| Fitness_model | 0.3631 | Watts_Strogats | 0.2418 | Wheel | 0.5035 |

Reminiscent of the Erdos-Renyi graph as the baseline case, the random geometric and the preferential attachment networks do not have a statistically significant different repercussion regarding tax behavior. Lattice, ring, small worlds and wheel structures impose a curtailed effect on tax evasion, statistically significant lower than the benchmark; these effects may be seen in the statistically significant negative coefficients that these dummies attained in Table A.1. Watts-Strogatz worlds seem to retain a statistically significant reduced effect with respect to the benchmark, nonetheless the estimated coefficient is relatively modest in comparison to the alternative networks. Ultimately, the fitness function model conveys a small increase in the aggregate tax levels, nevertheless limited to a minor statistical significance. As a final word, the closeness of wheel networks, as seen in Table A.2 is markedly high, however it is not efficient in the sense of enhancing tax compliance; consequently, a large centrality is no guarantee for discouraging tax evasion. A possible explanation may be that, for each network, the loss-aversion distribution changes. The fitness model, based on income proximity, accounts for the fastest speed of bell-shape convergence of $\rho$, making it close to reality, whereas other structures have large fractions of agents with very low, or very high, loss-aversion levels.

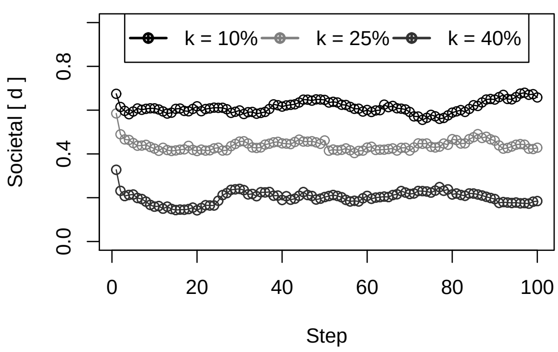


Figure A.7: Aggregate tax compliance

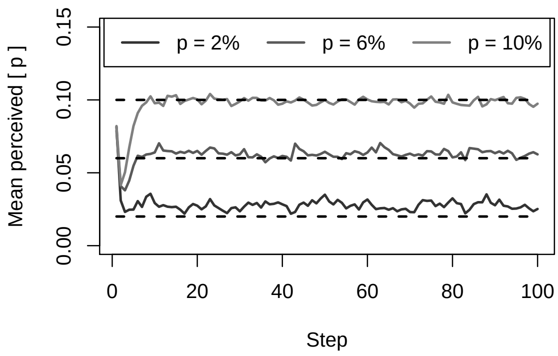


Figure A.8: Mean subjective probability

A robustness check took into account the aggregate convergence results provided by previous ABM's of tax compliance. Figure A.7 and Figure A.8 illustrate the emergence of a bottom-up compliance behavior, both in the fraction of aggregate declared income and for the average perceived audit probability. In Figure A.7, even if the agents act independently and do not know the exact declared income of others, they converge to an aggregate level of tax compliance; the oscillating convergence at three different steady states is presented with respect to their respective levels of societal tax morale, for $\kappa = \{10\%, 25\%, 40\%\}$ and $p = 5\%$, $\theta = 2$, and $\tau = 30\%$. In Figure A.8, in spite of the seemingly accurate mean perceived probability, a t-test proved that agents overestimated the true audit rate for $p = 2\%$ and $p = 6\%$ yet they underestimated it at the $p = 10\%$ level; where $\kappa = 25\%$, $\theta = 2$, and $\tau = 30\%$. Accordingly, agents consistently fail to discover the true audit rate both individually and collectively.

Alm, McClelland and Schulze (1992) studied individual tax evasion by means of economics and discovered that over two thirds of individuals either fully-evade or fully-comply, generating a dichotomous distribution of the share of income disclosed; a behavior which is not supported by the standard expected utility theory. Figure A.9 depicts the last idea that the power utility model has to offer by reproducing the dichotomous behavior of individual taxpayers found in economic experiments for different levels of tax morale. Intriguingly, a power utility model with social interactions may be able to replicate not only the aggregate, but also the individual level results found in the literature of experimental economics.

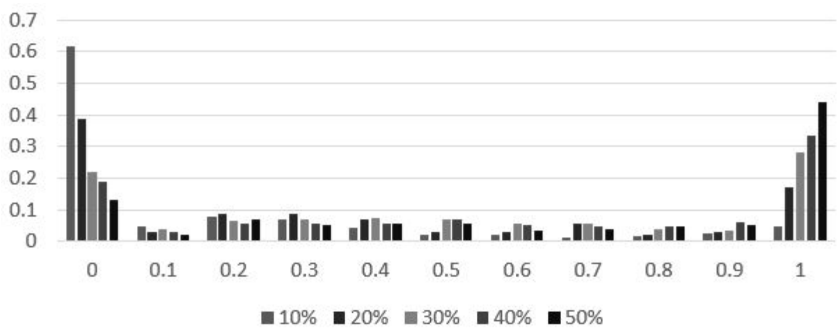


Figure A.9: Histogram of individually declared income for varying *tax-morale*

## A.5 Conclusions

An expected utility theory tax evasion model was presented under a power-utility function specification and implemented through an Agent-Based model with heterogeneous agents and local social interactions, simulated over different underlying network structures. Agents have limited knowledge about their surroundings yet may acquire endogenous parameters of loss-aversion and audit rates, depending not only on their income levels but also in the corresponding ones from their neighbors. An exploratory setup shed light in the possibility of choosing specific network structures which may yield a more realistic result, particularly for the calibration of endogenous parameters as loss-aversion. Following, a fitness-function model that accounts for age and social status (income) was questioned and deemed to be appropriate for modeling taxpayers' behavior. In top of that, the assumption on the information exchanged is relaxed from communicating evasion rates and payoffs to simply sharing their past memories about the occurrence or not of former audits.

There is a large area of action for public policy makers in the further study of how audit rates and fines non-linearly increase tax compliance, yet both tools tend to lose effect whenever over-enforced. Whilst tax rates have a non-linear negative impact on income disclosure, tax morale offers an opportunity for governments with an unreceptive image among their citizens to call for a larger voluntary tax contribution by attending for a better public image of government spending or by strengthening their political inclusion. Moreover, an interesting property of the model specification is its capability of reproducing both individual behavioral patters and aggregate convergence levels of tax compliance as the encountered in experimental economics literature. Lastly, a novel parameter for the closeness centrality of the networks was tested and found to be a non-linear channel through which societies may converge to higher tax compliance rates for more closely connected social structures.

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# Appendix B

# Network-based policies versus tax evasion

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**Abstract**

This paper explores the optimal income tax audit strategies from a social planner's perspective, whose objective is to minimize the aggregated tax evasion of a given society. Agents live in a social-cohesive network with homophilic linkages, meaning individuals connect only with people who are akin to them. Further, each period individuals share their memories about past audits and consequently update their subjective probability of being audited. The Tax Agency finds that network-based audit policies are inefficient, in the sense that they are just as good as random. Thus, the social planner credibly announces that, from now on, audit rates will be linearly proportionate to the agent's income, making richer people more prone of being audited. Audit rates are now endogenous and heterogeneous among agents, making it possible for the Tax Agency to find an optimal network-based policy following a local-average strategy where a 'key sector' of society is predominantly audited every period. Following this strategy, under a dynamic framework, the Nash Equilibrium for the average subjective audit rate is swiftly raised after just a few fiscal years. The enhanced subjective audit rate in turn unfolds as a larger tax revenue collection and a significant deterrence of income tax evasion.

**JEL classification:** C54 · D85 · H26
**Keywords:** AB Models · Networks · Quantitative Policy · Tax Evasion

## B.1 Introduction

Nowadays there exists a vast literature regarding the economics of crime, pioneered by the economic approach of crime and punishment by Becker (1968). Shortly after, Allingham and Sandmo (1972) studied the rational behavior behind the tax evasion phenomenon from an expected utility theory point of view. Despite the proposed model incurred in a few drawbacks, noted by the authors themselves,

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their study laid the foundations for plenty more research to come afterwards. Mittone and Patelli (2000) pondered the decision process of tax evasion from an imitative behavior framework, where agents could fully-comply, withhold a share of their income or free-ride on their tax duties. Mittone (2006) enlarged the literature to account for attitude towards risk under dynamic choices, where agents faced a repetitive decision-making process integrated in a simulated environment.

Korobow et al. (2007) proposed a novel Agent-Based Model where agents held heterogeneous characteristics and accounted for an intrinsic perception regarding the enforcement policies practiced by the social planner, or Tax Agency, which audits a fraction of individuals each fiscal period. Hokamp and Pickhardt (2010) further delved the research of income tax evasion to encompass ABM's where individuals responded to different government policies. The model designed by the authors not only accounted for time effects, but it was also able to grasp how heterogeneous agents optimized an exponential utility model, which accounts for a more realistic setting than previous papers had proposed. Alm et al. (2017) conducted an economic experiment which uncovered how 'neighbors', defined as all the agents with whom an individual shares information, have statistically significant peer-effects and do 'social pressure' on tax compliance. The authors identified how being surrounded by honest (cheating) tax payers encouraged individuals to be honest (cheating) themselves.

Modeling peer effects and social norms in group behavior has recurrently resourced to network structures accounting for complementarity effects. Ballester et al. (2006) studied how under a noncooperative game with a quadratic utility function, a social planner could identify a 'key player' based on a modified measure of Bonacich centrality. From a network-based point of view, whenever a social planner wants to minimize (maximize) the aggregate behavior, it must remove the node with highest (lowest) centrality measure. Whilst Ballester et al. (2006) consider complementarity effects in function of neighbors' *aggregate* actions, Ushchev and Zenou (2018) proposed an alternative mechanism where the effects are derived from the *average* value of neighbors' actions instead. Ushchev and Zenou (2018) proposed that whenever a game accounts for a social norm, network-based policies arising from local-aggregate models have little to no effect, as a local-average framework must be used instead. Specifically regarding networks of tax evasion, Andrei et al. (2014) studied how network effects played a non-negligible role in the aggregate tax behavior and concluded that network structures accounting for higher closeness centralities tend to enhance tax compliance. Garcia Alvarado (2019) further examined the 'neighbor' peer effects on tax evasion under homophily, meaning agents with similar characteristics tend to link between each other, and proposed a social-cohesive network formation model preserving a high closeness centrality measure.

The rest of the current paper develops as follows. Section B.2 details an Agent-Based Model implementation which considers a social-cohesive network formation where agents share information about past audit schemes. Further, individuals update their own subjective probability of being audited and compute the optimal fraction of income they will disclose to the Tax Agency (or social planner). The social planner then performs audits on a fraction of individuals and the cycle repeats in a dynamic setup for several generations. Section B.3 studies the model as a local-average (also called linear-in-means) game and finds the Nash Equilibrium and social norm of the game. Section B.4 identifies the optimal audit policy from a network-based perspective and establishes the validity of such optimal audit strategy by performing robustness checks over different scenarios. Section B.5 concludes the findings of this paper and calls for further research regarding the use of Agent-Based Models and networks to study tax evasion and tax compliance.

## B.2 Agent-based model implementation

The current section explores the dynamic mechanism through which individual agents interact between each other, and with the social planner, in a tax compliance model. Figure B.1 shows a flowchart depicting the five subroutines encompassed in the Agent-Based Model. First, agents are initialized with intrinsic, heterogeneous characteristics and assorted by means of a predefined network formation game. Later, agents derive the optimal fraction of income they wish to disclose $d^* \in [0, 1]$ to the Tax Agency. Afterward, the social planner singles out a group of agents to be audited by selecting one of the predefined audit strategies it might enforce. Immediately after, individuals communicate amongst themselves by sharing information with their set of 'neighbors'. Lastly, agents update their endogenous parameters, mainly their subjective probability of being audited and their loss-aversion coefficient. Once the fiscal cycle is closed, agents must optimally derive the fraction of income to be declared and repeat the game until they are retired from the labor market.

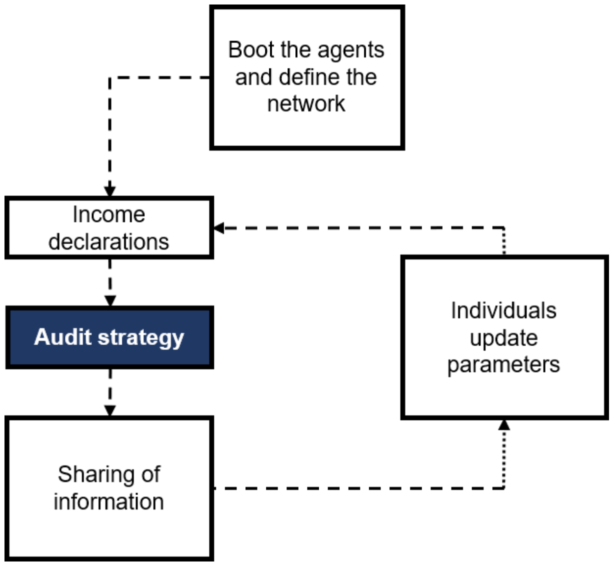


Figure B.1: A dynamic model of tax compliance

**Network formation**

The launching of the model starts by generating a collection of agents and assigning to each one of them a set of exogenous characteristics: {$\kappa$: tax-morale, $\rho$: loss-aversion, $p$: true audit rate, $\hat{p}$: subjective audit rate, $I$: income, and *age*}. Individuals will face their first ever tax compliance decision using their exogenously given parameters and will convert their characteristics to endogenous with each decision cycle that takes place. Defining a society-level tax morale of $\kappa_S \in (0, 0.5)$ which remains exogenous and constant along time, each individual is initialized with a personal tax morale sampled from a uniform distribution $\kappa \sim U(0, 2\kappa_S)$. Age is distributed uniformly between 18 and 65 years; thereafter each player who reaches the age of 65 will be retired from the labor market and replaced by a new agent aged 18. The agents' initial loss-aversion coefficient is inputed from the distribution $\rho \sim U(0, 1)$, yet the parameter will become endogenous as soon as the agent coexists within its network.

Immediately upon the parameter booting lies an essential part of the ongoing Agent-Based model with peer effects and social norms: the network formation process. Understanding by *closeness*-centrality the efficiency to spread information inside a network, Andrei et al. (2014) advocate the implementation of highly closeness-central structures to model tax evasion. Garcia Alvarado (2019) tested nine different network formation process and concluded that fitness model compositions have a statistically significant advantage to enhance tax compliance metrics over any other proposed structure. A basic, yet convenient, fitness-model network formation process which accounts for peer effects and social pressure may be mirrored from the one introduced by Billari et al. (2007).

The network construction commences by assigning to each individual exogenous and endogenous parameters: age and social-angle, respectively. Further, agents are mapped in a two-dimensional spatial model where the x-axis represents age and the y-axis stands for social angle. The age criterion is non-mutable by the agents and increases by one unit each fiscal cycle, while the social angle may be understood as income, which stochastically increases for the individual with respect to the time axis. The tax evasion model will be further measured in fractions of income, therefore the absolute value of wealth is not relevant for the network formation, i.e., the income position mapped as the y-axis is sufficient. After all agents have been laid out, they tend to move North-East in the Cartesian plane until they reach the age of sixty years old. Once that occurs, the agent is replaced by an offspring which is mapped with 18 years of age and a fraction of the leaving agent's income. The model is ran for three generations until the final structure resembles the one depicted in Figure B.2.

Figure B.2 represents each individual as a human-shaped node and each link by a direct connection between nodes. Moreover, agents are 'homophilic', implying they tend to link exclusively with individuals which are relevant or akin to themselves. Therefore, a node's neighbors would be the nodes which are close to itself, both in x-axis and y-axis, bringing by consequence social-cohesion to the network. Such arrangement follows the Ushchev and Zenou (2018) call for interest in modeling local-average games with

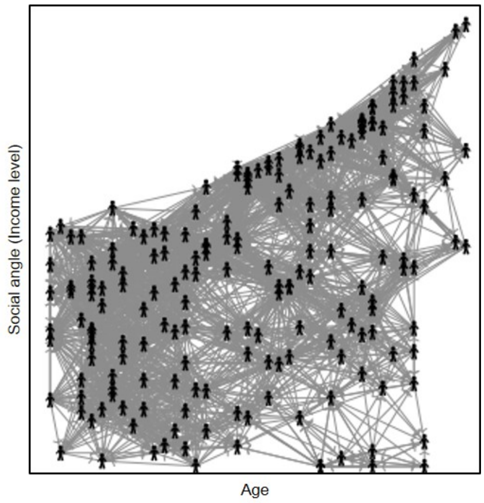


Figure B.2: A network with homophily and social-cohesion

networks which take into consideration homophily and social-cohesion. The clearcut advantage of this network formation rule over any random process is its pragmatic resemblance to a real-life scenario where people discuss their fiscal issues and experiences exclusively with individuals who are socially akin to themselves and not with randomly chosen nodes in the network.

### Tax evasion from the agent's point of view

The seminal expected utility model of tax evasion considers two states of the world for any agent: to be audited or not. Considering the micro-founded optimization problem where there is a probability $p$ of being audited, agents must derive the optimal fraction of disclosed income $d^* \in [0,1]$ such that Equation (B.1) is maximized:

$$EU[d] = p \cdot U(X) + (1-p) \cdot U(Y), \tag{B.1}$$

where $X$ is the net income after taxes and penalties in case an audit takes place, and $Y$ is the net income in case no audit takes place. Expected utility models of this nature are inherently limited to study non-observable incomes, particularly the tax behavior of individuals whose true gross incomes are not known by the Tax Agency. Likewise, even if a jurisdiction would be able to adopt an income-matching system for tax purposes, the model would still be valid for the non-observable fraction of the economy.

Expressing $X$ and $Y$ in terms of the gross earned income $I$, the applicable tax rate $\tau$, and the penalty rate $\theta$ applied to the taxes due from the undisclosed fraction of income in case an audit occurs, Equation (B.1) may be reformulated as:

$$EU = p \cdot U[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)] + (1-p) \cdot U[I - \tau(d \cdot I)] \tag{B.2}$$

Whenever the utility function to be maximized takes into consideration only the monetary values of the outcomes, Equation (B.2) suffers from a commonly known drawback: the equation highly overestimates the level of evaded income tax. Solving for optimality conditions, a fully rational individual would understate its income whenever the composed enforcement parameter $p \cdot \theta$ is sufficiently low, i.e., whenever $p \cdot \theta < 1$. Given that the probability $p \in [0,1]$ cannot be larger than one, the strict inequality implies that the fine rate $\theta$ must be strictly larger than one. This is a rather logical assumption, given that if the fine rate would be smaller than one, then it would be optimal for the taxpayer to be in the audit state of the world and face a tax payment of $\theta \cdot \tau < \tau$, thus the condition $\theta > 1$ is binding. Moreover, if the true audit rate $p$ would be valued zero, i.e., audits for sure will never take place, then the agents would have no utilitarian incentive to fully disclose their income.

Nonetheless, the enforcement parameter $p \cdot \theta$ is hardly ever larger than one. In fact, audit rates tend to oscillate between one and two percent of the population and fine rates rarely exceed a value of 2, meaning that the enforcement condition is seldom met and $p \cdot \theta \ll 1$. In order to overcome this setback, a model with tax morale and loss-aversion parameters is proposed in a power utility function as follows:

$$U(d, W) = (1 + d)^{\kappa} W^{(1-\rho)}, \tag{B.3}$$

where $W = \{X, Y\}$ is understood as the end-of-period wealth, $\kappa \in (0, 1)$ is the tax-morale level and $\rho \in (0, 1)$ is the loss-aversion coefficient. Moreover, individuals are not assumed to be omni-conscious, thus agents do not know their true probability of being audited ($p$) but instead optimize under their subjective probability of being audited ($\hat{p}$). Considering for each agent $i$ and each time $t$, yet discarding for simplicity the subindex, the expected utility to be maximized by each agent on every fiscal period is characterized as:

$$EU = \hat{p}(1 + d)^{\kappa}[I - \tau(d \cdot I) - \theta\tau(I - d \cdot I)]^{(1-\rho)} + (1 - \hat{p})(1 + d)^{\kappa}[I - \tau(d \cdot I)]^{(1-\rho)} \tag{B.4}$$

The loss aversion coefficient employed in Equation (B.3) and Equation (B.4) stands for the well-known wealth effect described by Tversky and Kahneman (1973). In this sense, a higher loss-aversion would concavely diminish the marginal utility of end-of-period wealth. On the other hand, a higher tax morale would yield a larger complying utility. Nonetheless, tax morale is a rather troublesome expression to be defined.

Tax morale has been a pivotal concern in tax compliance models ever since Myles and Naylor (1996) upheld a supplementary utility derived from conforming to societal rules. Accordingly, agents gain an additional benefit by following the established social norms. Although tax morale is ordinarily used as an umbrella term to accommodate a range of definitions, Luttmer and Singhal (2014) define tax morale as any intrinsic motivation, reciprocity, culture, biases and social influences which enhance tax compliance.

### Audit strategies

Taking advantage of the Agent-Based Model implementation, a wide set of audit strategies may be employed under diverse policy scenarios to computationally identify the optimal approach. Different audit schemes may be categorized into three main classifications: thumb-rules, simple strategies and sophisticated measures. Table B.1 shows the two thumb rules, four simple strategies based on the two dimensional fitness-model structure previously specified in this section, and four sophisticated schemes derived from their reciprocal network centrality measures.

Table B.1: Set of possible audit strategies

| Strategy | Method to choose the 'n' agents to be audited |
|---|---|
| Random | Agents are randomly sampled with replacement |
| Cutoff | The agents who declared the lowest income values |
| Up-right | Randomly sampled from the North-east sector: $I_i \geq \overline{I}$ and $\text{age}_i \geq \overline{\text{age}}$ |
| Up-left | Randomly sampled from the North-west sector: $I_i \geq \overline{I}$ and $\text{age}_i < \overline{\text{age}}$ |
| Down-right | Randomly sampled from the South-east sector: $I_i < \overline{I}$ and $\text{age}_i \geq \overline{\text{age}}$ |
| Down-left | Randomly sampled from the South-west sector: $I_i < \overline{I}$ and $\text{age}_i < \overline{\text{age}}$ |
| Degree | Individuals with the highest number of direct connections |
| Betweenness | Agents who control the flow of information |
| Closeness | Individuals which make the flow of information more efficient |
| Inter-centrality | 'Key Players' as understood in Ballester et al. (2006) |

### Communicating information

Besides the agents' predominant objective of maximizing their expected utility functions, individuals face a second noticeable ambition: to discover their true probability of being audited. Agents do not want to underestimate their faced audit rate given their loss-aversion of being audited, yet they do not wish to overestimate as they might disclose a fraction of income larger than optimal. Substituting $p$ for the subjective audit rates $\hat{p}$ in Equation (B.1) and deriving the First Order Conditions, it is trivial to see that the Expected Utility of an agent is reduced as the perceived audit rate increases:

$$\frac{\partial EU[d]}{\partial \hat{p}} = U(X) - U(Y) \leq 0 \tag{B.5}$$

Equation (B.5) is smaller or equal to zero given that the net income after an audit is performed, $X$, is smaller or equal to the net income when no audit is enforced, $Y$. The equality holds if and only if an individual decided to fully-declare its income.

Thus, in order to discover their true audit rates, individuals mutually exchange information. At the end of each period, once the audit schemes have taken place, agents are limited to only communicate whether they have faced audits or not in the previous periods. Preceding Agent-Based Models have assumed that individuals are able to share their past income disclosures and their post-audit monetary payoffs, or even sharing their subjective probability of being audited during the next period. Notwithstanding, this paper considers such assumptions to be too strong, as it would be hardly the case that in a real-life scenario people would be willing to freely share their tax evasion schemes along their neighborhood. Therefore, the assumption over their ability to communicate information is substantially relaxed to account for simple, observable, pieces of information. Moreover, Section B.4 offers a robustness test to check how this limited information attains more realistic results than communicating more complex messages, and further considers the case where an individual's attention might be biased into listening to some of its neighbors with more consideration than to others.

### Updating parameters

Without a doubt, the paramount parameter encompassed in this Agent-Based network model is the agent's subjective probability of being audited. Individuals may update their perceived audit rate through temporal and geographical means. Temporal updating techniques encompass two mechanisms, the agent's prior subjective audit rate and the individual's own memory about the number of audits it may recall in the past years. Furthermore, geographical updating refers to the information received from its neighbors regarding their own memories about previous audit schemes. Equation (B.6) defines the subjective audit probability to be employed by agent $i$ at time $t+1$ as a weighted average of the three updating channels: prior belief, personal memory and social influence.

$$\hat{p}_{i,t+1} = \lambda_1 \hat{p}_{i,t} + \lambda_2 \sum_{s=1}^{S_i} \frac{A_{i,t-s}}{S_i} + (1 - \lambda_1 - \lambda_2) \sum_{j \neq i}^{N_{i,t}} \frac{1}{N_{i,t}} \sum_{s=1}^{S_j} \frac{A_{j,t-s}}{S_j} \tag{B.6}$$

where $\lambda_1$ and $\lambda_2$ are convex averaging weights, $A_{i,t-s}$ is valued one if the agent $i$ was audited in the period $(t-s)$ and zero otherwise, $S_j$ is the memory or number of audit periods that agent $j$ can recall in the past, and $N_{i,t-1}$ is the number of neighbors of agent $i$ at time $t$ (without counting itself).

Figure B.3 and Figure B.4 show the long-run steady-state convergence of the average subjective audit rate. Remarkably, for practically all possible combinations of $\lambda_1$ and $\lambda_2$ the society reaches a steady-state convergence; with the exception of $\lambda_1 = 1$, in which case the agents never exchange information and keep no memory regarding audits in previous years. Particularly, Figure B.3 shows the weight on prior beliefs on the left axis and the importance of memory on the right axis. Figure B.4 depicts the influence of communication on the left axis and the importance of prior beliefs in the right axis. It may be observed how the steady state explodes whenever full attention is given to prior beliefs and zero emphasis is placed in the two remnant updating channels. A mathematical specification of this steady state is provided in Section B.3.

Despite the weighted average expression in Equation (B.6) allows for a different subjective audit rate per agent, the true audit rate is not endogenous itself. Hence, agents are still homogeneous amidst themselves with respect to the probability of being audited. Nonetheless, it would be safe to assume that any given Tax Agency would be more prone to audit individuals with soaring income levels and eye-catching wealth; whereas agents with low salaries might be less profitable to investigate.

In order to attain agent heterogeneity, an endogenous probability of being audited is fixed proportionally with respect to individuals' income level, thus agents with high endowments will be more susceptible to participate in audit schemes than their lower endowed counterparts. Following, the endogenous audit rate $q$ for agent $i$ is the homogeneous audit rate $p$ multiplied by the ratio of the agent's income over the average income of the population.

$$q_i = \frac{I_i}{\sum_{j=1}^{N} I_j} \cdot Np \tag{B.7}$$

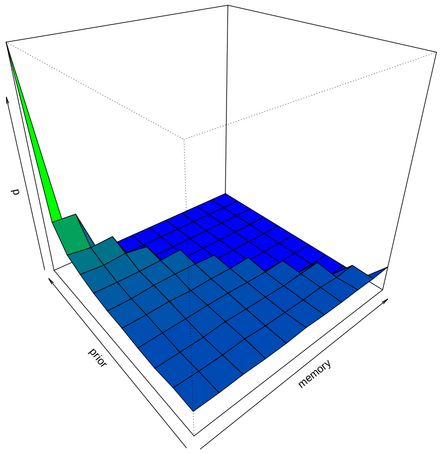


Figure B.3: Prior and Memory

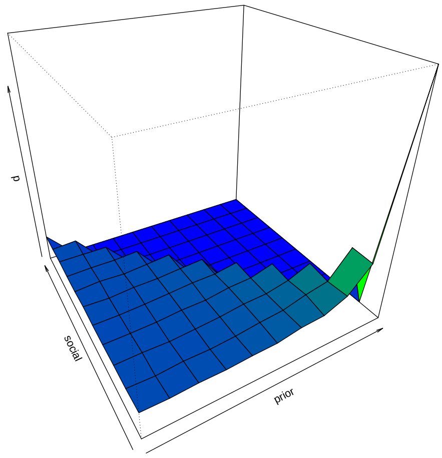


Figure B.4: Social influence and prior

Furthermore, this convenient adjustment allows for consistent testing of parameters, as the expected value of being audited remains constant regardless of the modification. Taking Equation (B.7) and summing over all agents $i$ and dividing by $N$ on both sides, we get $q = p$.

Analogously, other parameters are updated as well. The agents' income surges stochastically, their age increases by one unit and new agents enter and leave the labor market respectively. Another relevant benefit arising from the network formation process designed in this section is the possibility to transform the previously exogenous loss-aversion coefficient to an endogenous parameter. Recalling loss aversion as the agents' preference of avoiding a loss over attaining a win given its decreasing marginal utilities on wealth, it would be coherent to adjust such coefficient with respect to the individuals' income level. It follows from Equation B.8 that a local and endogenous loss-aversion parameter may be defined as the agent's relative income position with respect to its neighborhood $N$, divided by the total number of neighbors $|N|$ plus one.

$$\rho_i = \frac{\text{rank}(I_i)}{|N|+1} \tag{B.8}$$

Accordingly, the highest (lowest) loss-aversion quotas relate to the most (least) affluent agents. It is interesting to notice how the proposed social-cohesive structure allows for the global distribution of individual loss-aversion of $\rho$ to tend towards a bell-shape; while maintaining its symmetry around 0.50 as in the exogenous scenario. Such bell-shaped distribution permits a more realistic characterization of the decision making process.

## B.3 Nash equilibrium and social norms

The following section takes the social planner's point of view, whose primary objective is to find an audit policy such that the perceived audit rate is maximized given a limited budget of audits it may enforce in a single fiscal period. The standard *linear-in-means* model is suitable for games where peer effects and social norms play a role. Most of the results hereafter presented were first studied and derived by Ushchev and Zenou (2018). In this model, agents take into consideration the *average* value of actions enforced by their neighbors. Further, individuals exert an action defined by:

$$x_{ig} = z_{ig}\beta + y_g\gamma + \frac{\psi}{N_g}\sum_{j=1,j\neq i}^{n} x_{jg} + \epsilon_{ig} \tag{B.9}$$

where $x_{ig}$ is the action of agent $i$ who lives in group $g$, $z_{ig}$ are the individual-level covariates (tax morale and loss-aversion), $y_g$ are the group-level variables (tax and fine rates), and $\psi$ is defined as the agent's social interaction effect, which multiplies the average action exerted by its neighbors (not counting itself). It is important to notice how this particular game formalization is constitutionally different from the *local-aggregate* models studied in Ballester et al. (2006).

Consider an $n \times n$ adjacency matrix $\mathbf{H} = [h_{ij}]$ with entries $\{0,1\}$, specifically, $[h_{ij}] = 1$ if there is a direct connection from $i$ to $j$, and zero otherwise. Furthermore, $\mathbf{H}$ is an undirected matrix without self-loops. Consider $\mathbf{G}$ as the row-normalized version of $\mathbf{H}$ after dividing each entry by the degree of node $i$; $[g_{ij}] = [h_{ij}]/d_i$. It follows from this mathematical specification that $[g_{ij}]$ is the influence that player $j$ exerts on agent $i$, which resembles the last term from Equation (B.6).

Define a modified version of the well-known Bonacich centrality (Bonacich (1987)) as specified by Ushchev and Zenou (2018):

$$\mathbf{M} := (1-\lambda)(\mathbf{I} - \lambda\mathbf{G})^{-1}, \tag{B.10}$$

and re-write the definition as:

$$\mathbf{M} = (1-\lambda)\sum_{k=0}^{\infty}\lambda^k\mathbf{G}^k. \tag{B.11}$$

The $n \times n$ matrix $\mathbf{M}$ is well-defined and row-normalized for any $\lambda \in [0, 1)$, given that the matrix $\mathbf{G}$ is row-normalized. The matrix $\mathbf{M}$ will come in very useful to compute the Nash equilibrium. Consequently, $\mathbf{M}$ may be understood as the matrix which keeps track of the number of walks of length $k$ from node $i$ to $j$ ($g_{ij}^{[k]}$) discounted by a factor of $\lambda^k$, where each entry $m_{ij}$ may be expressed as:

$$m_{ij} = (1-\lambda)\sum_{k=0}^{\infty}\lambda^k g_{ij}^{[k]}. \tag{B.12}$$

Analogous to Section B.2, agents are interested in discovering the true audit rate they face on every fiscal period: underestimating the true value is risky while overestimating it would curtail their attained utility. Define $x_{it}$ as the updated value of the subjective probability for agent $i$ at time $t$. Moreover, $x_{it} = \hat{p}_{it}$ whenever true audit rates are homogeneous, whereas $x_{it} = \hat{q}_{it}$ for the case where rates are heterogeneous.

The concept of *social norm* for agent $i$ in a local-average game, like this one, is defined as the mean value of the actions exercised by the neighbors of $i$. Following,

$$\bar{x}_i = \sum_{j=1}^{n} g_{ij}x_j, \tag{B.13}$$

and in matrix form notation:

$$\bar{\mathbf{x}} = \mathbf{G}\mathbf{x}. \tag{B.14}$$

Define an alternative utility function, $v$, which measures the agent's additional benefit from adhering to the *social norm*, $\bar{x}_i$, roughly interpretable as the 'socially accepted' true audit probability. Agent's $i$ utility function $v_i$ is constructed as follows:

$$v_i(x_i, \mathbf{x}_{-i}, \mathbf{g}) = \alpha_i x_i - \frac{1}{2}x_i^2 - \frac{1}{2}\cdot\frac{\lambda}{1-\lambda}(x_i - \bar{x})^2 \tag{B.15}$$

The parameter $\alpha_i > 0$ in the linear-quadratic utility function specified in Equation (B.15) corresponds to an individual heterogeneity factor. The coefficient $\alpha_i$ may be inferred as an adjustment rate to be multiplied by the updated subjective probability of being audited $x_i$. Roughly speaking, $\alpha_i$ may be derived as the relative income position that agent $i$ has inside the network as previously proposed in Equation (B.7). It is worth mentioning for the scenario with homogeneous audit rates that $\alpha_i = \alpha_j$ $\forall\{i, j\}$.

The negative coefficient for the quadratic term of $x_i$ makes it not optimal for agents to infinitively increase their action $x_i$. Finally, the last term subtracts the quadratic value of the spread between the exerted action and the social norm. Following, agents have a *taste for conforming* to the established social norm. The last term could also be interpreted as the *peer effects* motivated by *group pressure*.

Deriving the First Order Conditions from Equation (B.15) with respect to $x_i$ and equalizing to zero yields:

$$\frac{\partial v_i(x_i, \mathbf{x}_{-i}, \mathbf{g})}{\partial x_i} = \alpha_i - x_i - \frac{\lambda}{1-\lambda}(x_i - \bar{x}_i) = 0. \tag{B.16}$$

Computing $x_i^*$ we obtain:

$$x_i^* = (1-\lambda)\alpha_i + \lambda \bar{x}_i, \tag{B.17}$$

reformulating the previous expression in matrix notation and substituting $\bar{\mathbf{x}} = \mathbf{G}\mathbf{x}$:

$$\mathbf{x} = (1-\lambda)\boldsymbol{\alpha} + \lambda \mathbf{G}\mathbf{x}, \tag{B.18}$$

applying linear algebra we compute the Nash Equilibrium $\mathbf{x}^*$ as:

$$\mathbf{x}^* = (1-\lambda)[\mathbf{I} - \lambda\mathbf{G}]^{-1}\boldsymbol{\alpha}, \tag{B.19}$$

which, applying Equation (B.10), may be simplified to:

$$\mathbf{x}^* = \mathbf{M}\boldsymbol{\alpha}. \tag{B.20}$$

Lastly, substituting Equation (B.14) in (B.20) we obtain the equilibrium social norm $\bar{\mathbf{x}}^*$:

$$\bar{\mathbf{x}}^* = \mathbf{G}\mathbf{M}\boldsymbol{\alpha}. \tag{B.21}$$

### Stochastic Nash equilibrium

Consider now the matrix $\mathbf{G} = [g_{ij}]$ as a transition probability matrix in the Markovian sense, i.e., the probability of moving to the next state depends only on the current state. There are $n$ states of the universe, characterized by the $n$ positions of the nodes inside the network. Consider as well the random variable $X_i$ as the action exerted by agent $i$, who has a heterogeneity factor $\alpha_i$ as previously defined. Seemingly, each agent has a true audit rate proportional to its relative income position $\alpha$.

The stochastic approach to Nash Equilibrium contemplates the game as a sequence of mimicking behaviors, where each agent $i$ at each step $t$ must mimic the actions of another agent. We will understand 'to mimic a behavior' as 'believing my true audit rate to be the true audit rate of agent $j$'. Therefore, agent $i$ will choose its own $\alpha_i$ with a probability $(1-\lambda)$ and will choose a neighbor $j$ with probability $\lambda$. Then, with probability $(1-\lambda)$, agent $i$ will mimic $\alpha_j$ and with probability $\lambda$ will choose a different neighbor $k$. The process will repeat until agent $i$ has mimicked the audit rate of another player in the network.

The probability that agent $i$ mimics the behavior of agent $j$ is the total number of walks from $i$ to $j$ weighted by a decaying factor according to the length of the walk $k$. Mathematically speaking, the random variable may be well defined as:

$$\mathbb{P}\{X_i = a_j\} = (1-\lambda)g_{ij}^{[0]}\alpha_j + (1-\lambda)\lambda g_{ij}^{[1]}\alpha_j + (1-\lambda)\lambda^2 g_{ij}^{[2]}\alpha_j + \dots \tag{B.22}$$

which simplifies to:

$$\mathbb{P}\{X_i = a_j\} = (1-\lambda)\sum_{k=0}^{\infty}\lambda^k g_{ij}^{[k]}, \tag{B.23}$$

where $g_{ij}^{[0]} = 1$ if $i = j$ and zero otherwise.

The last expression is equivalent to the one obtained in Equation (B.12). That is, $\mathbb{P}\{X_i = a_j\}$ is the probability that agent $i$ will mimic the behavior of agent $j$. Thus, substituting Equation (B.12) in (B.23), the expected value of the random variable $X_i$ is:

$$\mathbb{E}[X_i] = \sum_{j=1}^{n} m_{ij}\alpha_j, \tag{B.24}$$

which in matrix notation transforms to:

$$\mathbb{E}[\mathbf{X}] = (1-\lambda)\sum_{k=0}^{\infty}\lambda^k \mathbf{G}^k \boldsymbol{\alpha} = \mathbf{M}\boldsymbol{\alpha} = \mathbf{x}^*. \tag{B.25}$$

There are three reasons why the Nash Equilibrium computation is relevant for the current work. First, the equivalence between both deriving estimations suggest that the Nash Equilibrium is reached whether the agents are fully rational or merely stochastic decision makers. Therefore, bounded rationality or heuristic ruling would not limit the steady-state convergence. The second is that, using the row-normalized adjacency matrix, the Nash Equilibrium exists, is unique and it is interior as long as $\frac{\lambda}{1-\lambda} > 0$ . Finally, the Nash Equilibrium is expressed in terms of the agents' heterogeneity paramenter $\alpha$. Patacchini and Zenou (2012) demonstrated that for local-average games where all the $\alpha$ coefficients are homogeneous among agents, the outcome does not depend on the network structure nor on the total number of agents involved; which is not true for local-aggregate games as studied by Ballester et al. (2006). This last remark has utter policy implications for the social planner pursuing to maximize the steady state $\mathbf{x}^*$ with respect to a network-based strategy, as the success of strategies is dependent on the heterogeneity levels inside the network.

## B.4 Optimal audit policies

Ensuing the derivations computed in the previous section, it is germane to recall how the subjective audit rate, defined in Equation (B.6), resembles a local-average game. The perceived audit rate is updated in function of the agent's prior, memory and the information received from its neighbors. The last term in Equation (B.6) is analogous to the empirical mean audit rate experienced by $i$'s neighborhood ($N_i$) over all the periods of time for which the agents keep memory. Redefining this last term as:

$$\bar{A}_{i,t} = \sum_{j\neq i}^{N_{i,t}} \frac{1}{N_{i,t}} \sum_{s=1}^{S_j} \frac{A_{j,t-s}}{S_j}, \tag{B.26}$$

The updating mechanism may be reinterpreted as:

$$\hat{p}_{i,t+1} = f(\text{prior}_t) + g(\text{memory}_t) + \psi \bar{A}_{i,t}, \tag{B.27}$$

where $\bar{A}_{i,t}$ is the sample estimate for the 'social norm' of neighborhood $N_i$ at time $t$, multiplied by an influence parameter $\psi$. Accordingly, the dynamics of subjective audit rates may be understood and studied as local-average repeated games.

### Homogeneous audit rates

There is, however, an inconvenient in considering the subjective probability updating mechanism as a local-average game. Despite being able to compute the Nash Equilibrium in the previous section, there is no closed-form solution for a first-best maximization policy, given that the variable of interest is not observable, taxable, nor allows for subsidies. It is trivial, and perhaps humorous, to notice how it would be impossible for a social planner to 'tax away' an agent's subjective probability of being audited and 'redistribute' this beliefs to other individuals. Notwithstanding, the Agent-Based Model outlined in Section B.2 was implemented to test ten different audit schemes, referring to the random audits method as the benchmark case, and assessed whether or not any of such strategies may be deemed as superior with respect to randomization.

Hereafter all simulations will be understood as dynamic games with fifty fiscal periods, where 300 agents face a 30% flat tax rate, a 2.0 fine rate if caught, a fiscal memory of four periods, a tax morale level of 0.25, endogenous loss-aversion, randomly sampled initial prior beliefs at time zero, balanced weighting averages $\lambda_1 = \lambda_2 = (1-\lambda_1-\lambda_2) = 1/3$, and, most importantly, an homogeneous true audit rate of 5% indistinctly applicable to all agents.

Figure B.5 portrays the four sophisticated audit strategies contrasting against the random audit scheme (red). Optically, there seems to be little to no difference between all five strategies; the inter-centrality measure has, however, a marginal and statistically significant higher level. In a similar way,

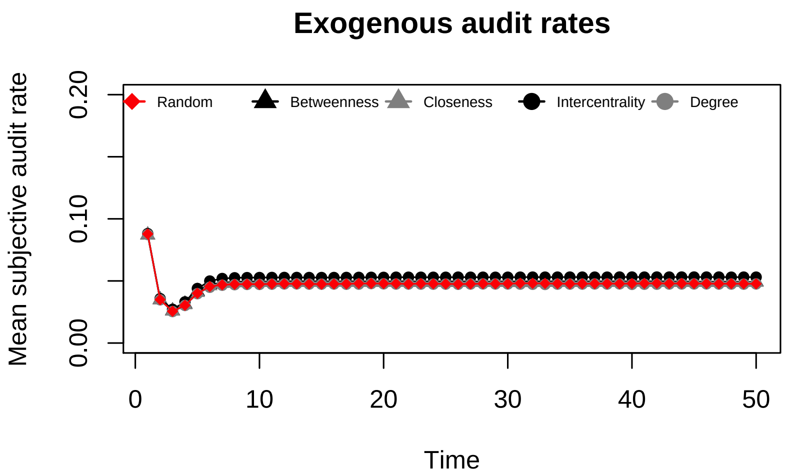


Figure B.5: Scenario where true audit rates are homogeneous

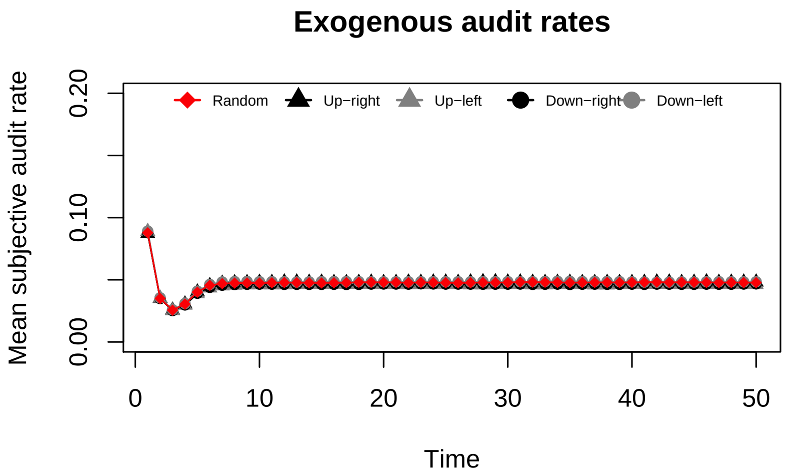


Figure B.6: Scenario where true audit rates are homogeneous

Table B.2: Comparing strategies under homogeneous audit rates

| Strategy | Average $\hat{p}$ | $\Delta\hat{p}$ | $\Delta d^*$ | $\Delta-$Revenue | $p$-value |
|---|---|---|---|---|---|
| Random | 4.77% | 0% | 0% | 0% | — |
| Cutoff | 4.68% | -2% | -6% | -6% | 0.626 |
| Betweenness | 4.93% | 3% | 3% | 1% | 0.243 |
| Closeness | 4.88% | 2% | 4% | 4% | 0.525 |
| Intercentrality | 5.31% | 11% | 3% | 1% | 0.001 |
| Up-right | 4.81% | 1% | 0% | 6% | 0.896 |
| Up-left | 4.61% | -3% | 0% | 0% | 0.272 |
| Down-right | 4.67% | -2% | 2% | -4% | 0.414 |
| Down-left | 4.84% | 1% | 0% | -6% | 0.629 |
| Degree | 4.76% | 0% | -2% | -3% | 0.827 |

*Note: Comparisons are made against the Random audit scenario*

Figure B.6 shows how the four two-dimensional audit instruments do not account for a statistically significant difference with respect to the random auditing process.

Table B.2 summarizes the results obtained from the simulations for each audit strategy. The second column depicts the sample's average subjective probability of being audited during the final step of the simulation (which computationally approximates the Nash Equilibrium). Column $\Delta\hat{p}$ is a goodness-of-fit metric which shows the percentage change of the average $\hat{p}$ attained by each strategy with respect to the value attained by the benchmark (random audits)[1]. The highest achiever according to this metric is the Intercentrality auditing scheme, which enlarged the sample's perceived audit rate by 11%. The next column, $\Delta d^*$, shows the increase gained for the average fraction of income declared by individuals. The Cutoff strategy seems to be counterproductive while three sophisticated strategies reaped an increase between three and four percent. Column $\Delta-$Revenue shows the ancillary return on actual tax payments collected. Following this metric, the Intercentrality scheme seems to have lost its appeal versus the Closeness-centered audits. It turns out that an increase of just 11% in the mean perceived audit rate is not enough to significantly enhance tax compliance and escalate fiscal revenues.

The last column of Table B.2 shows the $p$-values scored by a Welch two-sample *t-test* between the observed steady state of $\hat{p}$ for each evaluated strategy versus the outcome $\hat{p}$ arising from randomized audits; where the null hypothesis supposes that the true difference in means is equal to zero. Following, with the exception of the Intercentrality scheme, no strategy encompasses a statistically significant effect on the long-run average value of $\hat{p}$ with respect to the benchmark scenario. As anticipated from Ushchev and Zenou (2018), sophisticated local-aggregate strategies will play little to no effect whenever in a local-average framework. Moreover, as foreseen from the previous section, simple network-based policies have no effect whenever all agents have an homogeneous $\alpha$ coefficient, i.e., there is no agent heterogeneity with respect to the true audit rate. Agents thus converge to a Nash Equilibrium which is roughly the true audit rate, homogeneously applicable for all individuals.

### Heterogeneous audit rates

The previous subsection proved how, under homogeneous audit rates, network-based audit policies have little to no effect to enhance the audit rate perceived by agents. A social planner who is aware of this, might then attempt to add heterogeneity to the network. Assume a social planner, or Tax Agency, is capable of executing a credible message such that all individuals believe the news are true and binding. Aforesaid official communication would read something akin to *'From now on, the probability of being audited will be directly proportional to the income level of each individual.'*

Subsequently, individuals would update their subjective probability of being audited in an endogenous fashion, as established in Equation (B.7). Ensuing:

$$\hat{q}_{i,t+1} = \hat{p}_{i,t+1} \cdot \frac{I_i}{\sum_{j=1}^{N} I_j} \cdot N \tag{B.28}$$

Recurring to the same simulation parameters as previously defined, all strategies are re-examined under a new updating mechanism, where true audit rates are both endogenous and different for each individual. Figure B.7 sketches a nonexistent improvement for the sophisticated audit strategies. The logic behind this ineffectiveness can be explained by understanding how, in a local-average game, targeting a few 'key players' does not affect the 'social norm' of the group. From a network-based point of view, an optimal policy should attempt to change the agents' perception; in other words, it should induce individuals to believe their likelihood to be audited is higher than it actually is. Therefore, the social planner should target a specific *group* of agents in lieu of key individuals.[2]

Figure B.8 graphically depicts the main findings of this paper: agent-based policies may be pertinent for local-aggregate models, however, group-based policies are more appropriate for local-average games. It is immediate to notice the remarkably high long-run Nash Equilibrium emerging from the simplistic Up-right audit policy.

Table B.3 displays the performance of the audit strategies under heterogeneous audit rates and compares them versus the (homogeneous) random audit scheme presented in Table B.2. Although several

[1] The score is computed by subtracting the benchmark value from the strategy's outcome and diving by the same benchmark value: $\Delta = \frac{\hat{p}-\hat{p}_{BM}}{\hat{p}_{BM}}$; analogous for all $\Delta-$columns.

[2] For a more extensive discussion refer to Ushchev and Zenou (2018).

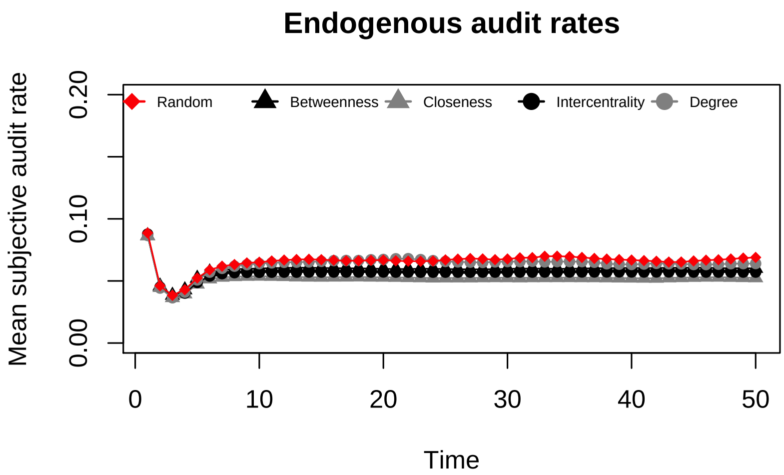


Figure B.7: Scenario where true audit rates are heterogeneous

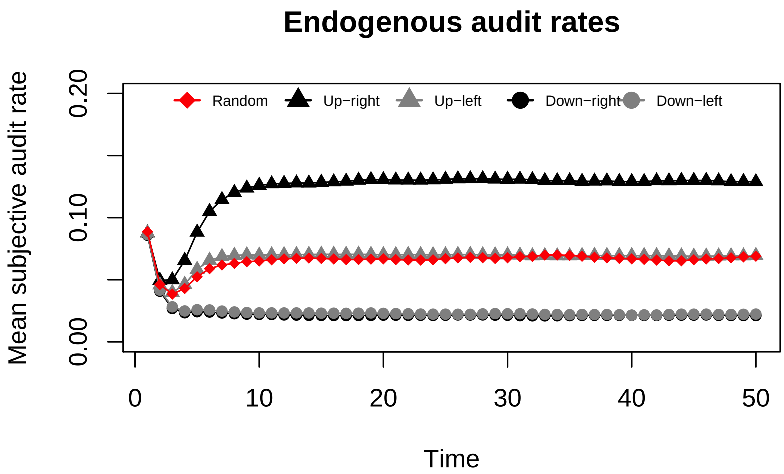


Figure B.8: Scenario where true audit rates are heterogeneous

Table B.3: Comparing strategies under heterogeneous audit rates

| Strategy | Average $\hat{q}$ | $\Delta\hat{q}$ | $\Delta d^*$ | $\Delta-$ Revenue | $p$-value |
|---|---|---|---|---|---|
| Cut-off | 4.24% | -11% | -5% | -9% | 0.000 |
| Betweenness | 6.01% | 26% | 6% | 2% | 0.000 |
| Closeness | 5.25% | 10% | 5% | -1% | 0.000 |
| Intercentrality | 5.71% | 20% | -1% | -7% | 0.000 |
| Up-right | 12.88% | 170% | 13% | 16% | 0.000 |
| Up-left | 6.95% | 46% | 9% | 5% | 0.052 |
| Down-right | 2.11% | -56% | -9% | -15% | 0.000 |
| Down-left | 2.23% | -53% | -8% | -14% | 0.000 |
| Degree | 6.40% | 34% | 3% | 0% | 0.169 |

*Note: Comparisons are made against the Random audit scenario presented in Table B.2.*

strategies earned a higher average $\hat{q}$ with respect to randomized audits, there is a striking steady state value of 12.88% secured by the Up-right policy. The spiking $\Delta\hat{q}$ score for the Up-right strategy reaches 170%, meaning that it nearly doubled the benchmark's average perceived audit rate. Column $\Delta d^*$ shows how the mean fraction of income declared rose an additional 13% for this same policy. Even more, metric $\Delta-$Revenue announces how revenues augmented by about 16% whenever auditing the North-East sector of the population (bear in mind that this outcome pertains only to the simulation and cannot be straightforwardly employed to forecast how a country's shadow economy could be expeditiously curtailed). Lastly, the column with $p$-values displays near-zero values for almost all strategies; implicating that under endogenous true probabilities, the selection of one or other audit strategy will have real and statistically significant effects in the outcome.

### Robustness checks

As a consequence from the results presented in Table B.3, which vastly favor the Up-right audit policy, this predominant strategy was further tested under a wide spectrum of diverse scenarios to allow for robustness checks.

Hereby and after, all *t-tests* are understood as two-sided Welch *t-tests* where the null hypothesis states that the difference between sample means is zero. Thirty simulations were ran per each scenario. The first robustness test, depicted in Figure B.9, studies the effect of modifying the initial prior distribution. The $p$-values attained from the *t-tests* proved that the null hypothesis cannot be rejected for any upper bound $P$ of the initial prior distribution $\sim U(0, P)$: in other words, the initial prior belief of agents does not play any role in the long-run average subjective audit rate. Figure B.10 illustrates a positive effect of the steady state with respect to memory length (number of fiscal years an agent can recall into the past). In fact, the *t-tests* revealed that there is a positive elasticity effect of memory. However, there was no statistically significance difference for remembrance spans larger than seven fiscal periods; thus memory has a marginal effect up to a certain extent.

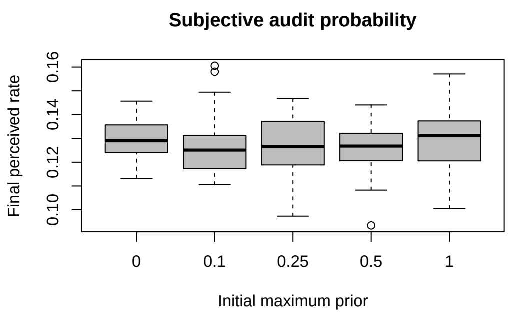


Figure B.9: Initial prior beliefs

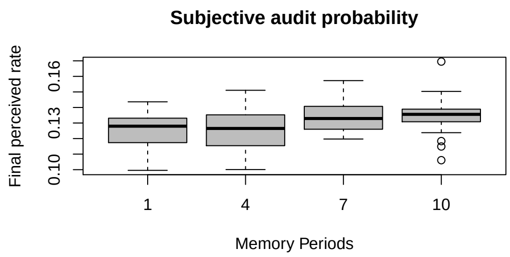


Figure B.10: Length of memory

The neighborhood size in Figure B.11, benchmarked as one, represents the spatial range of individuals that are available for each agent to form a link with. As long as the network remains ergodic, meaning that every node is reachable from any other node after a finite number of links, neighborhood size has no statistical significance in the perceived audit rate. The number of agents, as seen in Figure B.12 plays a nonlinear, statistically significant, positive effect on the steady state. Not only the long-run perceived audit rate marginally increases as the number of agents augments, but it also converges to the steady state with a smaller standard deviation. Figure B.13, accompanied by its respective set of *t-tests*, supports the asseveration that tax rates do not significantly affect the perceived audit rate. Moreover, further analysis was done employing a stepped-tax schedule and no statistically significant difference was encountered with respect to modeling under flat-tax rates. A different approach was employed in Figure B.14. As it would be rather obvious that the perceived audit rate would be significantly affected by the true audit rate, the y-axis of Figure B.14 measures the relative overestimation of the average true audit rate in the long-run. Following, for a mean audit rate of 0.05%, agents tend to overestimate it by nearly 80% of the true value. Ongoing, the social norm overestimates the expected probability of being audited of 1%, 2%, 5%, 10% and 20% by 150%, 170%, 160%, 130% and 60%, respectively. Thus, the Up-right group-based audit instrument would perform satisfactorily for any nonzero true audit rate.

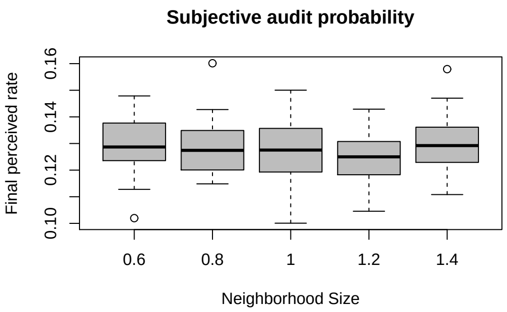


Figure B.11: Neighborhood size

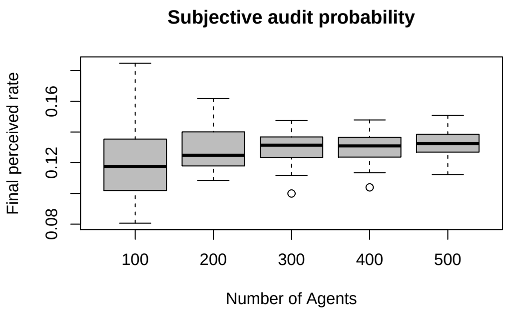


Figure B.12: Number of agents

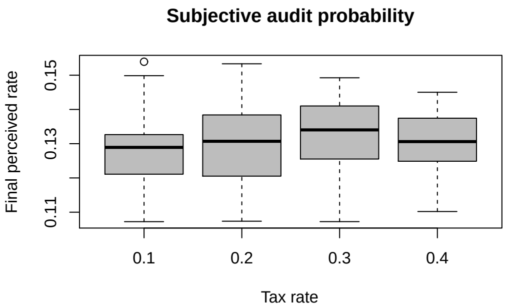


Figure B.13: Tax rate

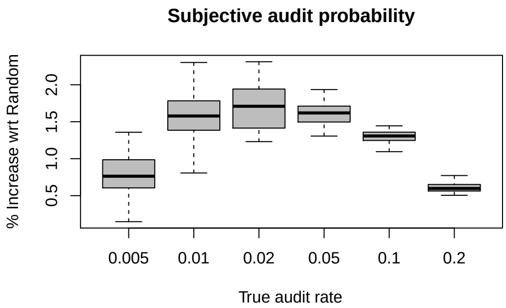


Figure B.14: Percentage increase in $\hat{q}$

Ultimately, two structural scenarios were tested. First, consider a more realistic environment where individuals are more prone to take fiscal advices from people who are either more affluent, older, or both. Defining an agent performing such an attention favoritism as to be ‘Up-right biased’, Figure B.15 portrays how this preference for counseling would lead to a statistically higher social norm whenever the Tax Agency enforces an Up-right policy scheme. The second structural setting modification allows agents to share their rationally updated subjective probability of being audited instead of being limited to communicate only their binomial memories about previous audit occurrences. Figure B.16 demonstrates an abysmal disparity between the two signaling channels. Whenever agents share their rationally updated probability of being audited (which, to begin with, is in no way a pragmatic assumption about the way agents behave in the real-life) the long-run average perceived audit rate is ludicrously intensified. Figure B.16, for example, shows how a true expected audit rate of 5% is largely overestimated and perceived as an audit rate of more than 30%. Ergo, the proposed audit strategy and signaling mechanisms not only resulted to be optimal in all simulated scenarios, but they also enjoy a certain anecdotal legitimacy.

It is worth mentioning that an extreme audit instrument, denoted ‘Corner’ strategy, targeted the agents at the uppermost rightmost sector of the structure, yet was found to be less profitable than the simple ‘Up-right’ scheme. Notwithstanding, more research is encouraged in the study of more complicated group-based audit policies.

Apparently, if a Tax Agency acts coherently respecting its announcement, the social norm of the group may be shifted to a higher level. Up to this time, targeting agents which are relatively more affluent, and older, in the North-East sector of the spatial network, yielded higher steady states of the subjective audit rates, enhanced the optimal fractions of income disclosed and augmented the revenue collections.

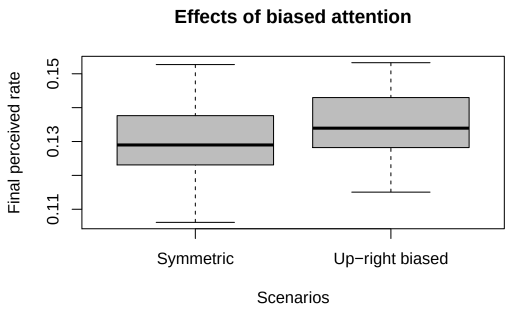


Figure B.15: Symmetric versus biased attention frames

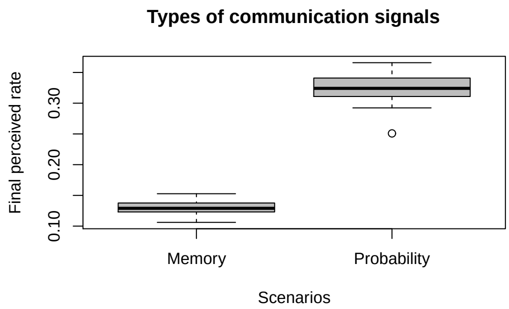


Figure B.16: Sharing $A_{i,t-s}$ versus sharing $\hat{p}_i$

## B.5 Conclusions

In this paper a tax evasion model is studied from the social planner's (Tax Agency) point of view. The Tax Agency employs a two-step optimal solution, which consists in initially emitting a credible and binding message, stating: *'From now on, the probability of being audited will be directly proportional to the income level of each individual.'* Assuming each agent faces an heterogeneous true audit rate, individuals attempt to discover their endogenous probability of being audited. Taxpayers are modeled as agents in a social-cohesive homophilic two-dimensional network, where individuals link only to 'relevant others' which are akin to themselves. Moreover, each fiscal period, agents attempt to update their subjective probability of being audited by taking into consideration the signals received from their neighbors. Every individual interacts under limited communication, informing to its peers only the agent's own observed audit frequency faced in the previous years, up to where the individual is able to remember. Considering the updating mechanism as a local-average game, the average perceived audit rate of the whole society converges to a Nash Equilibrium steady state in the long run.

Attempting to optimize the revenues accrued from tax payment collections, the social planner resorts to maximize the subjective audit rate perceived by the individuals. An Agent-Based Model implementation allowed the model to be tested under a wide set of possible audit strategies, ranging from thumb-rules to simple group-based schemes, and even to audit instruments based on sophisticated centrality measures. This paper found that, under homogeneous audit rates, practically no audit strategy is any better compared versus simple randomized income verifications. Under heterogeneous audit rates, however, a particular network-based audit policy deemed to be optimal by achieving an average perceived audit rate that almost doubled the benchmark and considerably increased the tax revenues in the simulated scenarios. Furthermore, the strategy proved to be robust under a collection of diverse settings, attaining a marginally stronger effect for larger number of agents and for longer memory spans. This paper calls for further research about the implementation of network-based policies and Agent-Based Modeling, particularly for criminal behavior networks, analogous to the case of tax evasion and tax compliance.

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# List of Figures

# List of Tables

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**Abstract for summary of the doctoral thesis**

| | |
|---|---|
| Student: | Fernando García Alvarado |
| Student ID: | 864861 |
| Program: | Economics |
| Cycle: | 33 |

Title: ***"Computational Models of Tax Evasion with Heterogeneous Agents"***

**Abstract:**


The purpose of the current dissertation is to further understand the roles played by taxpayer heterogeneity and social influence in tax-evasion dynamics, and to derive normative insights about optimal policy design considering both rational and non-rational taxpayers. How should fiscal policies be designed under the consideration of heterogeneous taxpayers? What is the role of social dynamics in public policy implementation? Which are the implications of rationality and (bounded) non-rationality of taxpayers in policy design?

To answer these and similar questions, the first objective of the current thesis is to build on recent developments from behavioral economics, experimental economics and economic psychology to derive models with heterogeneous agents which have strong empirical and analytical micro-foundations. Mathematical models of individual and collective taxpayer behavior, however, are often too complex to be fully characterized analytically. In order to overcome this obstacle, we incorporate state-of-the-art computational models to simulate taxpayer behavior under different fiscal environments and to study the potential implications of diverse policy implementations.

The second objective of my research concerns the optimal fiscal policy design under the consideration of taxpayer heterogeneity and social influence dynamics, with a normative focus. Acknowledging that taxpayer behavior evolves according to different dynamic processes, we employ recent insights from game theory and network theory applied to social networks and information diffusion to capture the effects and repercussions of social influence dynamics. It is of utmost importance for policymakers to understand not only the individual decision-making processes of taxpayers, but also the emergence of aggregate behaviors as a consequence of idiosyncratic beliefs, social interactions, policy announcements, taxpayer expectations, diffusion of tax-related information, enforcement measures and potential policy implementations.

The third objective of this dissertation aims to design optimal fiscal policies in diverse economic scenarios where a social planner faces strategic tax evaders who can observe and react against the implemented fiscal policies. Although harsher audit and penalty rates may affect taxpayer behavior, also taxpayers' expectations, social influence and non-pecuniary factors may play prominent roles in both individual and collective taxpayer behaviors. Taxpayer behavior is influenced not only by the probability of being audited and the possible incurred penalties, but also by tax rates, feelings of regret, uncertainty, risk aversion, psychic costs of evading, peer effects, social interactions, reciprocity, social norms, the behavior of fellow taxpayers, the efficiency of government expenditures, the perceived power of the government, tax morale and the degree of trust that citizens place in the authority; to mention a few. A central challenge is how to derive appropriate policy recommendations while considering the different ways in which taxpayers may behave, react, optimize and carry out their respective decision-making processes. Consequently, my research combines a set of interdisciplinary tools, ranging from behavioral economics, experimental economics and economic psychology to network theory, game theory and computer simulations.

**Modeling intrinsic and extrinsic taxpayer behavior**

The first chapter attempts to fill the gap between economic and behavioral literature on tax evasion. We propose a micro-founded model whose results are consistent with the 'slippery slope' framework and with the expected utility theory. Individual taxpayers face the problem of deciding the fraction of income they wish to disclose to the government, based on their trust and perceived power of authorities. Trust is modeled as the voluntary compliance originated by tax morale, and power is shaped by the perceived enforcement; mainly motivated by individual risk aversion. Furthermore, we make use of agent-based simulations to replicate the 'slippery slope' conditions and to test the effects of different parameters on tax evasion. Compliance is primarily enhanced by tax morale and risk aversion, while it is secondarily motivated by higher audit probabilities and penalty fees. Tax rates, however, play a negative effect on tax compliance, as agents are less willing to pay taxes whenever facing larger obligations. Additionally, we study taxpayer behavior when the audit rate is zero and when agents are inclined to make charitable donations. Above all, we derive the conditions under which individuals would fully-evade, partially evade, fully-comply or even over-comply as charitable giving in the absence of audits.

**Optimal audit policies with heterogeneous agents**

The second chapter considers a tax evasion game where the tax authority intends to prevent income under-reporting within a network of heterogeneous taxpayers who are engaged in social interactions and exchange information. This paper proposes a two-step game-theoretic optimal audit strategy from the point of view of the tax authority, which consists of a credible threat-to-audit message followed by a network-based audit policy. Subsequently, the tax authority targets taxpayers in function of their individual productivity and their position inside the network, triggering a series of spillover effects which eventually maximize the mean perceived subjective probability of being audited among all taxpayers. Moreover, the optimal audit strategy is robust to expected and non-expected utility theories, and it is invariant for any taxpayer utility function. Additionally, computer simulations determined that the proposed enforcement regime is robust to an ample range of parameter specifications and settings.

**The network structure of global tax evasion**

The third chapter builds on recent insights from network theory and on the rich dataset made available by the *Panama Papers* in order to investigate the micro-economic dynamics of tax evasion. We model offshore financial entities documented in the *Panama Papers* as links between jurisdictions in the global network of tax evasion. A quantitative analysis shows that the resulting network, far from being a random collection of bilateral links, has key features of complex networks such as a core-periphery structure and a fat-tail degree distribution. We argue that these structural features imply that policy must adopt a systemic perspective to mitigate tax evasion. We offer three sets of insights from this perspective. First, we show that the optimal deterrence strategies for a social planner facing a strategic tax evader in a Stackelberg competition can be characterized using the notion of Bonacich centrality. Second, we show that efficient tax treaties must contain exchange information clauses and link tax havens to non-haven jurisdictions. Third, we identify through centrality measures tax havens that ought to be priority policy targets.

Signature,

**Estratto per riassunto della tesi di dottorato**


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Titolo della tesi : ***"Computational Models of Tax Evasion with Heterogeneous Agents"***

**Abstract:**


Lo scopo della presente dissertazione è quello di comprendere ulteriormente i ruoli svolti dall'eterogeneità dei contribuenti e dall'influenza sociale nelle dinamiche di evasione fiscale, e di derivare intuizioni normative sulla progettazione di politiche ottimali considerando sia i contribuenti razionali che non razionali.

Per rispondere a queste e ad altre simili domande, il primo obiettivo della presente tesi è quello di costruire sui recenti sviluppi dell'economia comportamentale, dell'economia sperimentale e della psicologia economica per derivare modelli con agenti eterogenei che hanno forti micro-basi empiriche e analitiche. I modelli matematici del comportamento dei contribuenti individuali e collettivi, tuttavia, sono spesso troppo complessi per essere pienamente caratterizzati analiticamente. Al fine di superare questo ostacolo, incorporiamo modelli computazionali all'avanguardia per simulare il comportamento dei contribuenti in diversi ambienti fiscali e per studiare le potenziali implicazioni di diverse implementazioni politiche.

Il secondo obiettivo della mia ricerca riguarda la progettazione ottimale della politica fiscale tenendo conto dell'eterogeneità dei contribuenti e delle dinamiche di influenza sociale, con un focus normativo. Riconoscendo che il comportamento dei contribuenti evolve in base a diversi processi dinamici, utilizziamo recenti intuizioni della teoria dei giochi e della teoria delle reti applicate ai social network e alla diffusione delle informazioni, per catturare gli effetti e le ripercussioni delle dinamiche di influenza sociale. È della massima importanza che i responsabili politici comprendano non solo i processi decisionali individuali dei contribuenti, ma anche l'emergere di comportamenti aggregati come conseguenza di credenze idiosincratiche, interazioni sociali, annunci politici, aspettative dei contribuenti, diffusione di informazioni fiscali, misure di attuazione e potenziali implementazioni delle politiche.

Il terzo obiettivo di questa dissertazione mira a progettare politiche fiscali ottimali in diversi scenari economici in cui un pianificatore sociale affronta evasori fiscali strategici che possono osservare e reagire contro le politiche fiscali implementate. Il comportamento del contribuente è influenzato non solo dalla probabilità di essere sottoposto a controlli e dalle relative sanzioni, ma anche da aliquote fiscali, sentimenti di rimpianto, incertezza, avversione al rischio, costi psichici dell'evasione, interazioni sociali, reciprocità, norme sociali, comportamento dei colleghi contribuenti, efficienza della spesa pubblica, potere percepito del governo, valori civici e grado di fiducia che i cittadini ripongono nell'autorità; per citarne alcuni. Una sfida centrale è come derivare raccomandazioni politiche appropriate considerando i diversi modi in cui i contribuenti possono comportarsi, reagire, ottimizzare e attuare i rispettivi processi decisionali. Di conseguenza, questa ricerca combina una serie di strumenti interdisciplinari, che vanno dall'economia comportamentale, all'economia sperimentale e dalla psicologia economica alla teoria della rete, teoria dei giochi e simulazioni al computer.

### Modellazione del comportamento interno ed esterno del contribuente

Il primo capitolo tenta di colmare il divario tra la letteratura economica e quella comportamentale sull'evasione fiscale. Proponiamo un modello micro-fondato i cui risultati sono coerenti con il quadro della 'slippery slope' e con la teoria dell'utilità attesa. I singoli contribuenti affrontano il problema di decidere la quota di reddito che desiderano dichiarare al governo, in base alla loro fiducia e al potere percepito delle autorità. Il nostro modello considera due parametri principali: fiducia e potere percepito. La conformità volontaria è motivata dalla fiducia nelle autorità fiscali, mentre la conformità forzata è motivata dal potere percepito del governo. Inoltre, utilizziamo simulazioni computazionali per replicare le condizioni di 'slippery slope' e per testare gli effetti di diversi parametri sull'evasione fiscale. Una corretta dichiarazione dei redditi è principalmente motivata dal morale fiscale (valori civici) e dall'avversione al rischio, e solo secondariamente è stimolata da una maggiore probabilità di conrolli e sanzioni. Le aliquote fiscali, tuttavia, hanno un effetto negativo sulla conformità fiscale, poiché gli agenti sono meno disposti a pagare le tasse quando sono sottoposti ad contributi più elevati. Inoltre, studiamo il comportamento dei contribuenti quando il tasso di verifica fiscale è zero e quando gli agenti sono inclini a fare donazioni di beneficenza. Soprattutto, deriviamo le condizioni in base alle quali gli individui evaderebbero completamente, evaderebbero parzialmente e obbedirebbero pienamente in assenza di revisioni.

### Politiche di controllo ottimali con agenti eterogenei

Il secondo capitolo considera un gioco di evasione fiscale in cui l'autorità fiscale intende prevenire la sotto-dichiarazione dei redditi all'interno di una rete di contribuenti eterogenei coinvolti in interazioni sociali e scambio di informazioni. Questo documento propone una strategia di controllo fiscale ottimale basata sulla teoria del gioco in due fasi dal punto di vista dell'autorità fiscale, che consiste in un messaggio credibile di minaccia di controllo fiscale seguito da una politica di revisioni basata sulla rete. Successivamente, l'autorità fiscale si rivolge ai contribuenti in funzione della loro produttività individuale e della loro posizione all'interno della rete, innescando una serie di effetti di ricaduta che, alla fine, massimizzano la probabilità soggettiva media percepita di essere verificati tra tutti i contribuenti. Inoltre, la strategia di controllo ottimale è coerente con le teorie dell'utilità attesa e non attesa ed è invariante per qualsiasi funzione di utilità del contribuente. Inoltre, le simulazioni al computer hanno determinato che il regime di applicazione proposto è robusto per un'ampia gamma dei parametri utilizzati.

### La struttura a rete dell'evasione fiscale globale

Il terzo capitolo si basa sulle recenti intuizioni della teoria della rete e sul ricco set di dati messo a disposizione dai *Panama Papers* per indagare le dinamiche microeconomiche dell'evasione fiscale. Modelliamo le entità finanziarie offshore documentate nei *Panama Papers* come collegamenti tra le giurisdizioni nella rete globale di evasione fiscale. Un'analisi quantitativa mostra che la rete risultante, è lontana dall'essere una raccolta casuale di collegamenti bilaterali, bensì ha caratteristiche chiave di reti complesse come una struttura nucleo-periferia e una distribuzione dei gradi a coda lunga. Noi sosteniamo che queste caratteristiche strutturali implichino che la politica debba adottare una prospettiva sistemica per mitigare l'evasione fiscale. Offriamo tre serie di approfondimenti da questa prospettiva. In primo luogo, mostriamo che le strategie di deterrenza ottimali per un pianificatore sociale che affronta un evasore fiscale strategico in una competizione di Stackelberg possono essere caratterizzate utilizzando la nozione di centralità di Bonacich. In secondo luogo, dimostriamo che i trattati fiscali efficienti devono contenere clausole sullo scambio di informazioni e collegare i paradisi fiscali alle giurisdizioni non paradisiache. Terzo, individuiamo attraverso misure di centralità i paradisi fiscali che dovrebbero essere obiettivi politici prioritari.

Firma dello studente,