The Social Multiplier of Environmental Policy: Application to Carbon Taxation ⋆

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Abstract

We analyze the effectiveness of environmental policy when consumers are subject to social influence. To this end, we build a model of consumption decisions driven by socially-embedded preferences formed under the influence of peers in a social network. This setting gives rise to a social multiplier of environmental policy. In an application to climate change, we derive Pigouvian and target-achieving carbon taxes under socially-embedded preferences. Under realistic assumptions the social multiplier is equal to 1.30, allowing to reduce the effective tax by 38%. We show that the multiplier depends on four factors: strength of social influence, initial taste distribution, network topology and income distribution. The approach provides a basis for rigorously analyzing a transition to low-carbon lifestyles and identifying complementary information and network policies to maximize the effectiveness of carbon taxation.

Keywords: Carbon pricing, climate policy, externality taxation, endogenous preferences, social network
JEL: D11, D85, D91, H23, Q58.

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1. Introduction

Social psychology has long established the sensitivity of individual decision-making to peer influence (Festinger, 1954; Deutsch and Gerard, 1955; Nolan et al., 2008; Schultz et al., 2018). Research in behavioral economics affirms that choices cannot be fully explained by stable preferences and behavioral biases but that the social environment affects agents' decisions (Bowles, 1998; Postlewaite, 1998; Mailath and Postlewaite, 2010; Fehr and Hoff, 2011; Hoff and Stiglitz, 2016; Astier, 2018; Fatas et al., 2018). In addition, neuroeconomic studies support the role of social context in the formation of preferences (Fehr and Camerer, 2007; Mason et al., 2009; Engelmann and Hein, 2013).

In view of this, we develop a framework for the study of environmental and climate policies which explicitly recognizes that consumers' preferences are shaped by interactions with social peers. This can contribute to better design of policies aimed at promoting or discouraging the consumption of goods or services whose utility depends on social interactions. For example, price instruments can achieve a desired long-term outcome by shifting a social norm towards the consumption of goods that are less damaging to the environment (Nyborg et al., 2006, 2016; Dasgupta et al., 2016). In this study, we focus on carbon taxation as a key policy aimed at reducing global greenhouse gas (GHG) emissions.

Carbon taxation, and more generally carbon pricing, increases the relative prices of goods and services with a carbon-intensive production cycle, thus encouraging a reduction in their consumption and a shift to low-carbon alternatives (Baranzini et al., 2017b; Cramton et al., 2017; Stiglitz et al., 2017). Existing economic studies analyze carbon pricing under the assumption that agents have fixed preferences and do not interact with others (e.g. Belfiori, 2017; Goulder et al., 2018; Hart, 2019). The purpose of our study is to examine carbon taxation when preferences are subject to social influence.

That visible behavior affects peers has been confirmed for various types of consumption decisions with considerable mitigation potential (Wynes and Nicholas, 2017), such as energy consumption (Allcott, 2011; Ferraro et al., 2011; Allcott and Rogers, 2014), adoption of renewable energy technologies (Ozaki, 2011; Bollinger and Gillingham, 2012; Inhoffen et al., 2019), and choice of transportation mode (Bamberg et al., 2007; Grinblatt et al., 2008; Abou-Zeid et al., 2013; Pike and Lubell, 2018). For instance, Allcott (2011) show that agents decrease their consumption of energy when they receive information about the consumption of similar neighbors. Studies by Bollinger and Gillingham (2012), Baranzini et al. (2017a) and Baranzini et al. (2018) find that agents are more likely to adopt solar panels if neighbors have already done so. Such local diffusion is driven by imitation of conspicuous consumption and communication of positive information about solar panels among neighbors.

Few studies have addressed carbon taxation with changing or even endogeneous preferences. Mattauch et al. (2018) analyze non-social endogenous preferences and climate policies. They consider the case of a carbon tax directly affecting the preferences of agents, through crowding-in or -out of intrinsic preferences by the monetary incentives (Bowles and Hwang, 2008). A study by van den Bijgaart (2018) finds that endogenous habit formation causes persistence in consumption choices. She shows that, as a result, the optimal externality tax should initially be higher than the standard Pigouvian one and gradually decrease over time. Finally, Ulph and Ulph (2018) study the role of conformity in consumption decisions under Pigouvian taxation. They find that the existence of a consumption norm weakens the effectiveness of the tax unless it succeeds to change the norm. As an addition to this literature, we model the influence of carbon taxation on preferences explicitly through social network effects, which comes down to combining public economics with social network theory.

Our results show that a carbon tax induces two types of effects. A first-order or immediate effect is a reduction in carbon-intensive consumption by an agent through the usual price effect. A second-order or subsequent effect is a change in preferences due to changes in consumption in the social network, leading to further changes in the consumption choices of agents through socially-embedded preferences. We explore different hypotheses concerning the mechanism of imitation between agents, i.e. perfect and imperfect imitation. We show that the endogenous formation of preferences in a social network can lead to the emergence of a 'social multiplier' of carbon taxation (Glaeser et al., 2003). As a result, due to imitation between agents, the tax elasticity of carbon-intensive consumption is higher than the instantaneous price elasticity. It is worth noting that in our model agents evolve towards a stronger taste for low-carbon goods because of an imitation mechanism and not as a result of increased altruism or concern for climate change.

We derive the Pigouvian and target-achieving taxes under socially-embedded preferences. The target-achieving approach determines the lowest carbon tax sufficient to meet a given GHG emissions reduction target, which does not necessarily emerge from a welfare maximization exercise. This approach resembles the Intended Nationally Determined Contributions within the 2015 Paris Agreement. We demonstrate that through network effects a policy objective can be reached with a lower tax. In other words, considering the social context in which preferences are formed allows reducing the effective carbon tax rate, which in turn can raise public and political support for it. We further quantify the social multiplier of carbon taxation by simulating the outcomes of a tax in a large network. Under realistic assumptions, social interactions multiply the effect of the tax by 1.3 which allows to reduce the effective tax by 38%. In addition, the social-network simulations makes possible an analysis of how core social characteristics, such as the strength of social influence in the formation of preferences, the distribution of tastes, the topology of the social network, and the distribution of income influence the effectiveness of a carbon tax. A precise description of the context in which social interactions happen, through network modelling, can deal with relevant contextual factors that affect the social multiplier and are bound to differ between regions and countries (Andor et al., 2020).

Our findings indicate that a population with high polarization of tastes experiences a lower social multiplier of taxation. The reason is that agents with a strong taste for either high- or low- carbon goods are less sensitive to social influence, leading to a lower tax effect on consumption. Such polarization is more likely to happen when social influence plays a strong role in the formation of preferences. We further show that increasing the strength of social influence does not always raise the social multiplier. Finally, income distribution and network topology have a small impact on tax effectiveness when social influence is weak. However, when social interactions play a strong role in consumption decisions, asymmetry in degree distribution of the social network and income inequality can produce polarization by creating clusters of agents with similar tastes that weaken the effectiveness of carbon taxation.

Our results mean that if consumption decisions depend on social interactions, the design of environmental and climate policies should account for these. Moreover, the contextual social factors allow for defining additional instruments, such as information and network policies, which can reinforce the social multiplier and hence the effectiveness of the basic regulatory policy.

The remainder of this article is organized as follows. Section 2 describes the model of carbon taxation and socially-embedded preferences in the context of high- and low-carbon consumption. Section 3 derives the social multiplier of the carbon tax and the optimality conditions for Pigouvian and target-achieving taxation approaches. Section 4 presents numerical simulations to analyze the sensitivity of the social multiplier to the strength of social influence, initial taste distribution, network topology, and income distribution. Section 5 concludes, discusses policy implications and suggests questions for further research.

2. Modelling consumption choices of socially-embedded agents

We consider a population of agents interacting in a fixed social network N. They consume two types of conspicuous goods, namely a low- and a high-carbon one. L_i and H_i denote the quantities of low- and high-carbon goods, respectively, which agent i consumes. The choice by an agent is influenced by intrinsic taste for high- and low-carbon goods as well as by the choices of peers in her ego-network, N_i, i.e. the subset of peers agent i is connected to. We conduct our analysis in partial equilibrium to limit model complexity, allowing us to focus on agents that are primarily affected by social interactions, namely the consumers.

Without loss of generality, we assume that the low-carbon good has a zero carbon intensity and that a unit of consumption of the high-carbon good generates one unit of GHG emissions. We introduce negative externalities as a function of aggregate GHG emissions, $e\left(\sum_{j\in N} H_j\right)$, that agents by definition do not consider in their consumption decision. A carbon tax τ is levied to correct for the externality. The tax revenue is distributed among the agents as a lump-sum transfer. Agents maximize their utility, subject to a budget constraint:

$$
\begin{aligned}
&\max_{H_i,L_i}\ U_i(\alpha_i, H_i, L_i) \qquad (1)\\
&\text{s.t.}\ \ H_i(P_H+\tau)+L_iP_L \leq w_i + \tau\left(\sum_{j\in N}\frac{H_j}{N}\right)\\
&\text{with } U_i(\alpha_i,H_i,L_i) \equiv \left(\alpha_i H_i^{\frac{\sigma-1}{\sigma}} + (1-\alpha_i)L_i^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} - e\left(\sum_{j\in N} H_j\right).
\end{aligned}
$$

Here, $\alpha_i \in [0,1]$ represents the taste of agent i for high-carbon consumption goods,[1] σ the elasticity of substitution between the two goods, w_i the income, and P_L and P_H the prices of the goods. We denote with $P_H(\tau)$ the price after tax (i.e. $P_H(\tau) \equiv P_H + \tau$) and set P_L as the numeraire (i.e. $P_L = 1$). We primarily consider the case of high- and low-carbon goods being substitutes ($\sigma > 1$). This assumption captures the common case of a low-carbon option competing in consumption with a high-carbon one (e.g., transportation mode choice (Salvucci et al., 2019)).[2].

[1]The marginal utility of good H increases with α_i. Thus, a change in taste modifies the structure of preferences. In the rest of the paper, we refer to changes in taste as changes in the preference ordering.

[2]Macro studies indicate that at a larger scale high- and low- carbon goods may be complementary due to the relative inelasticity of the power generating sector (Ma et al., 2008; Li and Lin, 2016; Kim, 2019; Mair et al., 2020). In view of this, we also present numerical results for $\sigma < 1$ in the Appendix C.

We consider two components of taste: intrinsic $\pi_i \in [0,1]$ and social S_i. The intrinsic component of taste is fixed while the social one is subject to change. The latter is endogenously determined by the observed consumption within an agent's ego-network N_i, i.e. the subset of peers agent i is connected to.[3] If the consumption of high-carbon goods in one's network decreases (increases) then the socially-embedded taste also decreases (increases). This is formalized as follows:

$$\alpha_i \equiv \alpha(\pi_i, S_i) = (1-\gamma)\pi_i + \gamma S_i \tag{2}$$

$$S_i \equiv S([H_j]_{j\in N_i}, [L_j]_{j\in N_i}, P_H(\tau)) \text{ and } \frac{\partial S_i}{\partial H_j} > 0,\ \frac{\partial S_i}{\partial L_j} < 0 \tag{3}$$

Here $\gamma \in [0,1]$ denotes the strength of social influence in the formation of preferences. Note that if $\gamma = 0$ then the agents exhibit standard fixed preferences. The taste can change as a direct reaction to the tax, an effect known as crowding-in or -out of preferences, something addressed in other studies but beyond our approach here (Bowles and Polania-Reyes, 2012).

With socially-embedded preferences, the utility of agent i is a function of her consumption, her intrinsic taste, the relative price of the high-carbon good, and the consumption decisions and income of her social peers. More specifically, the consumption decisions of peers are strategic complements: an agent experiences a higher marginal utility of consuming a good as its popularity among her peers increases (Young, 1996).

In this system of social interactions, the equilibrium is defined as a vector of high-carbon consumption where no agent can be better off by deviating. The action space $\{H\}$, i.e. the set of possible consumption choices, is compact and convex, and the utility function is concave and continuous in the agent's own choice and the choice of her peers. The Marshallian demand of agent i that solves the optimization problem defined in Eq.(1) is conditional on the consumption of agents $j \in N_i$, captured by the endogenous taste α_i, is:

$$H_i^{BR}(\alpha_i, P_H(\tau), w_i) = w_i \left(\frac{\alpha_i}{P_H(\tau)}\right)^{\sigma} \frac{1}{\alpha_i^{\sigma} P_H(\tau)^{1-\sigma} + (1-\alpha_i)^{\sigma}}. \tag{4}$$

This demand function is equivalent to the best response given the consumption of peers, hence ^{BR} stands for best response. Assuming that the budget constraint is binding, the consumption of the other good is fixed and we denote the utility of agent i with $U_i(H_i, \alpha_i, P_H(\tau), w_i)$. The vector $H^{\star}$ is the equilibrium vector of high-carbon consumption if each agent is best-responding to the other agents best-response; that is:

[3] i is not an element of N_i.

$$
\begin{aligned}
H_i^\star &= \text{argmax}_{H_i} U_i(H_i, \alpha_i, P_H(\tau), w_i) \;\forall i \in N \\
&= \text{argmax}_{H_i} U_i(H_i, \{H_j^\star, w_j\}_{j\in N_i}, \pi_i, P_H(\tau), w_i) \;\forall i \in N.
\end{aligned} \tag{5}
$$

Note that the taste vector α is not an argument of the equilibrium consumption function, as consumption and tastes are jointly determined in equilibrium. Agents update their taste $\alpha_i(\{H_j, w_j\}_{j\in N_i}, P_H(\tau), \pi_i)$ based on the consumption decisions they observe in their ego-network. We denote with $\alpha_i^\star$ the taste of agent i in equilibrium:

$$
\alpha_i^\star \equiv \alpha(\{H_j^\star, w_j\}_{j\in N_i}, P_H(\tau), \pi_i). \tag{6}
$$

Therefore, Eqs. (4) and (5) are linked in the following way:

$$
H_i^\star = H_i^{BR}(\alpha_i^\star, P_H(\tau), w_i) \;\forall i \in N. \tag{7}
$$

As our system only exhibits local interactions,[4] the existence of the equilibrium follows from the concavity of the utility function via a fixed-point argument (Horst and Scheinkman, 2006; Ballester et al., 2006). It is widely recognized that social interactions can give rise to multiple equilibria. Glaeser and Scheinkman (2003) show that uniqueness of equilibrium depends on the relative influence of peers on an individual's decision. Our system has a unique equilibrium if $\left|\frac{\partial^2 U_i}{\partial H_i^2}\right| > \left|\frac{\partial^2 U_i}{\partial H_i \partial S_i}\right| \;\forall i$, that is, if the marginal utility of consuming high-carbon goods decreases faster in own consumption than it increases in consumption of peers. This is equivalent to imposing a positive upper bound $\gamma^c < 1$ on the strength of social influence γ. Intuitively, in the case of $\gamma = 1$ agents have no intrinsic taste but only imitate others, giving rise to multiple unstable equilibria, such as all agents consuming only either the high-carbon good or the low-carbon one. In the case of $\gamma = 0$, there is one obvious equilibrium with the taste vector being the intrinsic tastes of the agents. We show the value of this upper bound in Table 4 in Appendix B. In the next section, we derive the effect of carbon taxation for $\gamma < \gamma^c$.

3. Carbon tax under socially-embedded preferences

To explain the role of socially-embedded preferences on a carbon tax, we first describe the reaction of agents' consumption and taste when a tax is introduced. Then, we derive Pigouvian and target-achieving taxes under socially-embedded preferences.

[4] A network exhibits local interactions if the utility of an agent depends on the specific consumption decision of peers in her ego-network. Alternatively, in a system with global interactions the utility of an agent depends on the distribution of consumption in the whole population.

3.1. *The multiplier effect of carbon taxation*

Under socially-embedded preferences, a marginal decrease in the consumption of the high-carbon good of agent i induces a decrease in high-carbon consumption of her social peers:

$$\frac{\partial H_j^{BR}}{\partial H_i} = \frac{\partial H_j^{BR}}{\partial \alpha_j}\frac{\partial \alpha_j}{\partial H_i} > 0 \ \forall i, j \in N \times N_i. \tag{8}$$

This, in turn, drives further down the high-carbon demand of agent i. Therefore, in equilibrium, the total price effect on agent i's consumption is moderated by the social interactions among all agents in the network. If the social interactions reinforce the tax effect, we say that the tax has a positive social multiplier (Glaeser et al., 2003).

Proposition 1. *Under socially-embedded preferences, the tax has a positive multiplier if the taste for the high-carbon good decreases due to social interactions.*

$$\begin{aligned} &\frac{d\alpha_i}{d\tau} < 0 \ \forall i \\ \Leftrightarrow &\frac{\partial H_i^{\star}}{\partial \tau} < \frac{\partial H_i^{BR}}{\partial \tau} \ \forall i \in N. \end{aligned} \tag{9}$$

Proof. See Appendix A.

Distinct assumptions about the influence of peers' consumption on preferences lead to different tax effects. We present results for two formulations of socially-embedded preferences. The first one reflects that agents perfectly imitate their peers' tastes, taking into account the observed consumption and prices of the goods, and the second that they imperfectly imitate their peers, relying only on observed consumption.

3.1.1. *Perfect taste imitation*

Consumption depends on both taste and relative prices. Hence, agents can interpret a change of consumption of their peers in two ways: (i) as a taste shock, meaning that a change in observed consumption is due to a variation of taste, and (ii) as a price shock. For example, consider the choice between an electric vehicle and a combustion-engine car. With a carbon tax, electric vehicles are relatively cheaper and their share in total vehicles purchased increases due to the price effect. If an agent knows the demand function of its peers, she is able to infer that this variation is totally imputable to a change of price and not to a change of taste.

$$S_i^{\mathrm{P}}(x_i, P_H) \equiv D^{-1}(x_i, P_H). \tag{10}$$

Here $D(\alpha, P_H) \equiv \frac{H^{BR}(\alpha,P_H)}{L^{BR}(\alpha,P_H)}$ denotes the ratio of high- and low-carbon consumption for a given taste and $x_i \equiv \frac{\sum_{j\in \mathrm{N}_i} H_j}{\sum_{j\in \mathrm{N}_i} H_j+L_j}$ this ratio in agent i's ego-network.

Using the Marshallian demands, one obtains:

$$S_i^P(H_j, L_j) = \frac{P_H^{\frac{1}{\sigma}} \left(\sum_{j\in \mathrm{N}_i} H_j\right)^{\frac{1}{\sigma}}}{P_H^{\frac{1}{\sigma}} \left(\sum_{j\in \mathrm{N}_i} H_j\right)^{\frac{1}{\sigma}} + P_H^{\frac{1-\sigma}{\sigma}} \left(\sum_{j\in \mathrm{N}_i} L_j\right)^{\frac{1}{\sigma}}} \tag{11}$$

Proposition 2. *Under perfect taste imitation, a tax has a positive multiplier if agents underestimate the tax effect on their peer's consumption.*

Proof. See Appendix A.

The interpretation of Proposition 2 is that as agents observe a stronger decrease in consumption than expected based on the price effect, they attribute this to a change in the taste of their peers. Therefore, their own taste for high-carbon goods decreases by imitation, triggering a stronger effect of the carbon tax on their own consumption. Corollary 1 below shows that the gap between expected and observed peers' response to a tax depends on the shape of the demand functions. In particular, it formalizes for a CES utility function that the social multiplier is positive for complementary goods ($\sigma < 1$) and negative for substitute goods ($\sigma > 1$). It means that agents generally underestimate the tax effect when goods are complements and overestimate it when they are substitutes.

Corollary 1. *Under perfect taste imitation, a tax has a positive multiplier if:*

$$\frac{\partial H^{BR}(\alpha_1,.)/\partial\alpha}{\partial^2 H^{BR}(\alpha_1,.)/\partial\alpha\partial P_H} < \frac{\partial H^{BR}(\alpha_2,.)/\partial\alpha}{\partial^2 H^{BR}(\alpha_2,.)/\partial\alpha\partial P_H} \;\forall\alpha_1 < \alpha_2 \in (0,1)^2. \tag{12}$$

With our utility function, this condition becomes:

$$\sigma < 1 \tag{13}$$

Proof. See Appendix A.

3.1.2. Imperfect taste imitation

Alternatively, one can assume that agents imitate the average consumption of their peers, without taking into account the prices of the goods. This comes down to imperfect taste imitation. In this case, the tax does not directly affect the taste for goods, i.e. $\frac{\partial\alpha}{\partial\tau} = 0$. Using the same example as above, when an agent observes that the share of electric vehicles increases, she interprets it as a new descriptive norm (Schultz et al.,

2018) and her taste for electric vehicle increases, regardless of any changes in vehicle prices[5]. We believe that imperfect taste imitation is behaviorally more realistic as it does not assume that agents are capable of undertaking the complex calculations that involve prices and elasticity of substitution (as illustrated by Eq. 11 above), needed to infer the tastes of their peers.[6] To elaborate this case, we define the social component as follows:

$$S_i^I(x_i, P_H(\tau)) = \frac{\sum_{j \in \mathrm{N}_i} H_j}{\sum_{j \in \mathrm{N}_i} H_j + L_j} \tag{14}$$

Proposition 3. *Under imperfect taste imitation, the tax has a positive social multiplier:*

$$\frac{\partial H_i^\star}{\partial \tau} < \frac{\partial H_i^{BR}}{\partial \tau} \; \forall i \in N \tag{15}$$

$$\textit{with} \; \left[\frac{\partial H_i^\star}{\partial \tau}\right]_{i \in N} = \Omega \left[\frac{\partial H_i^{BR}}{\partial \tau}\right]_{i \in N}. \tag{16}$$

Here Ω denotes the social multiplier of carbon taxation.

Proof. See Appendix A.

The social multiplier captures the impact in equilibrium of the social interactions in each individual reaction to a marginal increase of the carbon tax. Proposition 3 formalizes that under imperfect taste imitation, the overall tax effect is always higher than the direct price effect. Note that the social multiplier of the tax Ω in Eq. (15) is linked to the network structure through the Bonacich centrality of its agents (Bonacich, 1987; Ballester et al., 2006).[7] This means that a more centrally positioned agent will be more sensitive to changes in consumption by other agents in the network, thus increasing the indirect and overall effect of the tax.[8]

Eq.(17) provides an approximation of the total tax effect on high-carbon consumption by an agent i when only interactions with peers and peers of peers are taken into account

[5] Under imperfect taste imitation, if all peers have the same intrinsic taste, they will have the same equilibrium taste, which may differ from their intrinsic taste. This means that even if all agents have identical intrinsic tastes, social interactions can still cause a change in these.

[6] Moreover, one can argue that individual agents do not possess information about the elasticity of substitution of their peers.

[7] According to Bonacich, an agent is more central if connected to peers having high centrality. In our case, a tax has a larger indirect effect on an agent if she is connected to agents that also experience larger direct and indirect effects from it.

[8] Acemoglu et al. (2012) makes a similar argument in the case of productivity shocks propagating through the intersectoral network of an economy. See also King et al. (2019) for a discussion on carbon tax in presence of interdependencies between sectors.

(i.e. $k = 2$).[9]

$$\frac{\partial H_i^\star}{\partial \tau} = \underbrace{\frac{\partial H_i^{BR}}{\partial \tau}}_{\text{Direct price effect}} \left(1 + \overbrace{\sum_{j \in N_i} \frac{\partial H_i^{BR}}{\partial H_j^\star} \frac{\partial H_j^{BR}}{\partial H_i^\star}}^{\text{Amplification of direct effect}} \right) + \underbrace{\sum_{l \in N} \frac{\partial H_l^{BR}}{\partial \tau} \left(\frac{\partial H_i^{BR}}{\partial H_l^\star} + \sum_{l \neq i \in N_j} \frac{\partial H_i^{BR}}{\partial H_j^\star} \frac{\partial H_j^{BR}}{\partial H_l^\star} \right)}_{\text{Indirect effect due to peers' reaction to the tax}}. \tag{17}$$

Figure 1 further illustrates Eq.(17) for the case of three connected agents. Let us focus on agent a. Firstly, the direct price effect modifies consumption of agent a, her peer - agent b, and the peer of b - agent c. For $k = 1$, agents a and b experience an amplification of the direct price effect by imitating consumption of each other. Agent a further changes her consumption because of her peer's reaction to carbon tax. For $k = 2$, the picture is complemented by the role of peers' of peers' (c) reaction to price effect changing consumption of agent b and, as a consequence, of agent a.

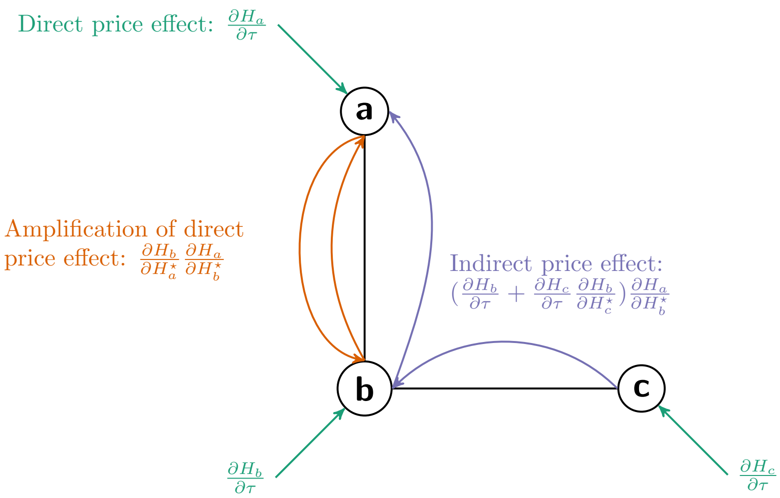

Figure 1: Total effect of carbon tax on agent a when first and second-order social interactions are accounted for, i.e. $k = 2$.

In what follows, we describe how the properties of our model determine the influence of social interactions. The social multiplier of a carbon tax is driven by two mechanisms

[9] To simplify the notation, we write $\frac{\partial H_i^{BR}}{\partial H_j^\star}$ instead of $\frac{\partial H_i^{BR}}{\partial \alpha_i} \frac{\partial \alpha_i}{\partial H_j^\star}$.

(see Eq. 8): (i) the endogeneity of tastes to the choices of peers $\frac{\partial \alpha_i}{\partial H_j}$; and (ii) the marginal effect of tastes on consumption choices $\frac{\partial H_i^{BR}}{\partial \alpha_i}$. The first mechanism captures how the consumption of peers influences the perception of the goods. Its magnitude affects the strength of social influence γ, as stated in Proposition 4. A higher γ can be interpreted either as a higher visibility of the consumption or a stronger compliance with social norms.[10]

Proposition 4. *The effect of choices of peers on tastes is increasing in the strength of social influence γ.*

Proof. See Appendix A.

The second mechanism captures how the change in goods' perception affects the consumption decision. In our model, this depends on the tastes of agents. As shown in Figure 2, agents with strong taste for either the high- or low-carbon good react less to a change in taste than agents with neutral tastes.

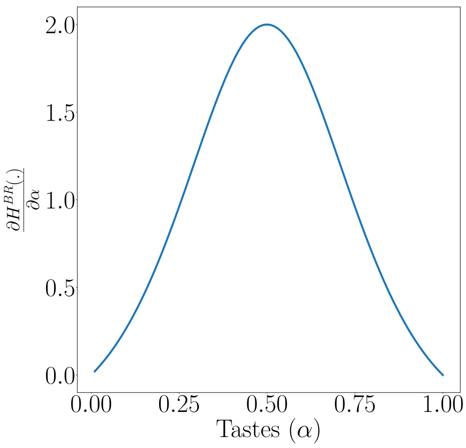

Figure 2: Partial derivative of the demand function for H with respect to taste for $P_H(\tau) = P_L$ and $\sigma = 2$.

Proposition 5. *There is a taste α_{max} such that the marginal effect of tastes on consumption choices is maximized, i.e. $\frac{\partial^2 H_i^{BR}}{\partial \alpha_i^2} = 0$, and $\alpha_{max} = \frac{P_H(\tau)}{P_H(\tau)+1}$.*

Proof. See Appendix A.

[10] In the case of solar panel diffusion, Baranzini et al. (2017a) show that households are more likely to adopt the technology if neighbors' panels are more visible.

Proposition 6. *The social multiplier of a tax decreases with the polarization of tastes if* $\mathbb{E}(\alpha) = \alpha_{max}$.

Proof. See Appendix A.

Proposition 5 formalizes that there is a taste α_{max} that maximizes the social multiplier of a carbon tax. This taste ensures that agents consume both goods equally at the optimum before the tax. If an agent consumes mainly one of the two goods before taxation then she will not respond as strongly to changes in consumption patterns in her ego-network. Intuitively, agents whose welfare depends primarily on the consumption of carbon-intensive goods are not as sensitive to social influence as agents with comparable consumption of the two goods. As formalized in Proposition 6, in a population with higher tastes polarization the social multiplier of carbon taxation is lower.

3.2. A Pigouvian tax under socially-embedded preferences

Let $v_i(P_H+\tau, w_i, e) \equiv U(\alpha_i^\star, H_i^\star, L_i^\star)$ denote the indirect utility of agent i. We suppose that utility is cardinal, thus enabling the comparison of indirect utilities, necessary for assessing social welfare. We define the social welfare W as a function of the vector of indirect utilities. This includes external costs associated with carbon emissions. The social planning problem is then as follows:

$$\max_\tau W\left([v_i(P_H+\tau, w_i, e)]_{i\in N}\right) \tag{18}$$

For a representative agent with fixed preferences, the Pigouvian tax is defined by the traditional F.O.C., $H\partial v/\partial w = \partial e/\partial H \times \partial H/\partial \tau$, leading to a carbon tax equal to the marginal damage cost. Under socially embedded-preferences, the Pigouvian tax depends on the social multiplier, as stated in Proposition 7.

Proposition 7. *The optimality condition for the Pigouvian carbon tax is:*

$$\sum_{i\in N} \frac{\partial W}{\partial v_i}\left(-\frac{\partial v_i}{\partial w_i}H_i^\star - \frac{\partial e}{\partial H}\sum_{j\in N}\frac{\partial H^\star}{\partial \tau} + \zeta_i\right) = 0 \tag{19}$$

with $\zeta_i = \frac{\partial U_i}{\partial \alpha_i}\frac{\partial \alpha_i^\star}{\partial \tau}$ *proportional to* $\left(L_i^{\star\frac{\sigma-1}{\sigma}} - H_i^{\star\frac{\sigma-1}{\sigma}}\right)$

Proof. See Appendix A

Proposition 7 shows that under socially-embedded preferences, the Pigouvian tax depends on three effects: an income effect $-\frac{\partial v_i}{\partial w_i}H_i^\star$, an externality reduction effect taking into account social interactions $-\frac{\partial e}{\partial H}\sum_{j\in N}\frac{\partial H^\star}{\partial \tau}$, and a taste effect ζ. While the first two terms are similar to the basic Pigouvian tax rule, the last one arises from the endogeneity of preferences. As explained above, in addition to modifying the budget constraint, the tax affects the taste for each good through social interactions, the net effect of which will determine the reduction in consumption related externalities. The taste for high-carbon consumption decreases[11] so that agents consuming more high- than low-carbon goods suffer a welfare loss. ζ_i can be considered either as a marginal cost when $H_i^\star > L_i^\star$ or a marginal benefit when $L_i^\star > H_i^\star$.

To derive more detailed insights about the role of social networks on the optimal tax, we employ numerical analysis. This is difficult to implement with a Pigouvian approach as it requires specifying a credible social welfare function, which in turn depends on, among others, the strong assumption that utility is cardinal. Hence, we proceed with another, more pragmatic and less contestable approach.

3.3. A target-achieving tax under socially-embedded preferences

An alternative method to set the carbon tax is to determine its lowest value that suffices to meet a particular GHG emissions reduction target (Kunreuther et al., 2013; van der Ploeg, 2018). This approach is consistent with the Paris Agreement's objective to limit global warming to 2°C above pre-industrial levels, translated into the intended nationally determined contributions of all participating countries.

Let Q denote the GHG emission target and Q_0 - the initial emission level. The objective is to find the lowest tax $\tau^\star$ that achieves the target, i.e. which solves:

$$\begin{aligned} &\tau^\star = \min \tau \\ &\text{s.t.} \sum_{i\in N} H_i^\star(P_H(\tau)) \leq Q. \end{aligned} \tag{20}$$

As $H_i^\star(\tau)$ is decreasing in τ, solving Eq.(20) is equivalent to finding $\tau^\star$ satisfying the following equality:

$$\sum_{i\in N} H_i^\star(P_H(\tau^\star)) = Q. \tag{21}$$

The social multiplier Ω reflects the effect of the carbon tax on demand that is achieved through social interactions. A higher (lower) social multiplier means that a lower (higher) carbon tax can yield the same emissions reduction target. Thus, we compare the effective tax between the cases with and without social interactions. High-carbon consumption

[11] Conversely, the taste for low-carbon increases.

before tax is a function of the vector of tastes $\alpha^{\star,0}$. If the social planner ignores the social influence on preferences, she decides on the level of the tax as if tastes were fixed: $\alpha_t = \alpha^{\star,0} \quad \forall t$. On the other hand, if the social planner takes into account the dynamics of preferences, the effective tax will take into account the social multiplier.

Without social interactions, the equilibrium consumption vector defined in Eq.(5) is the conditional best-response vector in Eq.(4) evaluated at $\alpha_i = \alpha_i^{\star,0}$.

The effective tax under fixed preferences τ^F is defined implicitly by:

$$\sum_{i \in N} H_i^{BR}(\alpha_i, P_H(\tau^F), w_i)\Big|_{\alpha_i = \alpha_i^{\star,0}} = Q. \tag{22}$$

To find the lowest tax that ensures a sufficient reduction of emissions, we integrate the marginal tax effect. When the integral is equal to the targeted reduction, its upper bound is the target-achieving tax:

$$\int_0^{\tau^\star} \sum_{i \in N} \frac{\partial H_i^\star}{\partial \tau} d\tau = \int_0^{\tau^F} \sum_{i \in N} \frac{\partial H_i^{BR}(\alpha_i^{\star,0}, P_H(\tau), w_i)}{\partial \tau} d\tau = Q_0 - Q. \tag{23}$$

From Eq.(15) we know that the marginal effect of the tax on high-carbon consumption is greater with socially-embedded preferences. Therefore, the target-achieving tax is lower when we take into account the social interactions. This is illustrated in Figure 3. We define the tax reduction due to the social multiplier, M, as the relative difference between the effective tax with socially-embedded preferences and its counterpart without social interactions:[12]

$$M \equiv 1 - \frac{\tau^\star}{\tau^F}. \tag{24}$$

The interpretation of M is the following: accounting for the role of social interactions allows to reduce the effective tax by $M \times 100\%$.

4. Numerical simulations

Now we will perform a numerical analysis to estimate the effects of a target-achieving tax with imperfect taste imitation. This will allow us to derive the social multiplier effect, namely by assessing the ratio between similarly effective taxes with and without social interactions.

[12] Note that the social multiplier of carbon taxation Ω is a matrix, whereas the tax reduction M is a scalar.

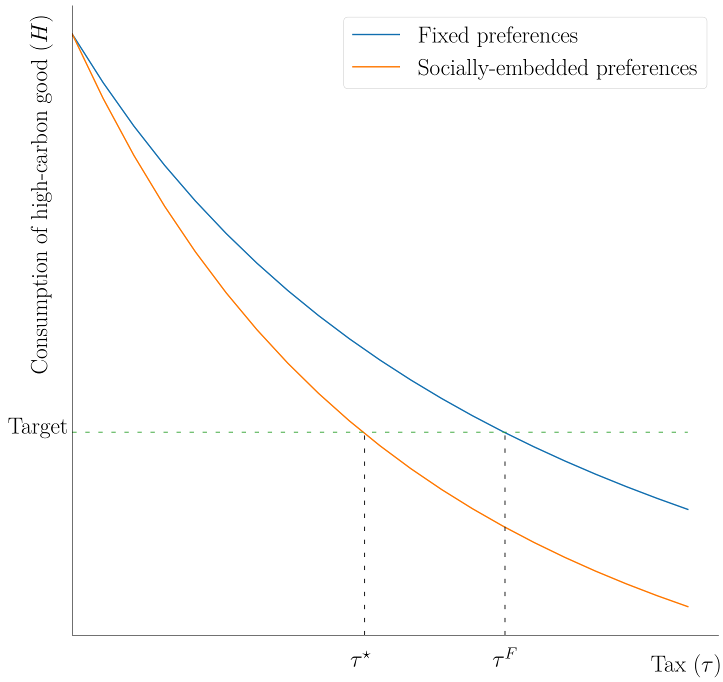

Figure 3: Reduction of high-carbon good consumption due the carbon tax under fixed and socially-embedded preferences.

We estimate a baseline social multiplier for a realistic set of parameters and study the impact of different factors: (i) the strength of social influence, (ii) the distribution of tastes, (iii) the topology of the social network and (iv) the income distribution. We set $P_H(0) = P_L$ and the target $Q = Q_0/2$. We focus on the case where high- and low-carbon goods are substitutes ($\sigma = 2$).[13]. We proceed with numerical simulations, following a four steps procedure:

1. Identify the consumption and taste vectors at the equilibrium (as defined in Eq.5);
2. Assess the minimum tax that yields a decrease of 50% of the carbon-intensive consumption with respect to the prior equilibrium (as defined by Eq.21);[14]
3. Determine the minimum tax that yields the same target but fixing the tastes at their equilibrium value prior to the tax (as defined by Eq.22);

[13]We estimate the social multiplier for complementary goods and show that the qualitative findings are not affected by this assumption (see Appendix C)

[14]To identify the extra effect due to social interactions, we also compute the decrease in carbon-intensive consumption with the effective tax and no social interactions ($\gamma = 0$).

4. Calculate the tax reduction M due to the social multiplier as defined in Eq.(24).

4.1. Parameter values

Table 1 summarizes the baseline model parametrization and alternatives tested. To study the interactions between the strength of social influence and the other factors mentioned above, we estimate numerically the social multiplier for $\gamma \in [0, 1)$ and for different taste distributions, networks, and income distributions. In the following we provide more details and motivation for each parameter.

Table 1: Overview of parameters varied in numerical simulations

	Baseline	Alternatives tested
Strength of social influence	$\gamma = 0.3$	$\gamma \in [0, 1)$
Distribution of intrinsic tastes	$\pi \sim B(1, 1)$	$B(0.1, 0.1), B(4, 4), B(15, 15)$
Network topology	Small world	Regular, random, scale free
Gini index	0.4	0.2, 0.3, 0.5

4.1.1. Strength of social influence

The strength of social influence γ determines how the tastes of agents react to changes in consumption in their social network. To our knowledge, no empirical study directly estimates this coefficient. To approximate a realistic value, we employ the results of an experiment undertaken by Falk et al. (2013). In a public good game setting, they estimate the effect of average contribution of the peers of an agent on her own contribution. They find a significant regression coefficient equal to 0.605. For our case, this translates to $\partial H_i, t/\partial S_{i,t} = 0.605$. Assuming $w_i = 1$, $P_H = 1$, $\alpha_i = 0.5$ and $\sigma = 2$, we have $\partial \alpha_{i,t}/\partial H_{i,t} = 0.5$. Therefore, a rough estimate of the strength of social influence on agent's tastes is $\gamma = 0.605 \times 0.5 \approxeq 0.3$.

As discussed in Section 2, social interactions can give rise to multiple equilibria. We find that the critical value γ^c depends on the network structure and the intrinsic taste distribution, and varies between 0.50 and 0.55 (Table 4 in Appendix B). With $\gamma < \gamma^c$, our system converges to a unique stable consumption equilibrium. With $\gamma \geq \gamma^c$, the system has two equilibria. In this case, it converges to one of them or oscillates between the two.[15] Clearly, for the baseline value $\gamma = 0.3$, we have a unique equilibrium irrespective of the social network structure and taste distribution.

[15] In the latter case, we report the average of the two equilibria.

4.1.2. Intrinsic taste distribution

We assume in the baseline that intrinsic taste for carbon-intensive goods follow a beta distribution, $\pi_i \sim B(1,1)$. This means that the tastes are uniformly distributed in the interval [0,1]. The variance of this distribution is $\sigma^2 = 0.083$.

To study the role of polarized tastes, we estimate the social multiplier for three alternative distributions, that are mean-preserving spread transformations of the uniform distribution. We report the variance of such distributions as a measurement of their polarization:[16]

(i) $B(15,15), \sigma^2 = 0.008$,

(ii) $B(4,4), \sigma^2 = 0.028$,

(iii) $B(0.1,0.1), \sigma^2 = 0.208$.

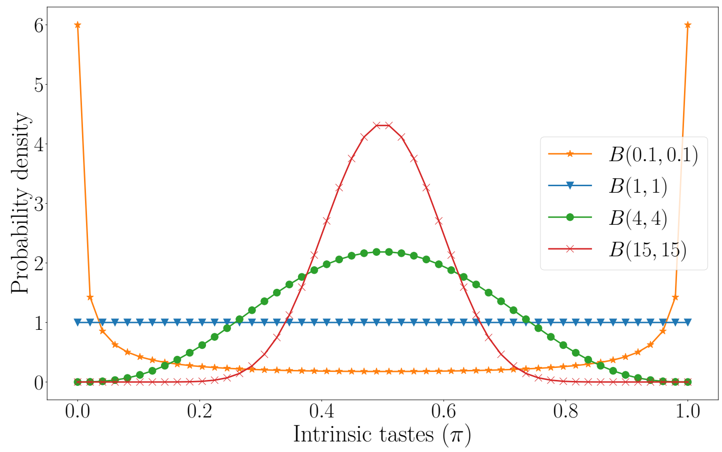

Figure 4: Distributions of intrinsic tastes.

4.1.3. Topology of the social network

We generate undirected networks[17] of 10,000 agents with 20,000 links,[18] which results in a mean degree of 4.[19] As we model the emergence of consumption norms, we are

[16]According to Axiom 3 in Esteban and Ray (1994), symmetric distributions with a higher variance have a higher polarization.

[17]A network is undirected if $j \in N_i \Leftrightarrow i \in N(j)$. In other words, i influencing j implies j influencing i.

[18]The trade-off in deciding on the number of agents is that more agents means that the results are less dependent on random initial conditions, while the computational time needed increases exponentially. A network of 10 000 agents is usually considered to ensure sufficient robustness with a relatively fast computational time.

[19]The degree of an agent is its number of peers in the network. A mean degree of 4 implies a very low social network density in line with empirical estimates by, e.g., Hu and Wang (2009) and a very sparse

interested in physical social networks (i.e. a neighborhood, workplace network or friendship network). Many of empirical social networks of these types exhibit two common characteristics (Amaral et al., 2000; Jin et al., 2001; Handcock et al., 2017): (i) high clustering, meaning that there is a high probability for two peers of an agent to be connected, and (ii) low average path length, meaning that any two agents are connected through a low number of links. We achieve these topological properties of a network by using the well-known small-world algorithm (Watts and Strogatz, 1998).[20]

To study the influence of topological characteristics of the social network on the effective tax, we simulate networks with different features (Table 2): (i) regular networks with high clustering and high average path length, (ii) random networks with low clustering and low average path length, and (iii) scale free networks with low clustering and average path length, and asymmetric degree distribution where few so-called 'star agents' can have a high number of peers, whereas the majority of agents have few connections (Barabási and Albert, 1999).

Table 2: Network characteristics for 10 000 nodes and 20 000 undirected links

	Average clustering	Average path length	Degree asymmetry
Regular lattice	50.00 %	1250.00	0.00
Small world	35.62 %	12.50	0.12
Random	0.04 %	6.76	0.50
Scale free	0.15 %	4.27	36.30

Note: Degree asymmetry of a network is measured by the skewness of its degree distribution.

4.1.4. Income distribution

Equation (2) shows that an agent with a higher income and thus signalling a higher level of consumption has a larger influence on the consumption norm. Thus, the effect of peer interaction depends on income. The assumption of a larger social influence of agents with a higher income is in line with Veblen (1899), who considers diffusion of conspicuous consumption norms to be instigated by wealthy agents. It is thus relevant to consider the distribution of income as it translates to weighted social interactions in the network.[21] We set the average income at 36,000 monetary units, the minimum income

social interactions matrix $\mathcal{A}$.

[20]The small-world algorithm involves generating a network in which agents are connected to a few nearest neighbors (i.e. a regular lattice), and then rewiring every link with a probability μ. As the probability goes to 1, the topology resembles a random network. The so-called small world network topology with high clustering (similar to regular lattice) but low average path length (similar to random network) is obtained for $\mu \in [0.001, 0.1]$.

[21]For more discussion of a social norm diffusing through weighted social interactions see Konc and Savin (2019).

at 20,000 and the maximum income at 1,000,000. We parametrize a bounded Pareto law such that we obtain a Gini index approximately equal to 0.4. This is consistent with empirical values for industrialized countries (Hellebrandt and Mauro, 2016). Income and degree distributions are slightly correlated[22] to take into account the positive relationship between a high degree and wealth accumulation (Fafchamps and Gubert, 2007). It also reflects that agents find it attractive to connect with wealthier peers. We estimate the social multiplier of the carbon tax for alternative income distributions characterized by Gini indexes equal to 0.2, 0.3 and 0.5.

4.2. Results

As the simulations imply generating random numbers, we report average results over 50 runs for each combination of parameters.[23] For the baseline parameter values, we find that social interactions multiply the effect of a tax by 1.30, leading to an average tax reduction M of 0.38. This result means the social multiplier magnifies the effect of the tax such that it can be lowered by 38%. We study the impact of the four above-mentioned factors on M.

First, we estimate the impact of the strength of social influence γ on the social multiplier.[24] We find a non-monotonous effect, namely an inverted U-shape (subplot (A) in Figure 5). On the one hand, stronger interactions contribute to increase the social multiplier via the role of consumption norms on tastes. On the other hand, stronger social influence leads to a more polarized distribution of tastes in equilibrium before the tax is implemented, thus undermining the social multiplier (Proposition 6).[25] Figure 6 shows the distribution of tastes in equilibrium before and after the tax is introduced. It illustrates that a higher strength of social influence is associated with a more polarized distribution. The highest social multiplier in Figure 5(A) is reached for $\gamma \approxeq 0.7$. Below this value, increasing the strength of social interactions has a positive effect on the multiplier –hence lowering the target-achieving tax– as the first mechanism dominates. For higher values of γ, the resulting polarization of the distribution of tastes weakens the social multiplier.

[22]The correlation coefficient is equal to 0.1

[23]For each simulation run, the allocation of income and tastes, and the position of the agents in the social network are randomized.

[24]In the following, we use the terms "social multiplier" and "tax reduction" interchangeably, as they both signal the socially-mediated effect of the tax.

[25]In other words, without any carbon tax, the initial taste distribution is different than the intrinsic taste distribution to social interactions. Low- and high-carbon consumption norms tend to cluster in different parts of the social network, causing a polarization of tastes. This polarization is due to the weighted and asymmetric nature of interactions.

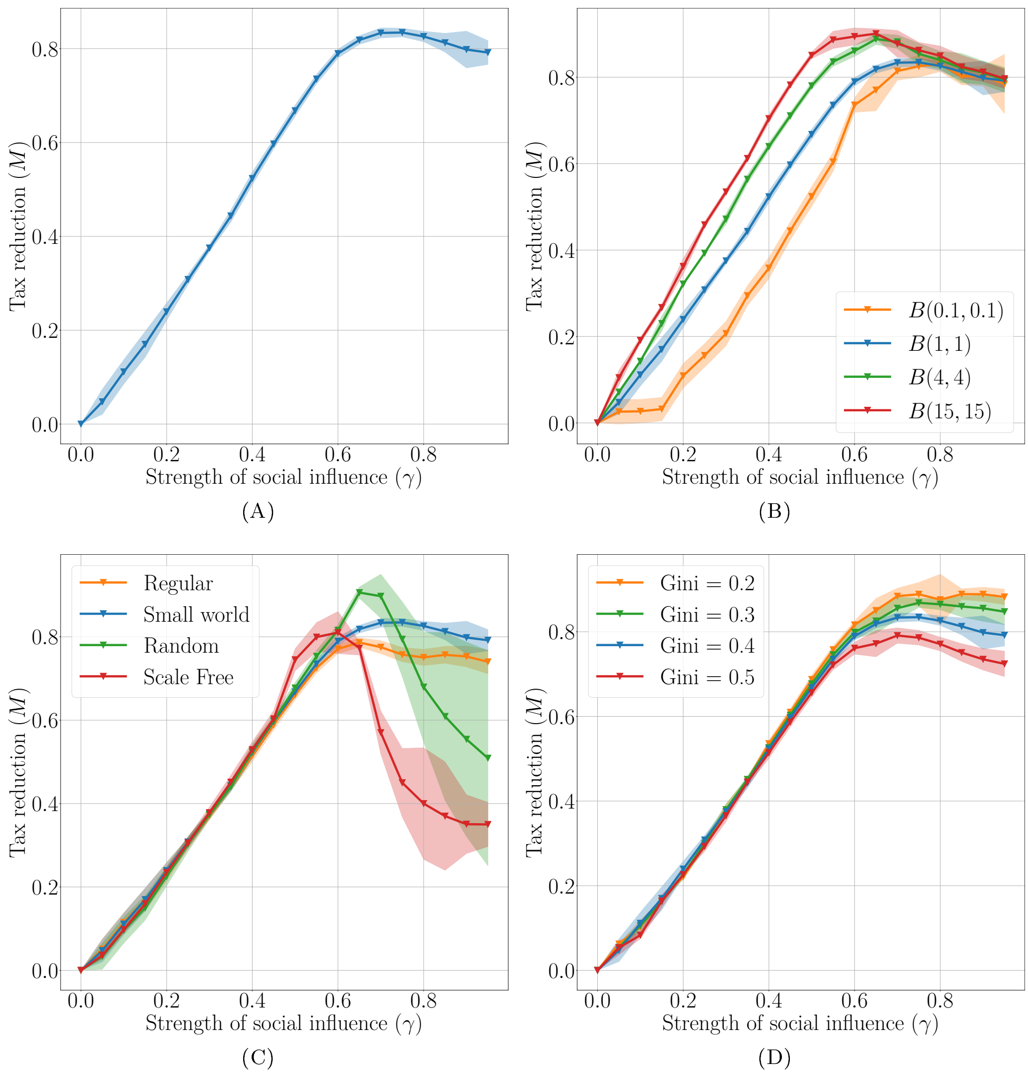

Figure 5: Reduction in effective carbon tax due to social multiplier effect for varying strength of social influence and (A) Baseline parameters; (B) different intrinsic taste distributions; (C) different network topologies; (D) different income distributions.
Note: Unless specified differently, the parameters are chosen according to the baseline scenario specified in Table 1. The shaded area represents +/- 1 standard deviation around the average.

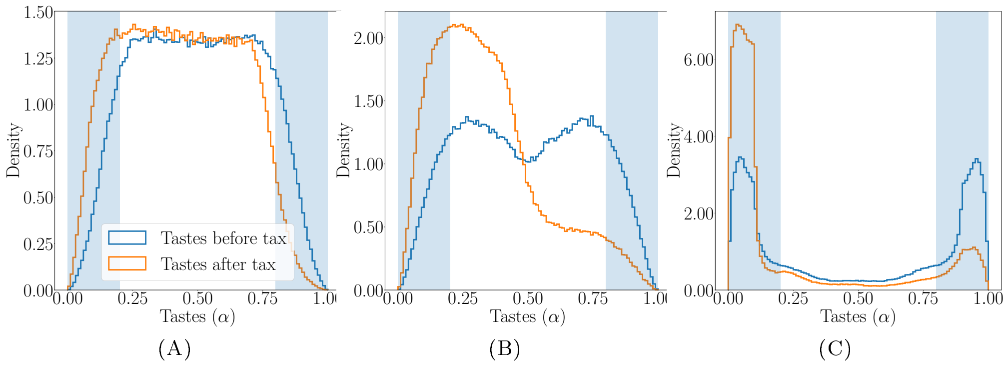

Figure 6: Taste distributions in equilibrium before and after target-achieving tax for (A) $\gamma = 0.3$, (B) $\gamma = 0.6$, (C) $\gamma = 0.9$. $\pi \sim B(1,1)$, small-world network and Gini index = 0.4.

Second, we estimate the social multiplier for alternative intrinsic taste distributions. Figure 5(B) shows the results. We find that higher polarization of initial tastes leads to a lower social multiplier. For higher strengths of social influence the polarization of tastes in equilibrium does not differ much across the four intrinsic taste distributions, and hence the social multiplier shows little differences between these cases.

Third, we estimate the social multiplier for different network topologies. We find that for $\gamma \leq 0.45$ the exact network topology does not affect the social multiplier. For $\gamma > 0.45$, however, considerable differences arise between distinct network structures (Figure 5C). In particular, we see that a scale-free network tends to produce the lowest social multiplier. The explanation for this is that taste polarization –hence the social multiplier– depends on structural properties of the networks. The emergence of clusters of agents with either high- or low-carbon tastes undermines the social effects of the carbon tax. In the scale-free network, agents with many peers and higher income serve as influence hubs contributing to the strongest polarization of tastes (Figure 7D). In the regular and small-world networks agents are embedded in clusters of strongly interconnected peers reinforcing each others' tastes, resulting in strong taste polarization (Figure 7A-B). Given the lower clustering value of the small-world network compared to the regular one (Table 2), there is a lower resistance of agents to change to low-carbon consumption resulting in higher social multiplier. Finally, the random network has little degree asymmetry and the lowest clustering which translates into the highest social multiplier and tax reduction for $\gamma \in [0.6, 0.7]$. Its performance quickly deteriorates though for $\gamma \to 1$ as even a moderate degree asymmetry becomes sufficient to produce taste polarization. To summarize, while short paths connecting distinct parts of a clustered social network increase the social multiplier, degree asymmetry –particularly under high social influence– reduces it. In other words, social network structures where people are exposed to a greater variety of opinions without strong opinion leaders are most beneficial in magnifying the effectiveness of a carbon tax.

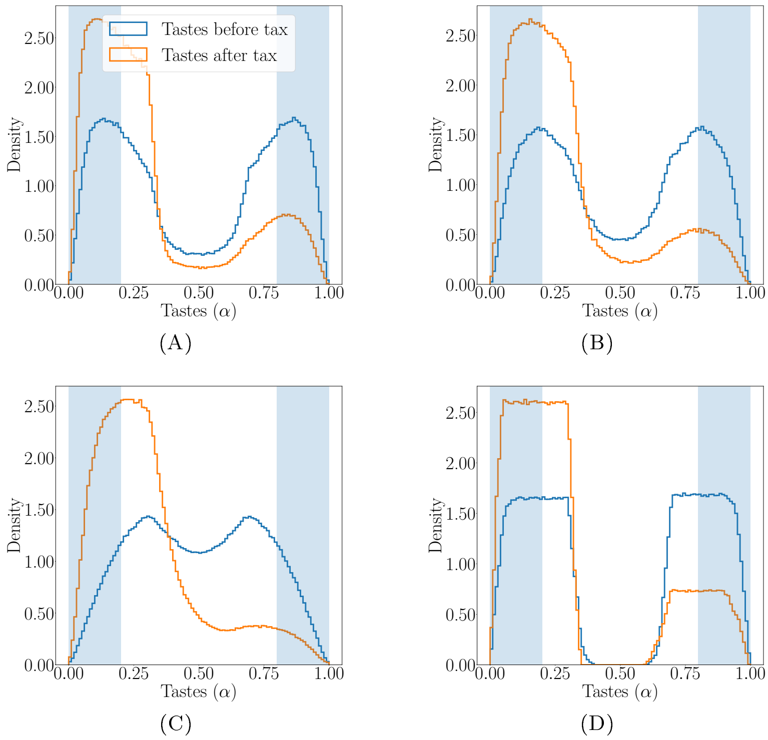

Figure 7: Taste distributions in equilibrium before and after target-achieving tax ($\gamma = 0.7$) for (A) regular network, (B) small world network, (C) random network, (D) scale free network.

Finally, we compute the social multiplier for income distributions with different Gini indices (Figure 5(D)). We find that income inequality does not influence the social multiplier for $\gamma \leq 0.5$. However, for higher γ, a lower income inequality leads to a higher socially mediated effect. This is because income inequality results in asymmetric interactions, where wealthier agents have a stronger effect on stationary consumption norm. This asymmetry dampens the social multiplier. Table 3 summarizes the results of our numerical experiments.

Table 3: Drivers of the social multiplier

Driver	Effect
Strength of social influence	Non-monotonic
Polarization of intrinsic taste	Negative
Degree asymmetry of the social network	Negative
Income inequality	Negative

5. Conclusions

Given substantial evidence that preferences of agents depend on social context, we extend environmental policy analysis with social interactions among consumers. In particular, empirical evidence shows that the consumption of many types of goods and services that generate considerable environmental externalities in production is subject to social influence. This underpins the relevance of analyzing of what we have called the "social multiplier of environmental policy". We applied our framework to carbon pricing analysis and developed a model of carbon-intensive consumption with socially-embedded agents. Their utility is a function of consumption of high- and low-carbon goods, intrinsic preferences for high-carbon goods, and consumption decisions of peers in their social network.

In this setting, consumption decisions are affected directly by the price effect and indirectly by consumption decisions of peers. We demonstrate that if agents are influenced by the observed consumption of peers without inferring their tastes, i.e. showing imperfect imitation, then interdependent preferences gives rise to a positive social multiplier of carbon taxation, which amplifies policy effectiveness. We further find that if agents try to perfectly imitate the tastes of their peers, social interactions either amplify or undermine the tax effectiveness, depending on the substitutability between low- and high-carbon goods. In particular, we show that if goods are substitutes the tax multiplier is negative if agents correctly anticipate the reaction of their peers to the tax and positive if they fail to do so.

Focusing on the first and arguably more realistic case, we estimated the impact of social interactions on a target-achieving tax through social network simulations. For realistic parameter values we find that social interactions create a social multiplier of 1.30, which reduces the effective tax rate by 38%. Numerical analysis shows that the socially-embedded effects of a tax depend on (i) the strength of social influence, (ii) intrinsic preference polarization, (iii) clustered or asymmetric social networks, and (iv) income inequality. In particular, the topology of the social network and the income distribution do not affect the social multiplier for a moderate strength of social influence. However, for a high social influence, the social multiplier decreases with income inequality and degree asymmetry of the social network. We further demonstrate that high polarization of preferences undermines the social multiplier of carbon pricing.

The fact that the effect of price variation on consumption decisions is not instantaneous but mediated by social interactions can help to explain differences between observed impacts of carbon taxation and fuel price fluctuations. Empirical studies indicate that the tax elasticity of fuel consumption is up to three times higher than the price elasticity (Li et al., 2014; Rivers and Schaufele, 2015; Andersson, 2019). This phenomenon is generally explained by salience of taxes or crowding-in of intrinsic preferences. Our study suggests another explanation, namely that taxes may have a stronger effect because they cause a long-term price change, in turn allowing consumer preferences to adjust through social interactions. In other words, the tax effect is stronger because it involves the effect of social influence on top of the direct price effect.

Our study has not only implications for the design of a first-best Pigouvian tax. The social planner may consider additional, complementary instruments that employ or modify the social network so as to make the environmental policy more effective. In line with the four factors mediating the strength of the social multiplier of taxation in our framework, illustrative instruments are:

1. Comparative feedbacks to reinforce the social context in the formation of preferences (Allcott, 2011; Astier, 2018). In the context of our model, this would translate into a higher social-influence parameter γ.

2. Information policies to correct misperceptions of climate change, which would alter the preference structure towards low-carbon consumption goods (Moxnes and Saysel, 2009). Alternatively, such policies could expose people to distinct opinions, and highlight the behavioral feasibility of alternative lifestyles.

3. Targeted subsidies or marketing policies to encourage the most interconnected agents in a social network (influence hubs) to adopt low-carbon options (Neilson and Wichmann, 2014; Bloch et al., 2016).

4. Revenue recycling schemes associated with the carbon tax to reduce income inequality, such as lump-sum redistribution or more ambitious re-distributive schemes.

By increasing the social multiplier, such additional policy instruments allow for a further reduction in the effective environmental tax. This in turn will improve the political feasibility of carbon taxation as an instrument of climate policy.

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Appendix A Proofs

A.1 Proposition 1

Proof. The optimal consumption of one agent is defined implicitly as a function of all other agent's consumption. Therefore, we cannot simply differentiate the demand function in Eq. (4) to derive the demand-response to a tax. Instead, we define a function of consumption and tax F that evaluates to 0 at the optimum consumption level, and use the implicit function theorem. Let this function be:

$$F_i(H, P_H(\tau), w_i) = H_i - H_i^{BR}(\alpha, P_H(\tau), w)\ \forall i \in N. \tag{25}$$

Here H is the vector of consumption of agents and $H^{BR}(.)$ was defined in Eq.(4) as the optimal consumption (best response) given consumption choices in the network. From Eq.(7) in equilibrium we have:

$$F_i(H^\star, P_H(\tau), w_i) = H_i^\star - H_i^{BR}(\alpha_j^\star, P_H(\tau), w_i) = 0\ \forall i \in N. \tag{26}$$

To find the change in $H^\star$ after a carbon tax, we apply the implicit function theorem on the linear mapping $F = [F_0(H), ..., F_i(H), ..., F_n(H)]$:

$$\left[\frac{\partial H_i^\star}{\partial \tau}\right]_{i\in N} = -\left[\frac{\partial F_i}{\partial H_j^\star}\right]^{-1}_{i,j\in N^2}\left[\frac{\partial F_i}{\partial \tau}\right]_{i\in N} \tag{27}$$

The second term on the RHS of Eq. (27) is the augmented price effect for all agents, i.e. the change in demand as if tastes were fixed to their equilibrium value before the tax plus the change in demand due to a direct effect of price:

$$-\left[\frac{\partial F_i}{\partial \tau}\right]_{i\in N} = \left[\frac{\partial H_i^{BR}}{\partial \tau} + \frac{\partial H_i^{BR}}{\partial \alpha_i}\frac{\partial \alpha_i}{\partial \tau}\right]_{i\in N}\Bigg|_{\alpha_i=\alpha_i^\star}. \tag{28}$$

The first term on the RHS of Eq.(27) is the inverse of the Jacobian matrix of F:

$$\left[\frac{\partial F_i}{\partial H_j^\star}\right]_{i,j\in N^2} = \left.\begin{bmatrix} 1 & \cdots & -\frac{\partial H_0^{BR}}{\partial H_j^\star} & \cdots & -\frac{\partial H_0^{BR}}{\partial H_n^\star} \\ \vdots & \ddots & & & \\ -\frac{\partial H_i^{BR}}{\partial H_0^\star} & & 1 & & -\frac{\partial H_i^{BR}}{\partial H_n^\star} \\ \vdots & & & \ddots & \\ -\frac{\partial H_n^{BR}}{\partial H_0^\star} & \cdots & -\frac{\partial H_n^{BR}}{\partial H_j^\star} & \cdots & 1 \end{bmatrix}\right|_{\alpha=\alpha^\star}. \tag{29}$$

The influence of agent j on agent i occurs through change in taste only. Using the chain rule, we can write:

$$\frac{\partial H_i^{BR}}{\partial H_j^\star} = \frac{\partial H_i^{BR}}{\partial \alpha_i}\frac{\partial \alpha_i}{\partial H_j^\star} \ \forall i,j \in N^2. \tag{30}$$

The carbon tax indirectly alters preferences through social interactions taking place between agents. By assumption, an increase in the consumption of the high-carbon good by agent $j \in N_i$ increases the taste for the same good of agent i :

$$\frac{\partial \alpha_i(.)}{\partial H_j} > 0 \ \forall i,j \in N \times N_i. \tag{31}$$

with $T_i \equiv \sum_{j\in \mathrm{N}_i}(1-P_H(\tau))H_j + w_j$ denoting the total consumption in agent's i ego-network, and $\tilde{H}_i \equiv \sum_{j\in \mathrm{N}_i} H_j$ the consumption of high-carbon goods in agent i ego-network. This change in taste induces a change in consumption for agent i equal to:

$$\frac{\partial H_i^{BR}(.)}{\partial \alpha_i} = \frac{\sigma w_i P_H(\tau)^\sigma(1-\alpha_i)^{\sigma-1}\alpha_i^{\sigma-1}}{(P_H(\tau)\alpha_i^\sigma + P_H(\tau)^\sigma(1-\alpha_i)^\sigma)^2} > 0 \tag{32}$$

The inverse of the matrix defined in Eq. (27) is given by the Neumann series:

$$\left[\frac{\partial F_i}{\partial H_j^\star}\right]^{-1}_{i,j\in N^2} = I + \sum_{k=1}^{\infty}\left(I - \left[\frac{\partial F_i}{\partial H_j^\star}\right]_{i,j\in N^2}\right)^k = I + \sum_{k=1}^{\infty}\mathcal{A}^k \equiv \Omega \tag{33}$$

with

$$\mathcal{A} = \left.\begin{bmatrix} 0 & \cdots & \frac{\partial H_0^{BR}}{\partial \alpha_0}\frac{\partial \alpha_0}{\partial H_i^\star} & \cdots & \frac{\partial H_0^{BR}}{\partial \alpha_0}\frac{\partial \alpha_0}{\partial H_n^\star} \\ \vdots & \ddots & & & \\ \frac{\partial H_i^{BR}}{\partial \alpha_i}\frac{\partial \alpha_i}{\partial H_0^\star} & & 0 & & \frac{\partial H_i^{BR}}{\partial \alpha_i}\frac{\partial \alpha_i}{\partial H_n^\star} \\ \vdots & & & \ddots & \\ \frac{\partial H_n^{BR}}{\partial \alpha_n}\frac{\partial \alpha_n}{\partial H_0^\star} & \cdots & \frac{\partial H_n^{BR}}{\partial \alpha_n}\frac{\partial \alpha_n}{\partial H_i^\star} & \cdots & 0 \end{bmatrix}\right|_{\alpha=\alpha^\star}. \tag{34}$$

$\mathcal{A}$ is an N by N matrix of social interactions whose ij element is the marginal change in the consumption of the high-carbon good of agent i induced by a change in high-carbon consumption of her social peer j. Note that this element is strictly positive if i and j are connected in the network (Eq. 31) and 0 otherwise. $\mathcal{A}$ raised to the power $k > 1$ represents the indirect social interactions between agents connected through k links. For instance, the elements of $\mathcal{A}^2$ represent indirect interactions of agents with one common peer. We call the matrix Ω the social multiplier of carbon taxation. As all entries of $\mathcal{A}$ are positive and at least one is strictly positive, it follows that all entries of Ω are positive and the diagonal entries are greater than 1.[26]

Combining Eqs. (27), (28), and (33), we find:

$$\left[\frac{\partial H_i^\star}{\partial \tau}\right]_{i\in N} = \Omega\left[\frac{\partial H_i^{BR}}{\partial \tau} + \frac{\partial H_i^{BR}}{\partial \alpha_i}\frac{\partial \alpha_i}{\partial \tau}\right]_{i\in N}. \tag{35}$$

Therefore, the total effect of the tax is stronger than the direct price effect if:

$$\begin{aligned} &\frac{\partial H_i^\star}{\partial \tau} < \frac{\partial H_i^{BR}}{\partial \tau}\ \forall i \in N \\ &\Leftrightarrow \Omega\left[\frac{\partial H_i^{BR}}{\partial \tau} + \frac{\partial H_i^{BR}}{\partial \alpha_i}\frac{\partial \alpha_i}{\partial \tau}\right]_{i\in N} < \left[\frac{\partial H_i^{BR}}{\partial \tau}\right]_{i\in N} \\ &\Leftrightarrow \Omega\left[\frac{\partial H_i^{BR}}{\partial \alpha_i}\frac{\partial \alpha_i}{\partial \tau}\right]_{i\in N} < (I-\Omega)\left[\frac{\partial H_i^{BR}}{\partial \tau}\right]_{i\in N} \\ &\Leftrightarrow \left[\frac{\partial H_i^{BR}}{\partial \alpha_i}\frac{\partial \alpha_i}{\partial \tau}\right]_{i\in N} < (\Omega^{-1}-I)\left[\frac{\partial H_i^{BR}}{\partial \tau}\right]_{i\in N}. \end{aligned} \tag{36}$$

From Eq.(33), the inverse of Ω is $\left[\frac{\partial F_i}{\partial H_j^\star}\right]_{i,j\in N^2}$ which is defined in Eq. (29). Substituting in Eq. (36), we find:

$$\begin{aligned} &\frac{\partial H_i^\star}{\partial \tau} < \frac{\partial H_i^{BR}}{\partial \tau}\ \forall i \in N \\ &\Leftrightarrow \left[\frac{\partial H_i^{BR}}{\partial \alpha_i}\frac{\partial \alpha_i}{\partial \tau}\right]_{i\in N} < \left(\left[\frac{\partial F_i}{\partial H_j^\star}\right]_{i,j\in N^2} - I\right)\left[\frac{\partial H_i^{BR}}{\partial \tau}\right]_{i\in N} \\ &\Leftrightarrow \left[\frac{\partial \alpha_i}{\partial \tau}\right]_{i\in N} < -\left[\frac{\partial \alpha_i}{\partial H_j}\right]_{i,j\in N^2}\left[\frac{\partial H_j^{BR}}{\partial \tau}\right]_{j\in N} \\ &\Leftrightarrow \frac{d\alpha_i}{d\tau} < 0\ \forall i \in N. \end{aligned} \tag{37}$$

□

A.2 Proposition 2

Proof. The social component of preferences S^{P} is

$$S_i^{\mathrm{P}}(x_i, P_H) \equiv D^{-1}(x_i, P_H). \tag{38}$$

[26] Theorem 8.3.1 in Jackson (2010) states that the power iteration $\sum_{k=1}^{\infty}\mathcal{A}^k$ converges if and only if every set of nodes that is strongly connected and closed is aperiodic. Note that the power iteration will converge if there is a single stable equilibrium, i.e. if $\gamma < \gamma^c$ (Horst and Scheinkman, 2006).

We examine the impact of price changes on the social component of preference, $\frac{dS_i^P}{dP_H}$:

$$\frac{dS_i^P(x_i, P_H)}{dP_H} = \frac{\partial S_i^P}{\partial x_i}\frac{\partial x_i}{\partial P_H} + \frac{\partial S_i^P}{\partial P_H} \tag{39}$$

Let $\bar{\alpha}_i \equiv S_i^{\mathrm{P}}(x_i, P_H)$ denote the inferred taste for a given observed consumption in agent's i ego-network. As S^R is the inverse function of D, we have:

$$\begin{aligned} & S_i^P(D(\bar{\alpha}_i, \sum w_j, P_H), P_H) = \bar{\alpha}_i \quad \forall P_H \\ \Leftrightarrow\ & \frac{dS_i^P(D(\bar{\alpha}), P_H)}{dP_H} = \frac{\partial S_i^P}{\partial x_i}\frac{\partial D(\bar{\alpha}_i)}{\partial P_H} + \frac{\partial S_i^P}{\partial P_H} = 0. \end{aligned} \tag{40}$$

Eq. 40 shows that if the inferred taste $\bar{\alpha}_i$ is the actual taste of all peers of agent i, then she is able to perfectly attribute all changes in observed consumption to the change in relative prices. Hence, her inference of peer's tastes and own socially-embedded taste will not change.

Comparison of (39) and (40) shows that the effect of a price change on taste depends on the gap between the real consumption change of peers $\frac{\partial x_i}{\partial P_H}$ and the expected consumption change given the inferred taste of peers $\frac{\partial D(\bar{\alpha}_i)}{\partial P_H}$.

$$\begin{aligned} \frac{dS_i^P(x_i, P_H)}{dP_H} < 0 \Leftrightarrow \frac{dS_i^P(x_i, P_H)}{dP_H} < \frac{dS_i^R(D(\bar{\alpha}), P_H)}{dP_H} \\ \Leftrightarrow \sum\nolimits_{j \in \mathrm{N}_i} \frac{\partial D(\alpha_j, P_H)}{\partial P_H} < \frac{\partial D(S^P(\sum_{j \in \mathrm{N}_i} D_j(\alpha_j, P_H), P_H))}{\partial P_H} \end{aligned} \tag{41}$$

By Proposition 1, the above implies that the tax effect is higher under socially-embedded preferences. □

A.3 Corollary 1

Proof. Underestimating the change of the share of H in the total consumption is equivalent to underestimating the average change in H. To simplify the notation, we define $G(\alpha_j) \equiv \frac{\partial H(\alpha_j, P_H)}{\partial P_H}$, $\tilde{G}_i \equiv \sum_{j \in N_i} \frac{G(\alpha_j)}{card(N_i)}$ and $\tilde{H}_i \equiv \sum_{j \in N_i} \frac{H(\alpha_j)}{card(N_i)}$:

$$\begin{aligned} \frac{dS_i^P}{dP_H} < 0 \Leftrightarrow & \sum\nolimits_{j \in \mathrm{N}_i} \frac{\partial D(\alpha_j, P_H)}{\partial P_H} < \frac{\partial D(S^R(\sum_{j \in \mathrm{N}_i} D_j(\alpha_j, P_H), P_H))}{\partial P_H} \\ \Leftrightarrow & \tilde{G}_i < G(H^{-1}(\tilde{H}_i)) \\ \Leftrightarrow & G^{-1}(\tilde{G}_i) < H^{-1}(\tilde{H}_i), \end{aligned} \tag{42}$$

because G and G^{-1} are increasing functions.

We now show that Eq. (42) is true if the utility function has certain properties. To simplify the proof, we study the case with $N_i = \{1, 2\}$ but the result can be generalized. Let α_1 and α_2 denote the tastes of agent i's peers, with $0 \leq \alpha_1 < \alpha_2 \leq 1$. We define $\bar{\alpha} \equiv H^{-1}(\tilde{H}_i)$ as the inferred average taste, therefore $H(\alpha_2) - H(\bar{\alpha}) = H(\bar{\alpha}) - H(\alpha_1)$. Following Cauchy's mean value theorem, we have:

$$\begin{aligned}
&\frac{H(\bar{\alpha}) - H(\alpha_1)}{G(\bar{\alpha}) - G(\alpha_1)} = \frac{H'(a)}{G'(a)} \text{ for some } a \in (\alpha_1, \bar{\alpha}) \\
&\text{and } \frac{H(\alpha_2) - H(\bar{\alpha})}{G(\alpha_2) - G(\bar{\alpha})} = \frac{H'(b)}{G'(b)} \text{ for some } b \in (\bar{\alpha}, \alpha_2) \\
&\text{therefore } \frac{G(\alpha_2) - G(\bar{\alpha})}{G(\bar{\alpha}) - G(\alpha_1)} = \frac{H'(a)}{H'(b)} \frac{G'(b)}{G'(a)}
\end{aligned} \tag{43}$$

If $\frac{G(\alpha_2) - G(\bar{\alpha})}{G(\bar{\alpha}) - G(\alpha_1)}$ is lower than one, then the average of $G(a)$ and $G(b)$ is reached for an argument lower than $\bar{\alpha}$, which means that $G^{-1}(\tilde{G}_i) < \bar{\alpha}$. Equation (42) can be rewritten as:

$$\begin{aligned}
\frac{dS^P}{dP_H} < 0 &\Leftrightarrow \frac{H'(a)}{G'(a)} < \frac{H'(b)}{G'(b)} \; \forall \alpha_1 < \alpha_2 \\
&\Leftrightarrow \frac{\partial}{\partial \alpha} \frac{H'(\alpha)}{G'(\alpha)} > 0.
\end{aligned} \tag{44}$$

Substituting with the partial derivatives from the Marshallian demand function defined in Eq. 4,

$$\frac{\partial H_i^{BR}}{\partial \alpha_i} = \frac{\sigma w_i P_H(\tau)^\sigma (1-\alpha_i)^{\sigma-1} \alpha_i^{\sigma-1}}{(P_H(\tau)\alpha_i^\sigma + P_H(\tau)^\sigma (1-\alpha_i)^\sigma)^2} \tag{45}$$

$$\frac{\partial^2 H_i^{BR}}{\partial \alpha_i \partial P_H} = \frac{\sigma w_i P_H(\tau)^\sigma (1-\alpha_i)^{\sigma-1} \alpha_i^{\sigma-1} [\alpha_i(\sigma-2) - \sigma(1-\alpha_i)^\sigma P_H(\tau)^{\sigma-1}]}{[P_H(\tau)\alpha_i^\sigma + P_H(\tau)^\sigma (1-\alpha_i)^\sigma]^3} \tag{46}$$

we obtain:

$$\frac{\partial H_i^{BR} / \partial \alpha_i}{\partial^2 H_i^{BR} / \partial \alpha_i \partial P_H} = \frac{P_H(\tau)\alpha_i^\sigma + P_H(\tau)^\sigma (1-\alpha_i)^\sigma}{\alpha_i(\sigma-2) - \sigma(1-\alpha_i)^\sigma P_H(\tau)^{\sigma-1}}, \tag{47}$$

so that the condition in Eq. (44) can be rewritten as:

$$\frac{\partial}{\partial \alpha} \left[\frac{\partial H_i^{BR} / \partial \alpha_i}{\partial^2 H_i^{BR} / \partial \alpha_i \partial P_H} \right] = \frac{2\sigma(1-\sigma) P_H(\tau)^{2+\sigma} (1-\alpha_i)^{\sigma-1} \alpha_i^{\sigma-1}}{[\alpha_i(\sigma-2) P_H(\tau) - \sigma(1-\alpha_i)^\sigma P_H(\tau)^\sigma]^2} > 0 \tag{48}$$

$$\Leftrightarrow \sigma < 1. \tag{49}$$

□

A.4 Proposition 3

Proof. From Eq. (35), if $\frac{\partial \alpha_i}{\partial \tau} = 0 \ \forall i \in N$ then:

$$\left[\frac{\partial H_i^{\star}}{\partial \tau}\right]_{i \in N} = \Omega \left[\frac{\partial H_i^{BR}}{\partial \tau}\right]_{i \in N} \tag{50}$$

All entries of Ω are positive and the diagonal entries are greater than 1, so:

$$\Leftrightarrow \frac{\partial H_i^{\star}}{\partial \tau} < \frac{\partial H_i^{BR}}{\partial \tau} \ \forall i \in N \tag{51}$$

□

A.5 Proposition 4

Proof. From Eq. (2) and (3), we derive that $\frac{\partial \alpha_i}{\partial H_j} = \frac{\partial \alpha_i}{\partial S_i}\frac{\partial S_i}{\partial H_j} = \gamma \frac{\partial S_i}{\partial H_j}$. In other words, the sensitivity of preferences to the choices of peers increases with the strength of social interactions. □

A.6 Proposition 5

Proof. Using Eq. (32) we derive:

$$\frac{\partial^2 H_i^{BR}}{\partial \alpha_i^2} = \big(f'(\alpha_i)g(\alpha_i) - f(\alpha_i)g'(\alpha_i)\big)g(\alpha_i)^{-2} \tag{52}$$

The condition for Eq. 52 being equal to 0 is:

$$f'(\alpha_i)g(\alpha_i) - f(\alpha_i)g'(\alpha_i) = 0$$

Substituting $f(\alpha_i) = \sigma w_i P_H(\tau)^{2\sigma-1}(1-\alpha_i)^{\sigma-1}\alpha_i^{\sigma}$

$f'(\alpha_i) = w_i \sigma P_H(\tau)^{2\sigma-1}\alpha_i^{\sigma}(1-\alpha_i)^{\sigma-1}\left(\sigma\frac{P_H(\tau)}{\alpha_i} + \frac{1-\sigma}{1-\alpha_i}\right)$

$g(\alpha_i) = \alpha_i(P_H(\tau)\alpha_i^{\sigma} + p^{\sigma}(1-\alpha_i)^{\sigma})^2$

and $g'(\alpha_i) = (P_H(\tau)\alpha_i^{\sigma} + p^{\sigma}(1-\alpha_i)^{\sigma})^{\sigma})^2 +$

$+\, 2\alpha_i\sigma P_H(\tau)\left(\alpha_i^{\sigma-1} - (1-\alpha_i)^{\sigma-1}P_H(\tau)^{\sigma-1}\right)\left(\alpha_i^{\sigma} + P_H(\tau)^{\sigma-1}(1-\alpha_i)^{\sigma}\right)$

we obtain:

$$f'(\alpha_i)g(\alpha_i) - f(\alpha_i)g'(\alpha_i) = \alpha_i\frac{1-\sigma}{1-\alpha_i} + \sigma P_H(\tau) + \frac{2\alpha_i\sigma P_H(\tau)(\alpha_i^{\sigma-1} - (1-\alpha_i)^{\sigma-1}P_H(\tau)^{\sigma-1})}{\alpha_i^{\sigma}P_H(\tau) + (1-\alpha_i)P_H(\tau)^{\sigma}} - P_H(\tau) \tag{53}$$

$\alpha_i = \frac{P_H(\tau)}{P_H(\tau)+1}$ is a solution to Eq. 53.

□

A.7 Proposition 6

Proof. From the axioms 2 and 3 in Esteban and Ray (1994), any symmetric shift of tastes from the central α_{max} to the lateral tastes (i.e. towards either 0 or 1) increases polarization. From Proposition 5, it follows that a lower density of agents with the taste $\alpha_{\max}$ translates into a lower social multiplier. □

A.8 Proposition 7

Proof. The social planning problem is $\max_\tau W\left([v_i(P_H+\tau, w_i, e)]_{i\in N}\right)$. Noting that $\frac{\partial v_i}{\partial \tau} = \frac{\partial U(H_i^\star, L_i^\star, \alpha_i^\star)}{\partial \tau}$, the first order condition can be written as:

$$\sum_{i\in N} \frac{\partial W}{\partial v_i}\left[-\frac{\partial U}{\partial H_i^\star}\frac{\partial H_i^\star}{\partial \tau} + \frac{\partial U}{\partial L_i^\star}\frac{\partial L_i^\star}{\partial \tau} - \frac{\partial e}{\partial H}\sum_{j\in N}\frac{\partial H_j^\star}{\partial \tau} + \frac{\partial U_i}{\partial \alpha_i}\frac{\partial \alpha_i^\star}{\partial \tau}\right] = 0. \tag{54}$$

The tax effect on the consumption of good H is:

$$\text{with } \frac{\partial H_i^\star}{\partial \tau} = \frac{\partial H_i^{BR}}{\partial \tau}\sum_{j\in N}\Omega_{i,j}\frac{\partial H_j^{BR}}{\partial \tau} < 0,$$

We define ζ_i as the taste effect of the tax:

$$\zeta_i \equiv \frac{\partial U_i}{\partial \alpha_i}\frac{\partial \alpha_i^\star}{\partial \tau},$$

$$\text{with } \frac{\partial \alpha_i^\star}{\partial \tau} = \sum_{j\in N_i}\frac{\partial \alpha_i}{\partial H_j^\star}\frac{\partial H_j^\star}{\partial \tau}, < 0$$

$$\text{and } \frac{\partial U_i}{\alpha_i^\star} = \frac{\sigma}{\sigma-1}\left(H_i^{\star\frac{\sigma-1}{\sigma}} - L_i^{\star\frac{\sigma-1}{\sigma}}\right)\left(\alpha_i^\star H_i^{\star\frac{\sigma-1}{\sigma}} + (1-\alpha_i^\star)L_i^{\star\frac{\sigma-1}{\sigma}}\right)^{\frac{1}{\sigma-1}}.$$

Since $\frac{\partial U}{\partial H_i^\star}\frac{\partial H_i^\star}{\partial \tau} + \frac{\partial U}{\partial L_i^\star}\frac{\partial L_i^\star}{\partial \tau} = -H_i^\star\frac{\partial v_i}{\partial w_i}$ by Roy's identity, the first order condition can be rewritten as:

$$\sum_{i\in N}\frac{\partial W}{\partial v_i}\left(-\frac{\partial v_i}{\partial w_i}H_i^\star - \frac{\partial e}{\partial H}\sum_{j\in N}\frac{\partial H_j^\star}{\partial \tau} + \zeta_i\right) = 0 \tag{55}$$

□

Appendix B Critical value γ_c

Table 4 shows the values γ^c such that if $\gamma < \gamma^c$ then the system of social interactions has a single equilibrium. We derived those values numerically, for different network structures and intrinsic preference distributions.

Table 4: Critical value γ^c for different network structures and intrinsic preference distributions

	B(0.1,0.1)	B(1,1)	B(4,4)	B(15,15)
Regular lattice	0.52	0.52	0.54	0.54
Small world	0.51	0.52	0.52	0.55
Random	0.50	0.50	0.50	0.51
Scale free	0.51	0.52	0.54	0.54

Appendix C Social multiplier for complementary goods, $\sigma = 0.5$

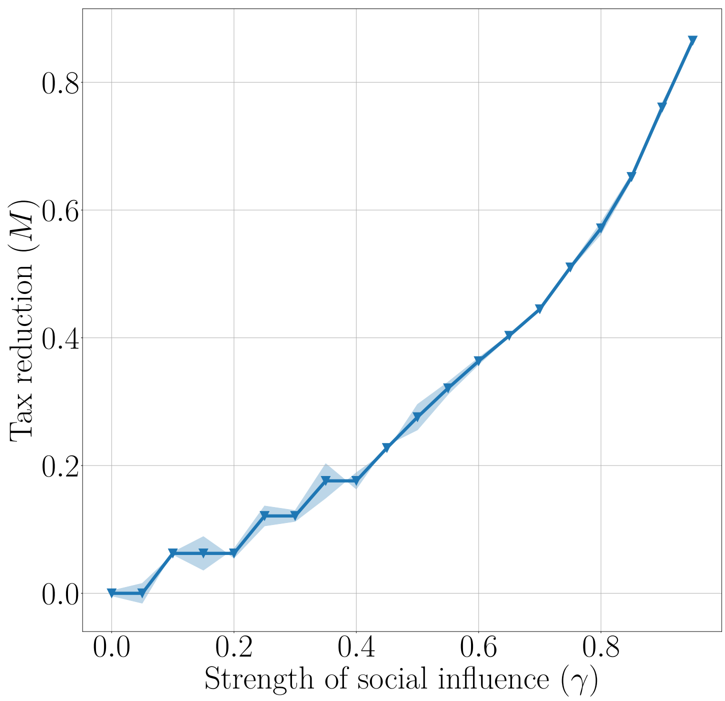

Figure 8: Reduction in effective carbon tax due to social multiplier effect for the baseline scenario specified in Table 1. The shaded area represents +/- 1 standard deviation around the average.