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Green transitions under changing preferences: Optimal intertemporal policy response[☆]

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ABSTRACT

Preferences can change during a green transition as they are formed by social contexts. A carbon tax aimed at reducing greenhouse gas emissions faces the intertemporal trade-off that lower taxes and higher carbon emissions today increase immediate welfare but decrease welfare of future people. The implications of changing preferences over climate-friendly and fossil fuel-based consumption goods for this trade-off has not been previously characterized, however. We build on Besley and Persson (2023), who pioneered incorporating endogenous preferences into a model of political competition for the green transition. Building on their framework, we characterize the optimal policy intervention under endogenous preferences on such a transition. We find that the optimal tax on the polluting good starts high and subsequently declines, as preferences become greener. Ignoring changes in preferences in climate policy design leads to large welfare losses.

1. Introduction

A carbon tax aimed at reducing greenhouse gas (GHG) emissions faces a fundamental intertemporal trade-off. Lower taxes and higher carbon emissions today increase immediate welfare but decrease welfare of future people. Conversely, higher taxes today decrease the welfare of the current generation to the benefit of future generations. Analysing the factors influencing this intertemporal trade-off, such as the discount rate (Arrow et al., 2013; Drupp et al., 2018), induced technological change (Gillingham et al., 2008; Acemoglu et al., 2012), risk aversion (Ackerman et al., 2013; Cai and Lontzek, 2018), the pure rate of time preferences (Fujii and Karp, 2008; Anthoff et al., 2009) and time-inconsistent preferences (Iverson and Karp, 2021), has been at the centre of scholarship in climate economics. The factors have been integrated in economic models to define the optimal carbon tax trajectory (Golosov et al., 2014; van den Bijgaart et al., 2016; van der Ploeg and Rezai, 2019; Dietz and Venmans, 2019; Hänsel et al., 2020).

This dynamic problem is not solely a matter of allocating consumption of high-carbon goods at different points in time, however, as it depends on preferences over those bundles (Bezin, 2019; Krysiak and Krysiak, 2006). As prior research has shown, preferences are, to an extent, shaped by price signals (Bowles and Polania-Reyes, 2012; Lanz et al., 2018; Mattauch and Hepburn, 2016), suggesting the process of preference formation should be part of the study of dynamic taxation. Including endogenous preferences, however, modifies the object that is being maximized. Instead of the sum of discounted welfare with respect to *today's preferences*, the objective function is the sum of discounted welfare accounting for *future changes in preferences due to the policy*. In the future, consumption of carbon-intensive goods may have a lower marginal utility, hence affecting the optimal allocation of polluting goods over time. Finding the intertemporal optimal policy is therefore not only a matter of correctly pricing the externality, but also of transferring carbon-intensive consumption to generations that would benefit most from it.

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Taxation can alter preferences through several channels, notably: crowding-in/-out of intrinsic motivation and interactions with peers. First, taxes can crowd-in or -out intrinsic preferences and motivation for environmental behaviour. A policy is likely to crowd-out intrinsic motivations if it is perceived as undermining self-determination and encouraging free-riding behaviour. Conversely, a policy is likely to have a crowding-in effect if it is perceived as supportive and informative, therefore facilitating the decision-making of agents (Bowles, 2016; Frey, 2012). For instance, subsidizing public transport may increase the willingness to pay for it Drevs et al. (2014), whereas a large feebate scheme for transportation can crowd-out the intrinsic motivation for environmentally-responsible behaviour (Hilton et al., 2014). Second, as noted by Bowles and Hwang (2008) and Bowles and Polania-Reyes (2012), taxes can change the social environment in which agents form their preferences. Empirical studies show the influence of conspicuous peer behaviour on consumption decisions such as energy conservation (Allcott, 2011; Ferraro et al., 2011; Allcott and Rogers, 2014), adoption of renewable energy technologies (Ozaki, 2011; Bollinger and Gillingham, 2012; Baranzini et al., 2017; Inhoffen et al., 2019), and choice of transportation mode (Pike and Lubell, 2018). Recent theoretical work in environmental economics and policy has discussed the implications of changing preferences (Weinberger and Goetzke, 2010; van den Bijgaart, 2018; Bezin, 2019; Konc et al., 2021; Severen and Van Benthem, 2022; Kreps, 2023). For example, time-inconsistent preferences can imply that lower carbon taxes are optimal (Iverson and Karp, 2021). In general, an optimal green transition depends on the effects of the policy on preferences (Mattauch et al., 2022).

Changing preferences also influence the political economy of climate policies. Besley and Persson (2023) make a fundamental contribution by including endogenous preferences in a model of political competition for the climate transition. In their framework, people with two types of preferences, "green" and "brown", coexist. A share of citizens holds green preferences which increase the utility derived from green goods and decrease the utility derived from brown goods.

When the relative price of the brown good increases, consumers react by switching type to hold the set of preferences maximizing their utility. Besley and Persson (2023) model, as a base case, probabilistic electoral competition between parties and show that voters will elect a party which optimizes present (but not intertemporal) welfare because parties cannot bind future legislation to higher tax rates.

Our paper contributes to scholarship studying how taxes can influence preferences by deriving the optimal dynamics of an environmental tax when preferences are endogenous, i.e., when the tax affects the formation of agents' preferences. Following Besley and Persson (2023), we study the politically feasible tax rate resulting from the political equilibrium. We measure the welfare losses due to the inability of current policymakers to commit to future tax rates. In doing so, we extend the argument of Besley and Persson (2023) by considering the intertemporal welfare effects of changes in preferences for the green transition. As a secondary contribution, we provide a simulation of the model in Besley and Persson (2023), which contains no numerical solution. We choose a time horizon of 50 years to do so, in accordance with current net-zero GHG emission targets of major economies extending to 2070 (and a complete preference transition possibly taking longer than reaching net-zero).

We find that the socially optimal tax policy path is greatly different from the politically feasible tax. In particular, we show that the optimal policy can be non-monotonous: it starts higher than the social cost of carbon, peaks and decreases when the share of citizens with green preferences is large enough. Such dynamics are reminiscent of the work by Lemoine and Rudik (2017) and Daniel et al. (2019) who suggest that declining tax rates are optimal because of the uncertainty of climate damages. Finally, we find that ignoring changes in preferences when designing policies leads to a welfare loss of 4.6% in the normalized and discounted welfare sum over 50 years.

To be clear, changes in preferences over climate-friendly or fossil fuel-based consumption goods is only a small part of behavioural approaches to environmental economics. Hoff and Stiglitz (2016) draw a distinction between earlier work in behavioural economics, in which a quasi-rational actor is influenced by the context of the moment of decision and has non-standard preferences, and an independent, more recent strand in which the social contexts to which she has become exposed shapes the actor's preferences. The modelling of this paper belongs to this second strand (see also Bowles, 2016; Konc et al., 2021; Mattauch et al., 2022, for extensive discussions). Besley and Persson (2023) emphasize especially the role of changing values underlying the preferences as a key assumption for the usefulness of their model in the context of green transitions, as do Mattauch et al. (2022). In particular, the intertemporal social optimum for our model is defined allowing preferences to co-evolve with the social and technological context.

In the framework applied in this paper, welfare analysis with changing preference is possible because the underlying preference structure remains in place as consumers update over time to like green goods more in accordance with changes in the economic equilibrium. The subsequent analysis therefore relies on the ability to compare utilities for different preferences in a meaningful way (see Mattauch and Hepburn, 2016; Mattauch et al., 2022). Our normative approach is therefore different from seminal contributions of conducting welfare analysis focusing on variants of the "quasi-rational", such as Gruber and Kőszegi (2004)'s model for evaluating the incidence of taxing addictive goods under time-inconsistent preferences or Bernheim and Rangel (2009)'s celebrated general approach to welfare analysis with non-standard preferences. Our model does not involve the difficulties of studying the full social optimum in overlapping generations models, as solved by Calvo and Obstfeld (1988) and Bishnu (2013), since our agents are not forward-looking. Yet another way of conducting welfare analysis with endogenous preferences, which we do not pursue here, is the equivalent income approach, which requires given reference prices (Fleurbaey and Tadenuma, 2014; Adler and Fleurbaey, 2016). In sum, our preferred approach to welfare analysis in the presence of specific but not fundamental preference change is based on the existence of 'meta-preferences'. A consumer may, for instance, like herself more when buying green products and being intrinsically motivated to do so (see e.g. Sen, 1977). Another approach is to proceed by assuming cardinal utility. If the intensity of utility changes is deemed meaningful, this provides a unit for comparing preferences (see e.g. Fleurbaey, 2009; Mattauch et al., 2022).

2. Intertemporally optimal policies with changing preferences for the green transition

We summarize the key elements from Besley and Persson (2023) needed for the subsequent analysis. Then, we analytically characterize the intertemporal social optimum before explaining the numerical approach to intertemporal optimization and the parameter choices.

2.1. Model

The economy comprises a continuum of goods, which can be either of the brown type or the green type, and a numeraire. Brown goods create a negative externality, while green goods do not. There is a continuum of monopolistic firms, which decide to produce either type. Similarly, consumers can have either brown or green preferences. As in Besley and Persson (2023), the fundamental preference structure of consumers does not change over time, while allowing specific preferences over green or brown goods to evolve. Households and firms are not optimizing intertemporally (they rather compare current period's utility or profits with green/brown preferences or products). Those with green preferences have a higher marginal utility when consuming green goods. The market equilibrium then depends on the share of green consumers, and the differences in production costs for the green and brown types of goods.

Demand-side. The utility functions for consumers with green preferences (U_g) and brown preferences (U_b) are:

$$U_g = \frac{1}{1-\sigma}\left[\int_0^{\gamma}(1+g)^{\sigma}y_g(i)^{1-\sigma}di + \int_{\gamma}^{1}(1-g)^{\sigma}Y_g(i)^{1-\sigma}di\right] + x_g - \lambda\bar{Y} \quad (1)$$

$$U_b = \frac{1}{1-\sigma}\left[\int_0^{\gamma}y_b(i)^{1-\sigma}di + \int_{\gamma}^{1}Y_b(i)^{1-\sigma}di\right] + x_b - \lambda\bar{Y} \quad (2)$$

with substitution elasticity σ, preference shift g, demand for green product $i \in [0,\gamma]$ by the citizen with green preferences $y_g(i)$, demand for brown product $i \in [\gamma,1]$ by the green citizen $Y_g(i)$, demands by citizens with brown preferences $y_b(i)$ and $Y_b(i)$, demand for numeraire good x_g, x_b, and the environmental externality $\lambda\bar{Y}$ with the total brown production $\bar{Y}$. The environmental externality is very stylized (see for a discussion of the effect of environmental damages on preferences in Section 4).

Citizens with green preferences obtain increased utility from consuming green products – represented by the term $(1+g)^{\sigma}$ –, and a reduced utility from consuming brown ones – represented by the term $(1-g)^{\sigma}$. The integral $\int_0^{\gamma}$ sums over all green products. When $\sigma \to 0$, the substitutability of varieties becomes very large and they enter the utility function linearly. The budget constraint of citizens with green preferences (similar with brown) is given by

$$R \geq x_g + \int_0^{\gamma} p(i)y_g(i)di + \int_{\gamma}^{1} P(i)Y_g(i)di \quad (3)$$

with income R, price for green goods $p(i)$, and price for brown goods $P(i)$. We assume that all consumers own an equal share of the firms, and receive tax revenues in a lump-sum fashion. The income is then made up of endowment I, tax revenue G, and the profits of green and brown firms $\pi(i)$, $\Pi(i)$:

$$R = I + G + \int_0^{\gamma}\pi(i)di + \int_{\gamma}^{1}\Pi(i)di \quad (4)$$

Supply-side. Firms produce either brown or green goods, and are monopolists for their variety i. The share of green firms is denoted by γ and, due to the monopolistic market, is also the share of green products. Firms maximize profits given the marginal costs χ, the additional marginal costs for green production ζ, and the taxes on green and brown products t and T.[1] Green technology also comes with fixed adoption costs $m \cdot i$ that depend on the variety $i \in [0,\gamma]$ produced by the firm. The profit of a green firm is given by

$$\pi(i) = (p(i) - (\chi + \zeta + t))y(i) - mi \quad (5)$$

with the total demand for green product i

$$y(i) = \mu y_g(i) + (1-\mu)y_b(i). \quad (6)$$

The profit of a brown firm is given by

$$\Pi(i) = (P(i) - (\chi + T))Y(i) \quad (7)$$

with total demand for brown product i

$$Y(i) = \mu Y_g(i) + (1-\mu)Y_b(i). \quad (8)$$

Profit maximization leads to the prices for green and brown products.[2]

$$p(i) = \frac{\chi + \zeta + t}{1-\sigma} \quad (9)$$

$$P(i) = \frac{\chi + T}{1-\sigma} \quad (10)$$

Tax revenues are given by

$$G = t\int_0^{\gamma} y(i)di + T\int_{\gamma}^{1} Y(i)di. \quad (11)$$

Equilibrium and welfare. In this paper, we focus on the welfare effects of different tax policy paths. Welfare Ω is given by the sum of utilities of green and brown citizens. Tax revenues and profits are part of the citizens' income (see Eq. (4)) and are thereby included in the welfare function:

$$\Omega = \mu U_g + (1-\mu)U_b \quad (12)$$

Following Besley and Persson (2023), in equilibrium the welfare is given by the following expression[3]:

$$\Omega(\mu,\gamma,T) = \gamma(1+\mu g)w(t) + (1-\gamma)(1-\mu g)W(T) + I - \frac{\gamma^2 m}{2} \quad (13)$$

with

$$w(t) = \frac{1}{1-\sigma}\kappa(\zeta+t) - (\chi+\zeta)\kappa(\zeta+t)^{\frac{1}{1-\sigma}}$$

and

$$W(T) = \frac{1}{1-\sigma}\kappa(T) - (\chi+\lambda)\kappa(T)^{\frac{1}{1-\sigma}}$$

and

$$\kappa(z) = \left(\frac{\chi+z}{1-\sigma}\right)^{1-\frac{1}{\sigma}}.$$

$w(t)$ and $W(T)$ represent the components of welfare related to green and brown products, respectively.

Besley and Persson (2023) show that politically-feasible tax rates *for the current period* are independent of μ and γ, because policy-makers cannot credibly commit to future tax rates. As a result, tax rates implemented by political parties seeking to win elections ignore the dynamic welfare effect of changing preferences.

$$T = (1-\sigma)\lambda - \sigma\chi \qquad t = -\sigma(\chi+\zeta) \quad (14)$$

Both taxes come with a negative part that compensates for the monopolistic market structure. The brown tax has a positive part correcting for the externality. Besley and Persson (2023) show that the politically-feasible tax rates are not efficient, but they do not characterize the optimal trajectory of taxes with changing preferences.

In the remainder of the paper, we assume for simplicity that only the tax on brown goods (T) is variable, while the tax on green goods (t) is fixed to the level given in Eq. (14) (which is the level correcting for imperfect competition).

Dynamics. We now characterize the dynamics of green preferences (μ) and green firms (γ) to solve the model dynamically and find the optimal trajectory of the tax on brown goods.

We assume that citizens and firms choose whether to go green or brown based on whether it would be benefit them *in the current period*. In other words, households adapt their preferences if they observe that such a change would already be beneficial today. Firms follow a similar dynamics and adjust their future production based on the current period's profits. This is a deviation from Besley and Persson (2023) who assume agents are forward-looking. Our assumption simplifies the numerical intertemporal optimization, while being realistic.[4]

Formally, the change in the share of green citizens μ over time depends linearly on the utility advantage of holding green preferences[5] $\Delta = U_g - U_b$ with preference imitation speed parameter d:

$$\dot{\mu} \equiv h(\mu(s),\gamma(s),T(s)) = \mu(s)(1-\mu(s)) \cdot d(s) \cdot \Delta(\gamma(s),T(s)) \quad (15)$$

[1] Later in the analysis, the tax on green goods turns out to be negative, as it corrects the market failure relating to the monopolistic structure. In the developed scholarship on technological, not preference transitions, typically the subsidy would correct endogenous learning of green technologies (Acemoglu et al., 2012; Mattauch et al., 2015). Both Besley and Persson (2023) and our analysis should be seen as abstracting from standard ways of modelling the technological transition for simplicity.

[2] Derivation shown in Appendix A.1.

[3] Derivation shown in Appendix A.1.

[4] Also, the deviation is minor: with sufficiently many time steps, changes in market conditions between successive periods will be small.

[5] Derivation shown in Appendix A.1.6.

with

$$\Delta(\gamma(s), T(s)) = \frac{\sigma g}{1-\sigma}\left[\gamma(s)\kappa(\zeta + t) - (1-\gamma(s))\kappa(T(s))\right], \tag{16}$$

and s denoting time.

The term $\mu(s)(1-\mu(s))$ in Eq. (15) ensures that the share of green citizens is between 0 and 1. Note that $\frac{\partial \Delta(\gamma,T)}{\partial T} > 0$, which means that an increased pollution tax improves the fitness of green preferences. This value transition function is a simplification of the value transition function in Besley and Persson (2023).[6]

The technology transition in Besley and Persson (2023) happens instantaneously. Firms that would make a higher profit with selling green goods can change their production immediately. Formally, for a given tax T and share of green citizens g, the optimal size of the green sector is given by[7]:

$$\frac{\sigma}{m}\left[(1+\mu g)\kappa(\zeta + t) - (1-\mu g)\kappa(T)\right] \tag{17}$$

In contrast, we assume that the technology transition does not happen instantaneously. This is consistent with a large body of intertemporal economic models on the energy transition that captures inertia in capital stocks, innovation and production (Acemoglu et al., 2012; Bauer et al., 2013; Mattauch et al., 2015; Keppo et al., 2021). In our model, the transition depends on the profitability of taking up green production but the share of green firms evolves only gradually.

$$\begin{aligned}\dot{\gamma}(\mu(s), \gamma(s), T(s)) &\equiv f(\mu(s), \gamma(s), T(s)) \\ &= e \cdot \left[\frac{\sigma}{m}\left[(1+\mu(s)g)\kappa(\zeta + t) - (1-\mu(s)g)\kappa(T(s))\right] - \gamma(s)\right].\end{aligned} \tag{18}$$

The transition speed is regulated by $e < 1$.[8] Similar to preferences, a higher tax T increases the fitness of green production.

2.2. Optimal intertemporal policy path

We define the Hamiltonian to find the optimal policy path given the discount factor β:

$$H = \Omega(\mu(s), \gamma(s), T(s)) + \psi(s)h(\mu(s), \gamma(s), T(s)) + \alpha(s)f(\mu(s), \gamma(s), T(s)) \tag{19}$$

with $\dot{\mu} = h(\mu(s), \gamma(s), T(s))$, and $\dot{\gamma} = f(\mu(s), \gamma(s), T(s))$.

For better readability, we drop the time argument s in the rest of the section. The necessary conditions for an optimum are:

$$\frac{\partial \Omega}{\partial T} + \psi\frac{\partial h}{\partial T} + \alpha\frac{\partial f}{\partial T} = 0 \tag{20}$$

$$\dot{\psi} = -\left(\frac{\partial \Omega}{\partial \mu} + \psi\left(\frac{\partial h}{\partial \mu} - \beta\right) + \alpha\frac{\partial f}{\partial \mu}\right) \tag{21}$$

$$\dot{\alpha} = -\left(\frac{\partial \Omega}{\partial \gamma} + \psi\frac{\partial h}{\partial \gamma} + \alpha\left(\frac{\partial f}{\partial \gamma} - \beta\right)\right) \tag{22}$$

Eq. (20) clarifies the role of changing preferences in this economy. Holding technological development constant, it implies that the marginal effect of the tax on instant welfare ($\frac{\partial \Omega}{\partial T}$) should be equal to the negative product of the shadow value of holding green preferences (ψ) and the increased speed at which preferences change with the tax ($\frac{\partial h}{\partial T}$). When the value of holding green preferences is positive ($\psi > 0$), the tax should be set such that $\frac{\partial \Omega}{\partial T} < 0$. In other words, the optimal trajectory reflects that a higher tax and lower instantaneous welfare are justified by the effect of the tax on future green preferences, leading to higher future welfare.

Proposition 1. *The optimal tax trajectory is defined by:*

$$\Leftrightarrow \dot{T} = -\frac{h\frac{\partial \eta}{\partial T} + f\frac{\partial \phi}{\partial T} - \eta\frac{\partial h}{\partial T} - \phi\frac{\partial f}{\partial T}}{\frac{\partial^2 \Omega}{\partial T^2} + \psi\frac{\partial^2 h}{\partial T^2} + \alpha\frac{\partial^2 f}{\partial T^2}}. \tag{23}$$

with $\eta = \left(\frac{\partial \Omega}{\partial \mu} + \psi\left(\frac{\partial h}{\partial \mu} - \beta\right) + \alpha\frac{\partial f}{\partial \mu}\right)$ *and* $\phi = \left(\frac{\partial \Omega}{\partial \gamma} + \psi\frac{\partial h}{\partial \gamma} + \alpha\left(\frac{\partial f}{\partial \gamma} - \beta\right)\right)$. *The overall marginal welfare effect of moving to green preferences is represented by* η *and* ϕ *denotes the overall marginal welfare effect of moving to green production.*

Proof. See Appendix A.2.

Corollary 1. *The optimal tax is decreasing if:*

$$h\frac{\partial \eta}{\partial T} + f\frac{\partial \phi}{\partial T} \le \eta\frac{\partial h}{\partial T} + \phi\frac{\partial f}{\partial T} \tag{24}$$

$$\Leftrightarrow h^2\frac{\partial(\eta/h)}{\partial T} + f^2\frac{\partial(\phi/f)}{\partial T} \le 0 \tag{25}$$

Proof. See Appendix A.3.

Corollary 1 shows that the optimal tax is decreasing when the welfare gains of changes in technology/preferences induced by a higher tax are smaller than the gains in accelerating the green transition. The LHS of Eq. (24) represents how a higher tax changes the value of having green preferences and using green technology, while the RHS shows the value of a higher tax as it accelerates the transitions towards such green preferences and green technology. In other words, the dynamics of the tax depends on (i) its effects on the value of the transitions, and (ii) its effects on the speed of the transitions. Eq. (25) further shows that the optimal trajectory depends on how the tax affects the ratio between the welfare gains from the preferences and technological transitions and the speed of the transitions ($\frac{\eta}{h}$ and $\frac{\phi}{f}$). If a higher tax accelerates the transition but makes the transition less valuable (i.e., both ratio $\frac{\eta}{h}$ and $\frac{\phi}{f}$ decrease with a higher tax), then the tax should decrease.

Intuitively, this means that an increasing tax is desirable if there are welfare gains to further accelerate the green transition. This might be the case early on, as an increasing tax allows to initiate the transition and move towards a greener equilibrium. Once more firms have adopted green technologies and preferences become greener, the transition becomes partly self-reinforcing. In this case, increasing the speed of the transition with an increasing tax becomes less valuable and the tax could decrease.

As we document in Section 3.1, the tax is initially increasing: there are early benefits to raising the tax slightly to catalyze the transition. Once a transition is under way, we confirm numerically that Corollary 1 holds and the tax decreases.

2.3. Numerical welfare optimization

To gain further insights, we solve the model numerically. We optimize welfare in discrete time s over the time horizon S, given the discount factor β and the two transition functions $\gamma_{s+1}(\cdot)$, $\mu_{s+1}(\cdot)$ to derive an optimal taxation path:

$$\max_{\{T_s\}_{s=0}^{S}} \sum_{s=0}^{S} \beta^s \Omega(\mu_s, \gamma_s, T_s) \quad \text{s.t.} \tag{26}$$

$$\mu_{s+1}(\mu_s, \gamma_s, T_s) = \mu_s + \mu_s(1-\mu_s)\cdot d \cdot \Delta(\gamma_s, T_s), \tag{27}$$

$$\gamma_{s+1}(\mu_s, \gamma_s, T_s) = \gamma_s + e \cdot \left[\frac{\sigma}{m}\left[(1+\mu_s g)\kappa(\zeta + t) - (1-\mu_s g)\kappa(T_s)\right] - \gamma_s\right] \tag{28}$$

We use a backward induction algorithm to carry out the computation as the model is fully deterministic.[9] We start in the last

[6] See their Appendix, Eq. (35).
[7] See Besley and Persson (2023), Eq. (21).
[8] Setting $e = 1$ would make our transition function equivalent to the one in Besley and Persson (2023).
[9] The Python implementation can be found at https://github.com/loooorenz/GreenTransitionTaxation.

period $s = S$ by maximizing the welfare given (μ_S, γ_S). We define $T^*_S(\mu_S, \gamma_S)$ as the optimal tax at (μ_S, γ_S). Similarly, $R^*_S(\mu_S, \gamma_S)$ is the maximum welfare at (μ_S, γ_S). The optimization is carried out for a grid of combinations (μ_S, γ_S) between 0 and 1, and the functions R^*_S and T^*_S are interpolations between the grid points. Formally, we compute:

$$T^*_S(\mu_S, \gamma_S) = \text{argmax } \Omega(\mu_S, \gamma_S, T_S) \tag{29}$$

$$R^*_S(\mu_S, \gamma_S) = \Omega(\mu_S, \gamma_S, T^*_S(\mu_S, \gamma_S)). \tag{30}$$

For the preceding period s, function V, which is the current welfare and the discounted value of R^*_{s+1}, is maximized. The arguments $(\mu_{s+1}, \gamma_{s+1})$ of R^*_{s+1} are defined by the current (μ_s, γ_s) using the transition functions. The value of V given the optimal tax is stored in R^*_s, so R^* contains the discounted welfare sum of the current and all subsequent periods. This optimization is computed for all periods until $s = 0$ for all grid points (μ_s, γ_s). We check numerically that the algorithm returns a global maximum, see Appendix B.1.

$$T^*_s(\mu_s, \gamma_s) = \text{argmax } V(\mu_s, \gamma_s, T_s) \tag{31}$$

$$R^*_s(\mu_s, \gamma_s) = V(\mu_s, \gamma_s, T^*_s(\mu_s, \gamma_s)), \tag{32}$$

$$\text{with } V(\mu_s, \gamma_s, T_s) = \Omega(\mu_s, \gamma_s, T_s) + \beta \cdot R^*_{s+1}(\mu_{s+1}(\mu_s, \gamma_s, T_s), \gamma_{s+1}(\mu_s, \gamma_s, T_s)) \tag{33}$$

$$\forall s \in [0, S).$$

After maximizing backwards, the optimal tax policy path given an initial (μ_0, γ_0) can be tracked forwards. It starts with $T^*_0(\mu_0, \gamma_0)$. Then, μ_{s+1} and γ_{s+1} are calculated using the transition functions and T^*_0. This is repeated for every period until $s = S$.

2.4. Parametrization

The choice of parameters for the simulation is given in Table 1. As Besley and Persson (2023) do not provide a numerical implementation of their model, we select values for the parameters, justified as follows. First, we calibrate to a set of stylized macroeconomic facts rather than to a specific economy. Importantly, we model the market for distinctively green or brown consumer goods which accounts for a small part of total economic output. Second, we calibrate remaining free parameters for internal consistency. We perform an extensive sensitivity analysis (see Section 3.2 and Appendix C) to ensure that the results do not hinge on a specific parameter combination.

Normalization and discounting. We set the endowment I to 1 to normalize the size of the economy, and the discount factor β, a normative parameter, close to 1 to represent the normative discounting of welfare.

Initial shares. The initial shares are taken as stylized facts. We set μ_0 and γ_0 such that initially 25% of consumers hold green preferences and 25% of firms provide green goods (Hassett et al., 2025; International Energy Agency, 2025).

Utility function. Parameters related to the utility function are the preference imitation speed d, substitution elasticity $\sigma \in [0, 1)$ and preference shift g. We set the parameters so that a full transition in both directions is possible during a simulation horizon of 50 periods. The speed parameter d regulates how fast people imitate rewarding preferences. For $\sigma \to 0$, every variety goes into the utility function linearly and the preference shift has no effect. For $\sigma \to 1$, the substitutability decreases and the preference shift gets stronger. The effect of green preferences on the green consumer is described by the term $(1 + g)^\sigma$ in the utility function (Eq. (1)), which under our calibration gives green consumers a reasonable utility benefit of 22% when consuming green goods. Due to the monotonic effect of σ and g on the trajectories of optimal tax and green shares found in the sensitivity analysis (see Section 3.2 and Appendix C), there are multiple parameter combinations that would lead to similar economic behaviour.

Table 1
Choice of parameters.

Parameter	Name	Value
I	Endowment	1.0
β	Discount factor	0.99
μ_0	Initial share of green citizens	0.25
γ_0	Initial share of green firms	0.25
d	Preference imitation speed	1.5
σ	Substitution elasticity	0.5
g	Preference shift of green consumers	0.5
e	Technology imitation speed	0.25
χ	Marginal cost of production	3.0
ζ	Additional marginal green cost	1.0
m	Fixed cost of green production for the most expensive firm	0.3
λ	Marginal damage of brown production (externality)	8.0

Production function. Parameters related to production are the technology imitation speed e, marginal costs χ, additional green marginal costs ζ, and green fixed costs m. We choose them to produce the reasonable economic behaviour of both types of goods being on the market throughout the simulation horizon, i.e., the share of green firms γ stays within $(0, 1)$. The sensitivity analysis reveals that e has only a minor impact on the outcome (see Section 3.2 and Appendix C). The additional marginal cost of green production ζ is chosen in relation to χ so that there is a green premium of +33%. Our choice of parameters leads to a market size of green and brown products of around 5% of GDP, with a changing value throughout the simulation because μ and γ are changing.

Externality. Finally, λ denotes the marginal damage of brown production. We choose its value so that the static brown tax (Eq. (14)) is positive, i.e., the distortion created by the environmental externality is larger than the one from the imperfect competition.

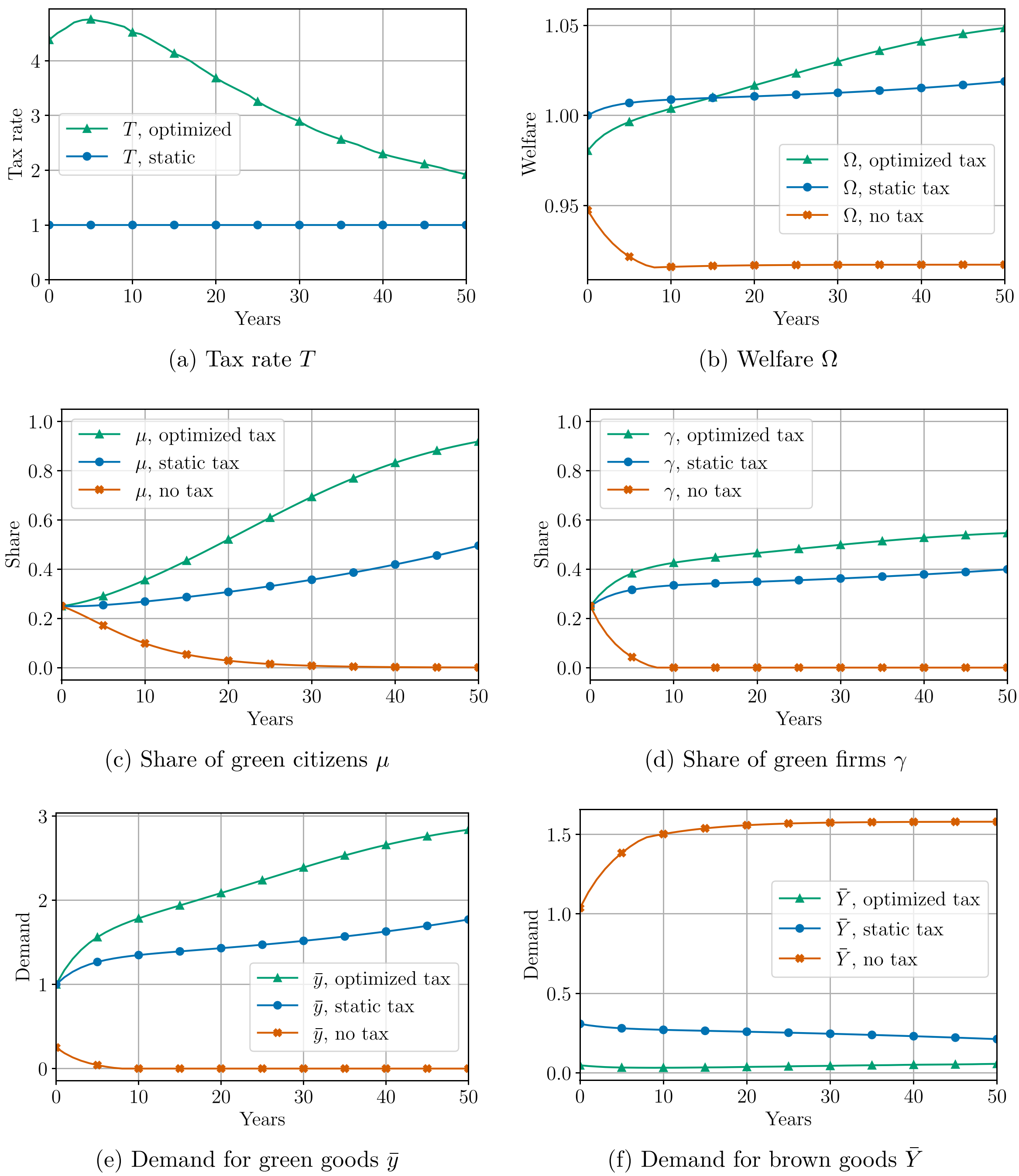
3. Numerical results

3.1. Main findings

The main numerical finding of our analysis is that, when preferences are endogenous, the optimal trajectory of a tax is non-monotonic. It starts high, somewhat increases and then declines. The intuition for this result is that a high tax level early accelerates the transition towards green preferences, and reduces the future welfare costs of taxing polluting goods. Failing to account for endogenous preferences yields a 4.6% decrease in the discounted sum of welfare.

Fig. 1(a), (b) show the optimal trajectory of the pollution tax T and of social welfare Ω. Without a tax on pollution, the economy converges to the brown steady state quickly (Fig. 1(c), (d)): there are no green preferences nor green products ($\mu = 0$, $\gamma = 0$). Taxing the polluting good increases the share of green citizens and provides incentives for green firms to operate.

Initially, the optimal tax is about four times larger than the constant tax rate which is statically optimal ("politically feasible"). The optimal tax rate increases for a few periods, and later decreases. This trajectory can be explained by the effect of taxation on preferences. A higher initial tax is initially costly in terms of welfare, but also increases the share of citizens with green preferences in the next periods (Fig. 1(c)). This shift in preferences induced by the tax contributes to the reduction in pollution and lowers the welfare costs of high pollution taxes in the future. As a result, the benefits of taxation are the highest during the first periods. Subsequently the tax decreases as the share of green citizens is high enough, so that demand for green goods increases even with a lower tax (Fig. 1(e)). Finally, the transition on production is slow because of relatively high additional costs for green technology $\zeta = 1$, $m = 0.3$. Optimal taxation leads to a higher share of green firms throughout the simulation (Fig. 1(d)).



(a) Tax rate T

(b) Welfare Ω

(c) Share of green citizens μ

(d) Share of green firms γ

(e) Demand for green goods $\bar{y}$

(f) Demand for brown goods $\bar{Y}$

Fig. 1. Simulation results. Note: Tax rate, welfare, and demand are normalized by their initial value with a static tax.

We have shown that the interplay between pollution taxes and preferences leads to a non-monotonic optimal tax trajectory. To evaluate the policy-relevance of this result, we now compare the social welfare from this optimal policy with the social welfare of a policy that would ignore the change in preferences. Concretely, we compute the optimal tax setting $d = 0$ (implying exogenous preferences), and calculate the welfare resulting from applying this tax schedule when preferences are in fact endogenous ($d = 1.5$). In other words, we calculate the welfare costs of ignoring that preferences are endogenous.

We find that implementing a tax schedule that does not account for changing preferences leads to a loss of 4.6% in the discounted sum of welfare over 50 years. We compute this value by subtracting the welfare sum with optimal tax from the welfare sum with a tax optimized while erroneously ignoring preference change.[10] Fig. 2 depicts the trajectory of a tax optimized under the incorrect assumption of fixed preferences compared to the fully optimal tax. It is almost constant due to ignoring preference endogeneity, however, a changing share of green firms is reflected in minor changes of the tax rate. This underlines that the qualitative shape of the intertemporally optimal tax rate over time

[10] The formula is given in Appendix A.4.

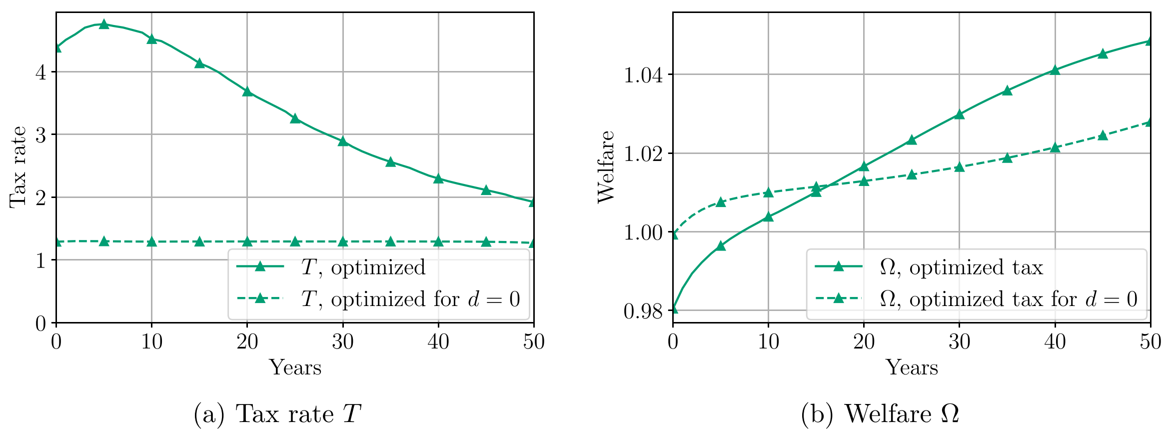


Fig. 2. Comparison to a tax optimized without considering preference change.
Note: Tax rate and welfare are normalized by their initial value with a static tax.

is entirely driven by the changes in consumer behaviour. The welfare losses are high in the long term, as the transition to green preferences is slowed down. Fig. 2 shows that in the long-term the welfare gain is approximately two percentage points. To put the result in context, note that the economy is calibrated so that only around 5% of GDP are related to green or brown production.

3.2. Sensitivity analysis

We perform a comprehensive sensitivity analysis and find that the model outcome is sensitive to changes in the substitution elasticity σ and the discount factor β. Therefore, their sensitivity deviations are chosen small to maintain results within a reasonable space. The influence of the technology imitation speed e and the initial values μ_0, γ_0 is minor, such that large sensitivity ranges are used.

Table 2 shows the parameter ranges simulated and the resulting changes in welfare losses of ignoring preference change during tax optimization for different parameter changes. Appendix C collects the corresponding plots.

Importantly, the analysis confirms that the non-monotonicity of the tax trajectory is robust to a large variety of parametrizations. The welfare loss from ignoring changing preferences remains substantial across the analysis. The dynamics are similar for significantly different initial shares of green citizens and firms (see Figs. 5 and 6 in Appendix C).

For the following parameters, an *increase* simplifies the transition to green preferences, implying a higher peak in the optimal tax rate, a faster green transition, and higher levels of welfare: discount factor β, preference imitation speed d, substitution elasticity σ, preference shift g, technology imitation speed e, and externality λ (see Figs. 4, 7, 8, 9, 10 and 14 in Appendix C).

For the other parameters, the opposite is the case: a *decrease* leads to a higher peak in the optimal tax rate, a faster green transition, and higher levels of welfare. They are marginal costs χ, green marginal costs ζ, and green fixed costs m (see Figs. 11, 12 and 13 in Appendix C).

Increasing the preference imitation speed d leads to a higher peak in the optimal tax and lower tax rates in later periods. The other parameters (apart from μ_0, γ_0) have a monotonic influence on the trajectories: an increase leads to higher optimal tax and higher shares of green citizens and firms throughout the whole simulation horizon, or vice versa.

Changes in the value of the externality λ lead to largely different optimal tax rates but result in only minor differences in the shares of green citizens and firms under optimal taxation.

4. Concluding discussion

When a green transition is taken to involve changes in preferences as well as in production, an optimal tax on the product causing environmental damage starts high and peaks early before it decreases over time, as the tax incentivizes preference change. Adapting the model of Besley and Persson (2023) to study intertemporal optimality, we formally show that the optimal tax is in this sense non-monotonic and much higher than the tax resulting from political equilibrium. Implementing a policy that does not take into account changes in preferences in a world where preferences are endogenous leads to sizeable welfare losses.

An important limitation of the model is the assumption about separating “green” and “brown” products with explicit preferences: Electricity is a homogeneous good with most consumers indifferent as to whether it is produced by low-carbon sources. Rather, key applications include choosing between combustion-engine cars and low-carbon transport modes, or between high- and low-carbon food choices. By contrast, for aviation or construction no equivalent low-carbon alternatives are widely available.

In practical fiscal policy, other factors such as short-term growth objectives, social justice and lobbyism will dominate setting carbon prices. However, the model pioneered by Besley and Persson (2023) clearly exhibits the policy implications of endogenous preferences in a green transition. Furthermore, both Besley and Persson (2023) and our analysis abstracts from heterogeneity in households’ energy needs or income and an interaction with how their preferences evolve – see however Konc et al. (2021) for a related point on socially-embedded low- and high-carbon preferences.

Moreover, one could explore the welfare implications of a true first-best policy in which the government had an instrument to suitably adjust preferences directly over time, such as education. Moral considerations aside, it would assume that there was no trade-off with costs for such an instrument to believe that such a case could restore a true social optimum. It is for that reason that our analysis ruled out this case by analogy to individualized lump-sum taxes in public finance (Mattauch et al., 2022) and focused on welfare-optimal tax schedules.

Taken together, a future study evaluating policy instruments with heterogeneity in endogenous preferences might examine interventions targeting individuals with a higher likelihood to change their preferences. An unresolved fairness implication would be that policies rewarding financially citizens with the ‘right’ characteristics to switch their preferences might likely lead to regressive results, similar to

Table 2
Welfare loss of ignoring preference change for marginal deviations in parameters (base case: −4.6%).

Parameter	Name	Value (sensitivity analysis)	Welfare loss
β	Discount factor	0.99 (0.97, 1)	(−2.4%, −6.0%)
μ_0	Initial share of green citizens	0.25 (0.15, 0.35)	(−1.6%, −4.0%)
γ_0	Initial share of green firms	0.25 (0.15, 0.35)	(−4.4%, −4.7%)
d	Preference imitation speed	1.5 (1.0, 2.0)	(−1.1%, −6.9%)
σ	Substitution elasticity	0.5 (0.49, 0.51)	(−2.1%, −7.2%)
g	Preference shift of green consumers	0.5 (0.45, 0.55)	(−2.2%, −7.0%)
e	Technology imitation speed	0.25 (0.1, 0.4)	(−2.2%, −5.2%)
χ	Marginal cost of production	3.0 (2.5, 3.5)	(−4.2%, −0.8%)
ζ	Additional marginal green cost	1.0 (0.75, 1.25)	(−5.5%, −2.2%)
m	Fixed cost of green production	0.3 (0.25, 0.35)	(−6.2%, −1.3%)
λ	Marginal damage of brown production	8.0 (6.0, 10.0)	(−5.2%, −2.9%)

energy policy studies finding that subsidies for low-carbon end-use goods are regressive (Allcott et al., 2015; Funke, 2025).

A further limitation of our – and Besley and Persson (2023)'s – analysis is the exclusion of how preferences could vary with environmental damages. There is empirical evidence that exposure to damages increases pro-environmental preferences (Broomell et al., 2015; Demski et al., 2017; López-Feldman and González, 2024; Spence et al., 2011). The consequences of such dynamics on macroeconomic outputs and on optimal policy are unclear. Preference and environmental changes might create a feedback loop in the sense that environmental degradation increases pro-environmental preferences, which in turn decreases environmental degradation.

Two broader implications follow from our results. First, if a society cannot implement an intertemporal optimum due to self-interest of political competitors, delegation to an independent authority with a technical mandate such as a "climate central bank" could help (Grosjean et al., 2016; Mattauch and Srivastav, 2023) – the UK Committee on Climate Change is a real-world example. Second, politicians appear to easily forget that, as a result of political reform, the preferences of their electorate may change. If changing values necessitate high and declining tax rates to steer the transition in preferences, as we formally show, this implies the new argument that politicians enacting environmental reform will be punished less for it at the ballot box than they might think when assuming fixed preferences.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Derivations

A.1. Derivation of indirect welfare

A.1.1. Utility and demand

The utility of green citizens is

$$U_g = \frac{1}{1-\sigma}\left[\int_0^{\gamma}(1+g)^{\sigma}y_g(i)^{1-\sigma}di + \int_{\gamma}^{1}(1-g)^{\sigma}Y_g(i)^{1-\sigma}di\right] + x_g - \lambda\bar{Y}. \tag{34}$$

With symmetric firms and varieties this becomes

$$U_g = \frac{1}{1-\sigma}\left[\gamma(1+g)^{\sigma}y_g(i)^{1-\sigma} + (1-\gamma)(1-g)^{\sigma}Y_g(i)^{1-\sigma}\right] + x_b - \lambda\bar{Y}. \tag{35}$$

The Lagrangian for utility maximization with budget restriction is

$$\begin{aligned} L_g =& \frac{1}{1-\sigma}\left[\gamma(1+g)^{\sigma}y_g(i)^{1-\sigma} + (1-\gamma)(1-g)^{\sigma}Y_g(i)^{1-\sigma}\right] + x_g - \lambda\bar{Y} \\ &+ \alpha\left[R - x - \gamma p(i)y_g(i) - (1-\gamma)P(i)Y_g(i)\right]. \end{aligned} \tag{36}$$

Deriving the Lagrangian yields the demand of a green citizen for a green product $y_g(i)$ and for a brown products $Y_g(i)$.

$$\frac{\partial L_g}{\partial x_g} = 1 - \alpha \stackrel{!}{=} 0$$

$$\Rightarrow \alpha = 1$$

$$\frac{\partial L_g}{\partial y_g(i)} = \gamma(1+g)^{\sigma}y_g(i)^{-\sigma} - \alpha\gamma p(i) \stackrel{!}{=} 0$$

$$\Rightarrow y_g(i)^{-\sigma} = (1+g)^{-\sigma}p(i)$$

$$\Rightarrow y_g(i) = (1+g)p(i)^{-\frac{1}{\sigma}} \tag{37}$$

$$\frac{\partial L_g}{\partial Y_g(i)} = (1-\gamma)(1-g)^{\sigma}Y_g(i)^{-\sigma} - \alpha(1-\gamma)P(i) \stackrel{!}{=} 0$$

$$\Rightarrow Y_g(i)^{-\sigma} = (1-g)^{-\sigma}P(i)$$

$$\Rightarrow Y_g(i) = (1-g)P(i)^{-\frac{1}{\sigma}} \tag{38}$$

Utility of brown citizens is obtained from (35) with $g = 0$.

$$U_b = \frac{1}{1-\sigma}\left[\gamma y_b(i)^{1-\sigma} + (1-\gamma)Y_b(i)^{1-\sigma}\right] + x_b - \lambda\bar{Y} \tag{39}$$

Inserting $g = 0$ into (37) and (38) yields the brown citizens' demands for green $y_b(i)$ and brown $Y_b(i)$ varieties.

$$y_b(i) = p(i)^{-\frac{1}{\sigma}} \tag{40}$$

$$Y_b(i) = P(i)^{-\frac{1}{\sigma}} \tag{41}$$

Summing up the demand from both types of citizens gives the aggregated demands for a green and a brown good.

$$\begin{aligned} y(i) &= \mu y_g(i) + (1-\mu)y_b(i) \quad | \text{ with (37), (40)} \\ &= \mu(1+g)p(i)^{-\frac{1}{\sigma}} + (1-\mu)p(i)^{-\frac{1}{\sigma}} \\ &= (1+\mu g)p(i)^{-\frac{1}{\sigma}} \end{aligned} \tag{42}$$

$$\begin{aligned} Y(i) &= \mu Y_g(i) + (1-\mu)Y_b(i) \quad | \text{ with (38), (41)} \\ &= \mu(1-g)P(i)^{-\frac{1}{\sigma}} + (1-\mu)P(i)^{-\frac{1}{\sigma}} \\ &= (1-\mu g)P(i)^{-\frac{1}{\sigma}} \end{aligned} \tag{43}$$

A.1.2. Profits and prices

The profit of green firm i is given by

$$\begin{aligned} \pi(i) &= (p(i) - (\chi+\zeta+t))y(i) - mi \quad | \text{ with (42)} \\ &= (p(i) - (\chi+\zeta+t))(1+\mu g)p(i)^{-\frac{1}{\sigma}} - mi \\ &= (1+\mu g)\left[p(i)^{1-\frac{1}{\sigma}} - (\chi+\zeta+t)p(i)^{-\frac{1}{\sigma}}\right] - mi. \end{aligned} \tag{44}$$

The firms set the price as monopolists for their variety i.

$$\frac{\partial \pi(i)}{\partial p(i)} = (1+\mu g)\left[\left(1-\frac{1}{\sigma}\right)p(i)^{-\frac{1}{\sigma}} + \frac{1}{\sigma}(\chi+\zeta+t)p(i)^{-\frac{1}{\sigma}-1}\right] \stackrel{!}{=} 0 \quad | \cdot \sigma p(i)^{1+\frac{1}{\sigma}}$$

$$\Rightarrow (\sigma-1)p(i) = -(\chi+\zeta+t)$$

$$\Rightarrow p(i) = \frac{\chi + \zeta + t}{1 - \sigma} \tag{45}$$

Inserting this into (44) yields the profit of a green firm.

$$\begin{aligned}
\pi(i) &= (1 + \mu g)\left[p(i)^{1-\frac{1}{\sigma}} - (\chi + \zeta + t)p(i)^{-\frac{1}{\sigma}}\right] - mi \\
&= (1 + \mu g)\left[\left(\frac{\chi + \zeta + t}{1 - \sigma}\right)^{1-\frac{1}{\sigma}} - (\chi + \zeta + t)\left(\frac{\chi + \zeta + t}{1 - \sigma}\right)^{-\frac{1}{\sigma}}\right] - mi \\
&= (1 + \mu g)\left[\left(\frac{\chi + \zeta + t}{1 - \sigma}\right)^{1-\frac{1}{\sigma}} - (1 - \sigma)\left(\frac{\chi + \zeta + t}{1 - \sigma}\right)^{1-\frac{1}{\sigma}}\right] - mi \\
&= \sigma(1 + \mu g)\left(\frac{\chi + \zeta + t}{1 - \sigma}\right)^{1-\frac{1}{\sigma}} - mi \\
&= \sigma(1 + \mu g)\kappa(\zeta + t) - mi
\end{aligned} \tag{46}$$

with

$$\kappa(z) = \left(\frac{\chi + z}{1 - \sigma}\right)^{1-\frac{1}{\sigma}}. \tag{47}$$

The profits of brown firms are given by

$$\begin{aligned}
\Pi(i) &= (P(i) - (\chi + T))Y(i) \qquad | \text{ with } (43) \\
&= (P(i) - (\chi + T))(1 - \mu g)P(i)^{-\frac{1}{\sigma}} \\
&= (1 - \mu g)\left[P(i)^{1-\frac{1}{\sigma}} - (\chi + T)P(i)^{-\frac{1}{\sigma}}\right].
\end{aligned} \tag{48}$$

Profit maximization yields the price for brown varieties.

$$\frac{\partial \Pi(i)}{\partial P(i)} = (1 - \mu g)\left[\left(1 - \frac{1}{\sigma}\right)P(i)^{-\frac{1}{\sigma}} + \frac{1}{\sigma}(\chi + T)P(i)^{-\frac{1}{\sigma}-1}\right] \stackrel{!}{=} 0 \qquad | \cdot \sigma P(i)^{1+\frac{1}{\sigma}}$$

$$\Rightarrow (\sigma - 1)P(i) = -(\chi + T)$$

$$\Rightarrow P(i) = \frac{\chi + T}{1 - \sigma} \tag{49}$$

Inserting this into (48) yields the profit of a brown firm.

$$\begin{aligned}
\Pi(i) &= (1 - \mu g)\left[P(i)^{1-\frac{1}{\sigma}} - (\chi + T)P(i)^{-\frac{1}{\sigma}}\right] \\
&= (1 - \mu g)\left[\left(\frac{\chi + T}{1 - \sigma}\right)^{1-\frac{1}{\sigma}} - (\chi + T)\left(\frac{\chi + T}{1 - \sigma}\right)^{-\frac{1}{\sigma}}\right] \\
&= (1 - \mu g)\left[\left(\frac{\chi + T}{1 - \sigma}\right)^{1-\frac{1}{\sigma}} - (1 - \sigma)\left(\frac{\chi + T}{1 - \sigma}\right)^{1-\frac{1}{\sigma}}\right] \\
&= \sigma(1 - \mu g)\left(\frac{\chi + T}{1 - \sigma}\right)^{1-\frac{1}{\sigma}} \\
&= \sigma(1 - \mu g)\kappa(T)
\end{aligned} \tag{50}$$

A.1.3. Externality

The negative external effect $\lambda\bar{Y}$ which is part of the utility function depends on the total production of brown goods $\bar{Y}$.

$$\begin{aligned}
\lambda\bar{Y} &= \lambda\int_{\gamma}^{1} Y(i)\, di \qquad | \text{ with } (43) \\
&= \lambda(1 - \gamma)(1 - \mu g)P(i)^{-\frac{1}{\sigma}} \qquad | \text{ with } (49) \\
&= \lambda(1 - \gamma)(1 - \mu g)\left(\frac{\chi + T}{1 - \sigma}\right)^{-\frac{1}{\sigma}} \\
&= \lambda(1 - \gamma)(1 - \mu g)\kappa(T)^{\frac{1}{1-\sigma}}
\end{aligned} \tag{51}$$

A.1.4. Tax revenues

$$\begin{aligned}
G &= t\int_{0}^{\gamma} y(i)di + T\int_{\gamma}^{1} Y(i)di \\
&= t\gamma y(i) + T(1 - \gamma)Y(i) \qquad | \text{ with } (42), (43) \\
&= t\gamma(1 + \mu g)p(i)^{-\frac{1}{\sigma}} + T(1 - \gamma)(1 - \mu g)P(i)^{-\frac{1}{\sigma}} \qquad | \text{ with } (45), (49) \\
&= t\gamma(1 + \mu g)\left(\frac{\chi + \zeta + t}{1 - \sigma}\right)^{-\frac{1}{\sigma}} + T(1 - \gamma)(1 - \mu g)\left(\frac{\chi + T}{1 - \sigma}\right)^{-\frac{1}{\sigma}} \\
&= t\gamma(1 + \mu g)\kappa(\zeta + t)^{\frac{1}{1-\sigma}} + T(1 - \gamma)(1 - \mu g)\kappa(T)^{\frac{1}{1-\sigma}}.
\end{aligned} \tag{52}$$

A.1.5. Welfare

Reordering the budget constraint of green citizens with income R yields their demand for the numeraire good x_g.

$$\begin{aligned}
x_g &= R - \int_{0}^{\gamma} p(i)y_g(i)di - \int_{\gamma}^{1} P(i)Y_g(i)di \\
&= R - \gamma p(i)y_g(i) - (1 - \gamma)P(i)Y_g(i) \qquad | \text{ with } (37), (38) \\
&= R - \gamma(1 + g)p(i)^{1-\frac{1}{\sigma}} - (1 - \gamma)(1 - g)P(i)^{1-\frac{1}{\sigma}} \qquad | \text{ with } (45), (49), (47) \\
&= R - \gamma(1 + g)\kappa(\zeta + t) - (1 - \gamma)(1 - g)\kappa(T).
\end{aligned} \tag{53}$$

Inserting the demands for green and brown goods (37), (38), and for the numeraire (53) into the utility function of green citizens (35) yields

$$\begin{aligned}
U_g &= \frac{1}{1 - \sigma}\left[\gamma(1 + g)^{\sigma}y_g(i)^{1-\sigma} + (1 - \gamma)(1 - g)^{\sigma}Y_g(i)^{1-\sigma}\right] + x_g - \lambda\bar{Y} \\
&= \frac{1}{1 - \sigma}\left[\gamma(1 + g)\kappa(\zeta + t) + (1 - \gamma)(1 - g)\kappa(T)\right] + x_g - \lambda\bar{Y} \\
&= \frac{\sigma}{1 - \sigma}\left[\gamma(1 + g)\kappa(\zeta + t) + (1 - \gamma)(1 - g)\kappa(T)\right] + R - \lambda\bar{Y}.
\end{aligned} \tag{54}$$

Similarly, the utility of brown citizens given by

$$U_b = \frac{\sigma}{1 - \sigma}\left[\gamma\kappa(\zeta + t) + (1 - \gamma)\kappa(T)\right] + R - \lambda\bar{Y}. \tag{55}$$

The income R consists of endowment I, tax revenue (52), and profits (46), (50).

$$\begin{aligned}
R &= I + G + \int_{0}^{\gamma} \pi(i)di + \int_{\gamma}^{1} \Pi(i)di \\
&= I + t\gamma(1 + \mu g)\kappa(\zeta + t)^{\frac{1}{1-\sigma}} + T(1 - \gamma)(1 - \mu g)\kappa(T)^{\frac{1}{1-\sigma}} \\
&\quad + \gamma\sigma(1 + \mu g)\kappa(\zeta + t) - \frac{\gamma^2 m}{2} + (1 - \gamma)\sigma(1 - \mu g)\kappa(T)
\end{aligned} \tag{56}$$

The welfare function consists of the utilities of all citizens, using (54), (55), (56), (51).

$$\begin{aligned}
\Omega &= \mu U_g + (1 - \mu)U_b \\
&= \mu\frac{\sigma}{1 - \sigma}\left[\gamma(1 + g)\kappa(\zeta + t) + (1 - \gamma)(1 - g)\kappa(T)\right] \\
&\quad + (1 - \mu)\frac{\sigma}{1 - \sigma}\left[\gamma\kappa(\zeta + t) + (1 - \gamma)\kappa(T)\right] + R - \lambda\bar{Y} \\
&= \frac{\sigma}{1 - \sigma}\left[\gamma(1 + \mu g)\kappa(\zeta + t) + (1 - \gamma)(1 - \mu g)\kappa(T)\right] + R - \lambda\bar{Y} \\
&= \frac{\sigma}{1 - \sigma}\left[\gamma(1 + \mu g)\kappa(\zeta + t) + (1 - \gamma)(1 - \mu g)\kappa(T)\right] \\
&\qquad + I + t\gamma(1 + \mu g)\kappa(\zeta + t)^{\frac{1}{1-\sigma}} + T(1 - \gamma)(1 - \mu g)\kappa(T)^{\frac{1}{1-\sigma}} \\
&\qquad + \gamma\sigma(1 + \mu g)\kappa(\zeta + t) - \frac{\gamma^2 m}{2} + (1 - \gamma)\sigma(1 - \mu g)\kappa(T) \\
&\qquad - \lambda(1 - \gamma)(1 - \mu g)\kappa(T)^{\frac{1}{1-\sigma}} \\
&= \gamma(1 + \mu g)\left[\left(\frac{\sigma}{1 - \sigma} + \sigma\right)\kappa(\zeta + t) + t\kappa(\zeta + t)^{\frac{1}{1-\sigma}}\right] \\
&\qquad + (1 - \gamma)(1 - \mu g)\left[\left(\frac{\sigma}{1 - \sigma} + \sigma\right)\kappa(T) + (T - \lambda)\kappa(T)^{\frac{1}{1-\sigma}}\right] + I - \frac{\gamma^2 m}{2}
\end{aligned} \tag{57}$$

The first part in square brackets is

$$\begin{aligned}
w(\zeta + t) &= \left(\frac{\sigma}{1 - \sigma} + \sigma\right)\kappa(\zeta + t) + t\kappa(\zeta + t)^{\frac{1}{1-\sigma}} \\
&= \frac{(2 - \sigma)\sigma}{1 - \sigma}\kappa(\zeta + t) + \frac{1 - \sigma}{1 - \sigma}(\chi + \zeta + t)\kappa(\zeta + t)^{\frac{1}{1-\sigma}} - (\chi + \zeta)\kappa(\zeta + t)^{\frac{1}{1-\sigma}} \\
&= \frac{(2 - \sigma)\sigma}{1 - \sigma}\kappa(\zeta + t) + (1 - \sigma)\kappa(\zeta + t) - (\chi + \zeta)\kappa(\zeta + t)^{\frac{1}{1-\sigma}} \\
&= \frac{1}{1 - \sigma}\kappa(\zeta + t) - (\chi + \zeta)\kappa(\zeta + t)^{\frac{1}{1-\sigma}}.
\end{aligned} \tag{58}$$

The second part in square brackets is

$$W(T) = \left(\frac{\sigma}{1 - \sigma} + \sigma\right)\kappa(T) + (T - \lambda)\kappa(T)^{\frac{1}{1-\sigma}}$$

$$= \frac{(2-\sigma)\sigma}{1-\sigma}\kappa(T) + \frac{1-\sigma}{1-\sigma}(\chi+T)\kappa(T)^{\frac{1}{1-\sigma}} - (\chi+\lambda)\kappa(T)^{\frac{1}{1-\sigma}}$$
$$= \frac{(2-\sigma)\sigma}{1-\sigma}\kappa(T) + (1-\sigma)\kappa(T) - (\chi+\lambda)\kappa(T)^{\frac{1}{1-\sigma}}$$
$$= \frac{1}{1-\sigma}\kappa(T) - (\chi+\lambda)\kappa(T)^{\frac{1}{1-\sigma}}. \tag{59}$$

A.1.6. Green utility advantage

The difference in utility of holding green instead of brown preferences is given by the utility advantage.

$$\Delta = U_g - U_b \quad | \text{ with (54), (55)}$$
$$= \frac{\sigma g}{1-\sigma}\left[\gamma\kappa(\zeta+t) - (1-\gamma)\kappa(T)\right] \tag{60}$$

A.1.7. Total market size

The total production is given by

$$\mu x_g + (1-\mu)x_b + \gamma y(i) + (1-\gamma)Y(i) \tag{61}$$

with demand for green and brown products (42), (43) and demand for the numeraire (53) (with R given in (56)).

A.2. Proof of Proposition 1

With continuous time and infinite horizon, we solve the following current value Hamiltonian:

$$H = \Omega(\mu(s),\gamma(s),T(s)) + \psi(s)h(\mu(s),\gamma(s),T(s)) + \alpha(s)f(\mu(s),\gamma(s),T(s)) \tag{62}$$

with $\dot{\mu} = h(\mu(s),\gamma(s),T(s))$, and $\dot{\gamma} = f(\mu(s),\gamma(s),T(s))$

$\dot{\mu}$ and $\dot{\gamma}$ are time derivatives.

Deriving $\dot{T}$. Necessary conditions:

$$\frac{\partial\Omega}{\partial T} + \psi(s)\frac{\partial h}{\partial T} + \alpha(s)\frac{\partial f}{\partial T} = 0 \tag{63}$$
$$\dot{\psi} = -\left(\frac{\partial\Omega}{\partial\mu} + \psi(s)(\frac{\partial h}{\partial\mu} - \beta) + \alpha(s)\frac{\partial f}{\partial\mu}\right) \tag{64}$$
$$\dot{\alpha} = -\left(\frac{\partial\Omega}{\partial\gamma} + \psi(s)\frac{\partial h}{\partial\gamma} + \alpha(s)(\frac{\partial f}{\partial\gamma} - \beta)\right) \tag{65}$$

The boundary conditions are

$$\lim_{S\to\infty}\psi(S) = 0 \tag{66}$$
$$\lim_{S\to\infty}\alpha(S) = 0 \tag{67}$$

Time-differentiating Eq. (63) yields:

$$\frac{d}{ds}\left(\frac{\partial\Omega}{\partial T}\right) + \frac{d}{ds}\left(\psi\frac{\partial h}{\partial T}\right) + \frac{d}{ds}\left(\alpha\frac{\partial f}{\partial T}\right) = 0 \tag{68}$$
$$\Leftrightarrow \frac{\partial^2\Omega}{\partial\mu\partial T}h + \frac{\partial^2\Omega}{\partial\gamma\partial T}f + \frac{\partial^2\Omega}{\partial T^2}\dot{T} + \dot{\psi}\frac{\partial h}{\partial T} + \psi\left(\frac{\partial^2 h}{\partial\mu\partial T}h + \frac{\partial^2 h}{\partial\gamma\partial T}f + \frac{\partial^2 h}{\partial T^2}\dot{T}\right)$$
$$+ \dot{\alpha}\frac{\partial f}{\partial T} + \alpha\left(\frac{\partial^2 f}{\partial\mu\partial T}h + \frac{\partial^2 f}{\partial\gamma\partial T}f + \frac{\partial^2 f}{\partial T^2}\dot{T}\right) = 0 \tag{69}$$

Substituting $\dot{\alpha}$ and $\dot{\psi}$ by Eqs. (65) and (64):

$$\Leftrightarrow \frac{\partial^2\Omega}{\partial\mu\partial T}h + \frac{\partial^2\Omega}{\partial\gamma\partial T}f + \frac{\partial^2\Omega}{\partial T^2}\dot{T} - \left(\frac{\partial\Omega}{\partial\mu} + \psi(\frac{\partial h}{\partial\mu} - \beta) + \alpha\frac{\partial f}{\partial\mu}\right)\frac{\partial h}{\partial T}$$
$$- \left(\frac{\partial\Omega}{\partial\gamma} + \psi\frac{\partial h}{\partial\gamma} + \alpha(\frac{\partial f}{\partial\gamma} - \beta)\right)\frac{\partial f}{\partial T} + \psi\left(\frac{\partial^2 h}{\partial\mu\partial T}h + \frac{\partial^2 h}{\partial\gamma\partial T}f + \frac{\partial^2 h}{\partial T^2}\dot{T}\right)$$
$$+ \alpha\left(\frac{\partial^2 f}{\partial\mu\partial T}h + \frac{\partial^2 f}{\partial\gamma\partial T}f + \frac{\partial^2 f}{\partial T^2}\dot{T}\right) = 0 \tag{70}$$

Finally, we solve for $\dot{T}$:

$$\left(\frac{\partial^2\Omega}{\partial T^2} + \psi\frac{\partial^2 h}{\partial T^2} + \alpha\frac{\partial^2 f}{\partial T^2}\right)\dot{T} + \frac{\partial^2\Omega}{\partial\mu\partial T}h + \frac{\partial^2\Omega}{\partial\gamma\partial T}f$$
$$- \left(\frac{\partial\Omega}{\partial\mu} + \psi(\frac{\partial h}{\partial\mu} - \beta) + \alpha\frac{\partial f}{\partial\mu}\right)\frac{\partial h}{\partial T}$$
$$- \left(\frac{\partial\Omega}{\partial\gamma} + \psi\frac{\partial h}{\partial\gamma} + \alpha(\frac{\partial f}{\partial\gamma} - \beta)\right)\frac{\partial f}{\partial T}$$
$$+ \psi\left(\frac{\partial^2 h}{\partial\mu\partial T}h + \frac{\partial^2 h}{\partial\gamma\partial T}f\right) + \alpha\left(\frac{\partial^2 f}{\partial\mu\partial T}h + \frac{\partial^2 f}{\partial\gamma\partial T}f\right) = 0 \tag{71}$$

With $\eta = \left(\frac{\partial\Omega}{\partial\mu} + \psi(\frac{\partial h}{\partial\mu} - \beta) + \alpha\frac{\partial f}{\partial\mu}\right)$ and $\phi = \left(\frac{\partial\Omega}{\partial\gamma} + \psi\frac{\partial h}{\partial\gamma} + \alpha(\frac{\partial f}{\partial\gamma} - \beta)\right)$, we have:

$$\Leftrightarrow \dot{T} = -\frac{h\frac{\partial\eta}{\partial T} + f\frac{\partial\phi}{\partial T} - \eta\frac{\partial h}{\partial T} - \phi\frac{\partial f}{\partial T}}{\frac{\partial^2\Omega}{\partial T^2} + \psi\frac{\partial^2 h}{\partial T^2} + \alpha\frac{\partial^2 f}{\partial T^2}}. \tag{72}$$

A.3. Proof of Corollary 1

By assumption, functions Ω, h, and f are concave in T, so the denominator of Eq. (72) is negative, i.e. $\frac{\partial^2\Omega}{\partial T^2} + \psi\frac{\partial^2 h}{\partial T^2} + \alpha\frac{\partial^2 f}{\partial T^2} < 0$.

We then have that

$$\dot{T} \le 0 \Leftrightarrow h\frac{\partial\eta}{\partial T} + f\frac{\partial\phi}{\partial T} \le \eta\frac{\partial h}{\partial T} + \phi\frac{\partial f}{\partial T} \tag{73}$$
$$\Leftrightarrow h\frac{\partial\eta}{\partial T} - \eta\frac{\partial h}{\partial T} + f\frac{\partial\phi}{\partial T} - \phi\frac{\partial f}{\partial T} \le 0 \tag{74}$$

We note that $\frac{\partial(\eta/h)}{\partial T} = (h\frac{\partial\eta}{\partial T} - \eta\frac{\partial h}{\partial T})/h^2$ and $\frac{\partial(\phi/f)}{\partial T} = (f\frac{\partial\phi}{\partial T} - \phi\frac{\partial f}{\partial T})/f^2$. Substituting these expressions in Eq. (74) yields:

$$\dot{T} \le 0 \Leftrightarrow h^2\frac{\partial(\eta/h)}{\partial T} + f^2\frac{\partial(\phi/f)}{\partial T} \le 0 \tag{75}$$

A.4. Calculation of welfare differences in discrete time

Welfare differences are calculated using the following formula.

$$\frac{\sum\Omega_{\text{changed}} - \sum\Omega_{\text{base case}}}{\sum\Omega_{\text{base case}}}\cdot 100\% \tag{76}$$

The welfare time series are normalized by the welfare in the case without any tax with standard parameter set.

$$\sum\Omega_{\text{changed}} = \sum_{s=0}^{S}\beta^s\left[\Omega_{\text{s, changed}} - \Omega_{\text{s, no tax}}\right] \tag{77}$$
$$\sum\Omega_{\text{base case}} = \sum_{s=0}^{S}\beta^s\left[\Omega_{\text{s, base case}} - \Omega_{\text{s, no tax}}\right] \tag{78}$$

Appendix B. Optimization algorithm

The python code used for the optimization is available at https://github.com/loooorenz/GreenTransitionTaxation.

B.1. Global maximum verification

The simulation outputs the entire value function over a bounded interval (see Fig. 3). During the backward induction algorithm, the value function $V(T)$ consisting of current and future welfare is maximized by choosing the optimal tax rate $T \in [0,20]$ many times: for every period, for every (μ,γ) on a grid between 0 and 1, and for all parameter sets. Note that this simply is a bounded one-dimensional optimization problem. Since $V(T)$ is defined piecewise (due to the contained interpolations) and is not necessarily concave, we still confirm that the Scipy optimizer has always converged to a global maximum. If so, the whole trajectory is optimal since the subsequent periods have already been optimized before.

To check global optimality of $V(T)$, $T \in [0,20]$, we use the straightforward approach of calculating $V(T)$ for many different values of T and choosing the maximum. The corresponding T is then compared to T^* from the optimization. The used code "global_maximum_check.py" can be found in the repository as well.

In all considered cases, the global maximum has been found. Either the difference in T^* is insignificant (present due to a limited resolution when discretizing T), or the difference in $V(T^*)$ is insignificant. The

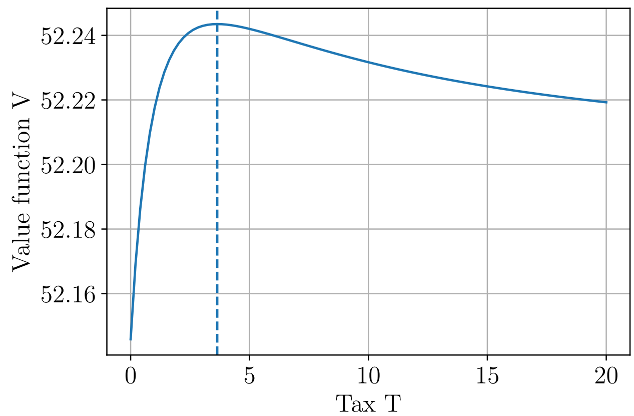


Fig. 3. Value function at period 0 over tax T and optimization result (dotted line) for base case parameters.

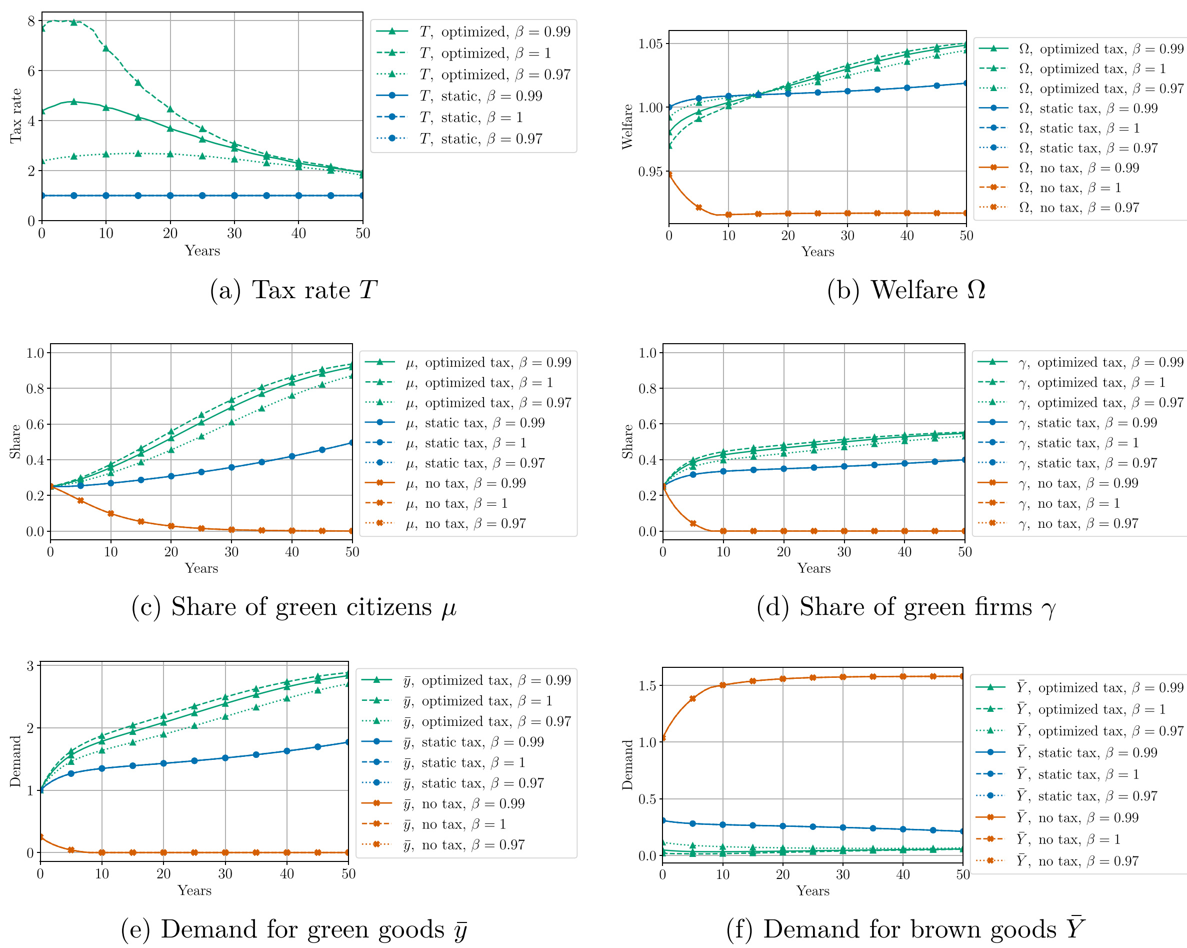


Fig. 4. Change in discount rate β. Note: Tax rate, welfare, and demand are normalized by their initial value with a static tax and the basecase parameters.

latter is the case when $V(T)$ is very flat (which occurs, e.g., in unrealistic edge-cases like $\mu \approx 0, \gamma \approx 1$, i.e., no green preferences but only green firms).

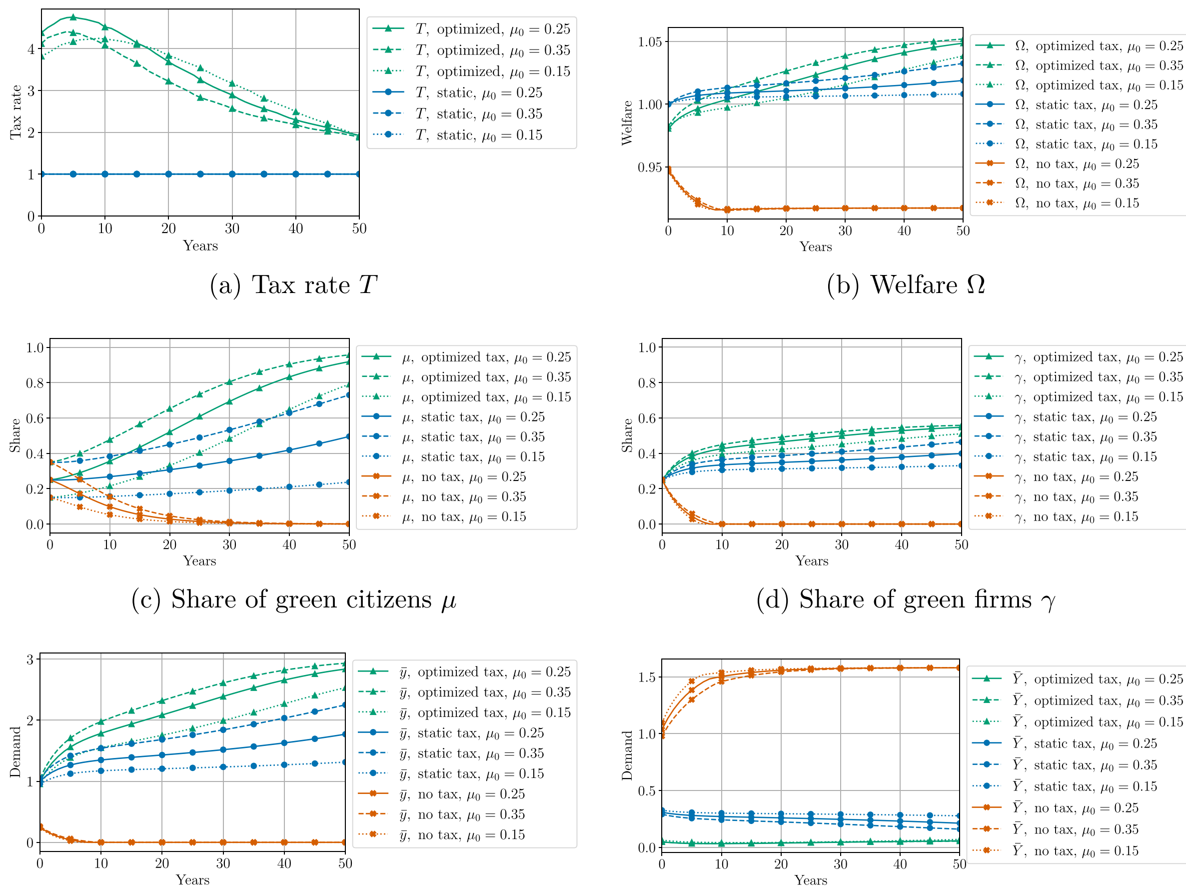
Appendix C. Sensitivity analysis

The following figures show deviations of the model parameters.

Data availability

See Research Data attachment with link to an external repository

10.17632/n9ddyhmwdp.1 (Original data) (Mendeley Data)



(a) Tax rate T (b) Welfare Ω

(c) Share of green citizens μ (d) Share of green firms γ

(e) Demand for green goods $\bar{y}$ (f) Demand for brown goods $\bar{Y}$

Fig. 5. Change in initial share of green citizens μ_0.
Note: Tax rate, welfare, and demand are normalized by their initial value with a static tax and the basecase parameters.

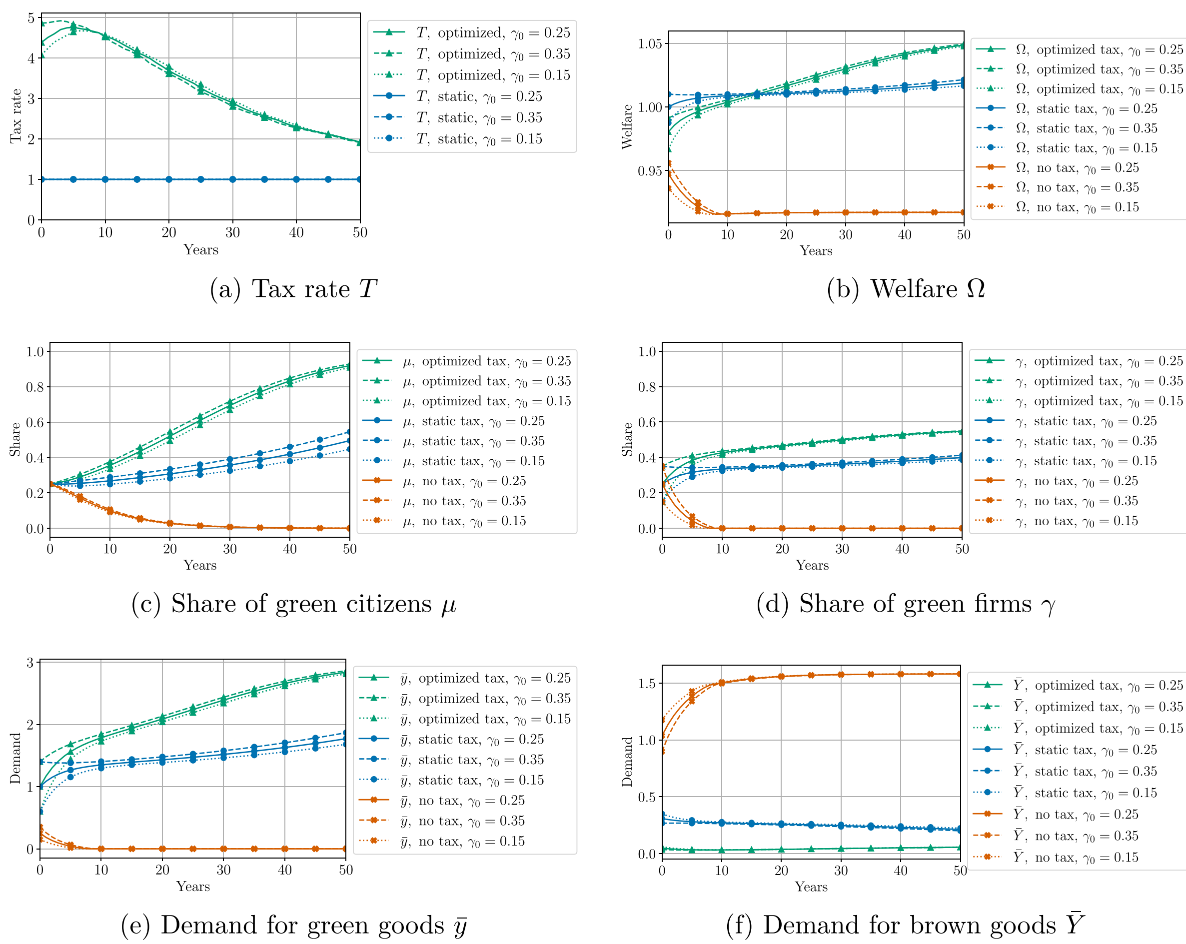
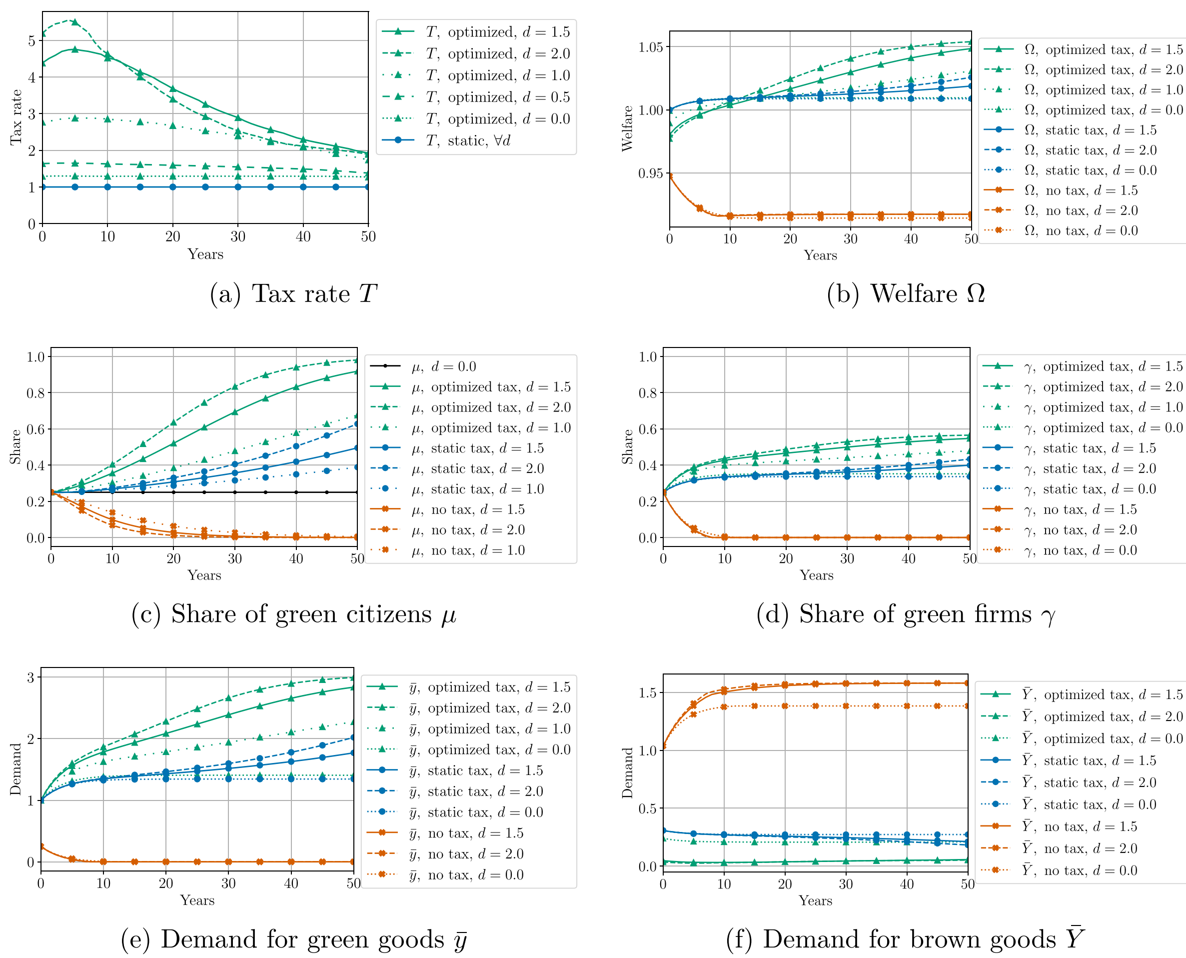


Fig. 6. Change in initial share of green firms γ_0.
Note: Tax rate, welfare, and demand are normalized by their initial value with a static tax and the basecase parameters.

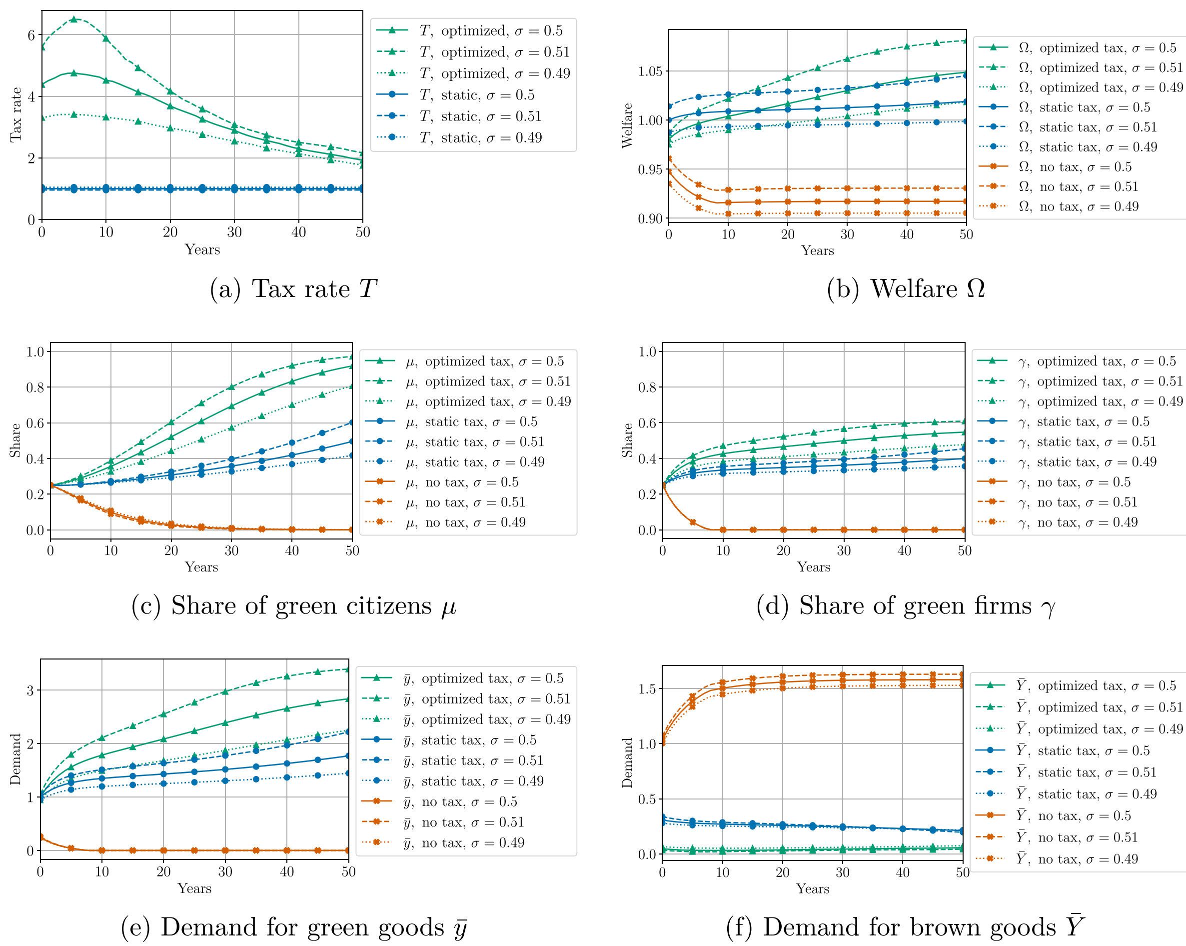


(a) Tax rate T (b) Welfare Ω

(c) Share of green citizens μ (d) Share of green firms γ

(e) Demand for green goods $\bar{y}$ (f) Demand for brown goods $\bar{Y}$

Fig. 7. Change in value transition speed d.
Note: Tax rate, welfare, and demand are normalized by their initial value with a static tax and the basecase parameters.



(a) Tax rate T

(b) Welfare Ω

(c) Share of green citizens μ

(d) Share of green firms γ

(e) Demand for green goods $\bar{y}$

(f) Demand for brown goods $\bar{Y}$

Fig. 8. Change in substitution elasticity σ.
Note: Tax rate, welfare, and demand are normalized by their initial value with a static tax and the basecase parameters.

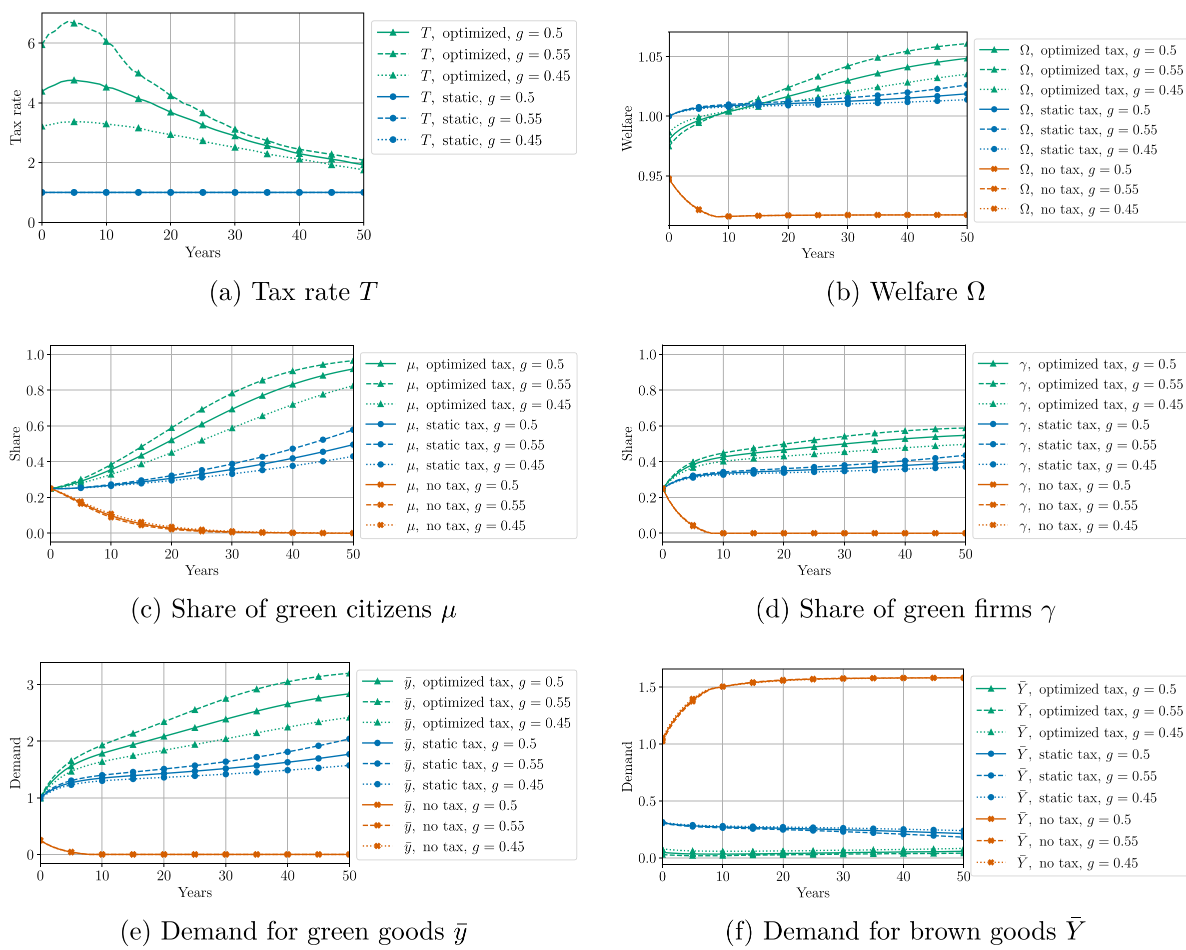
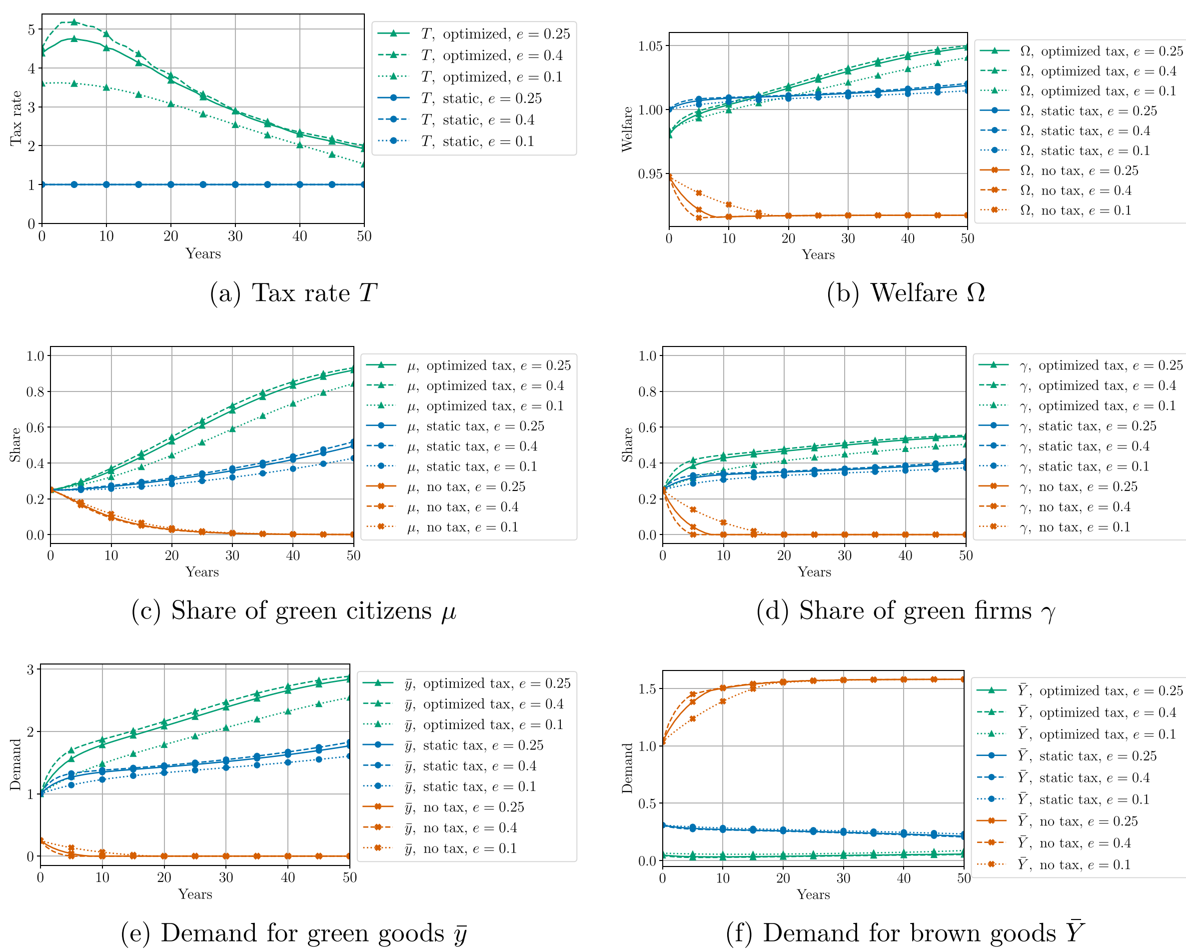


Fig. 9. Change in preference shift g. Note: Tax rate, welfare, and demand are normalized by their initial value with a static tax and the basecase parameters.

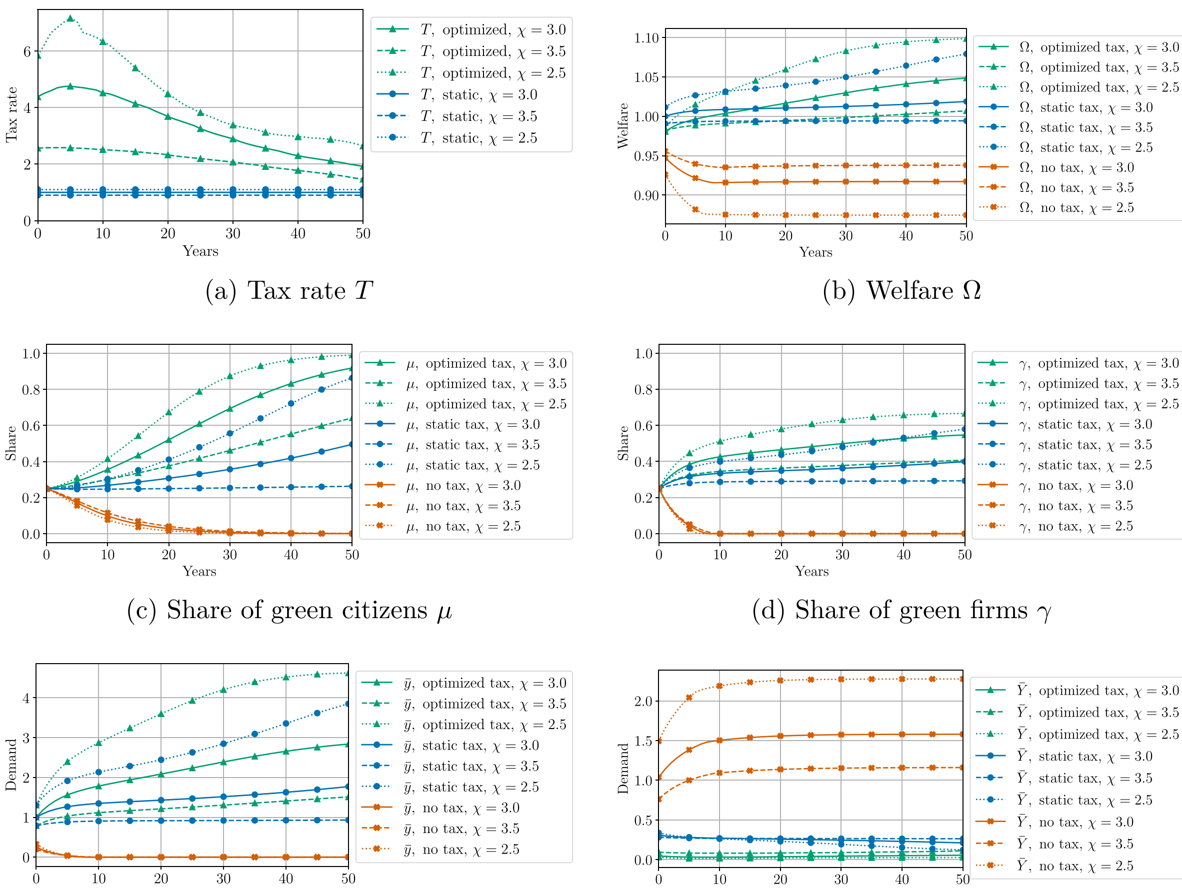


(a) Tax rate T (b) Welfare Ω

(c) Share of green citizens μ (d) Share of green firms γ

(e) Demand for green goods $\bar{y}$ (f) Demand for brown goods $\bar{Y}$

Fig. 10. Change in technology transition speed e.
Note: Tax rate, welfare, and demand are normalized by their initial value with a static tax and the basecase parameters.



(a) Tax rate T

(b) Welfare Ω

(c) Share of green citizens μ

(d) Share of green firms γ

(e) Demand for green goods $\bar{y}$

(f) Demand for brown goods $\bar{Y}$

Fig. 11. Change in marginal costs χ. Note: Tax rate, welfare, and demand are normalized by their initial value with a static tax and the basecase parameters.

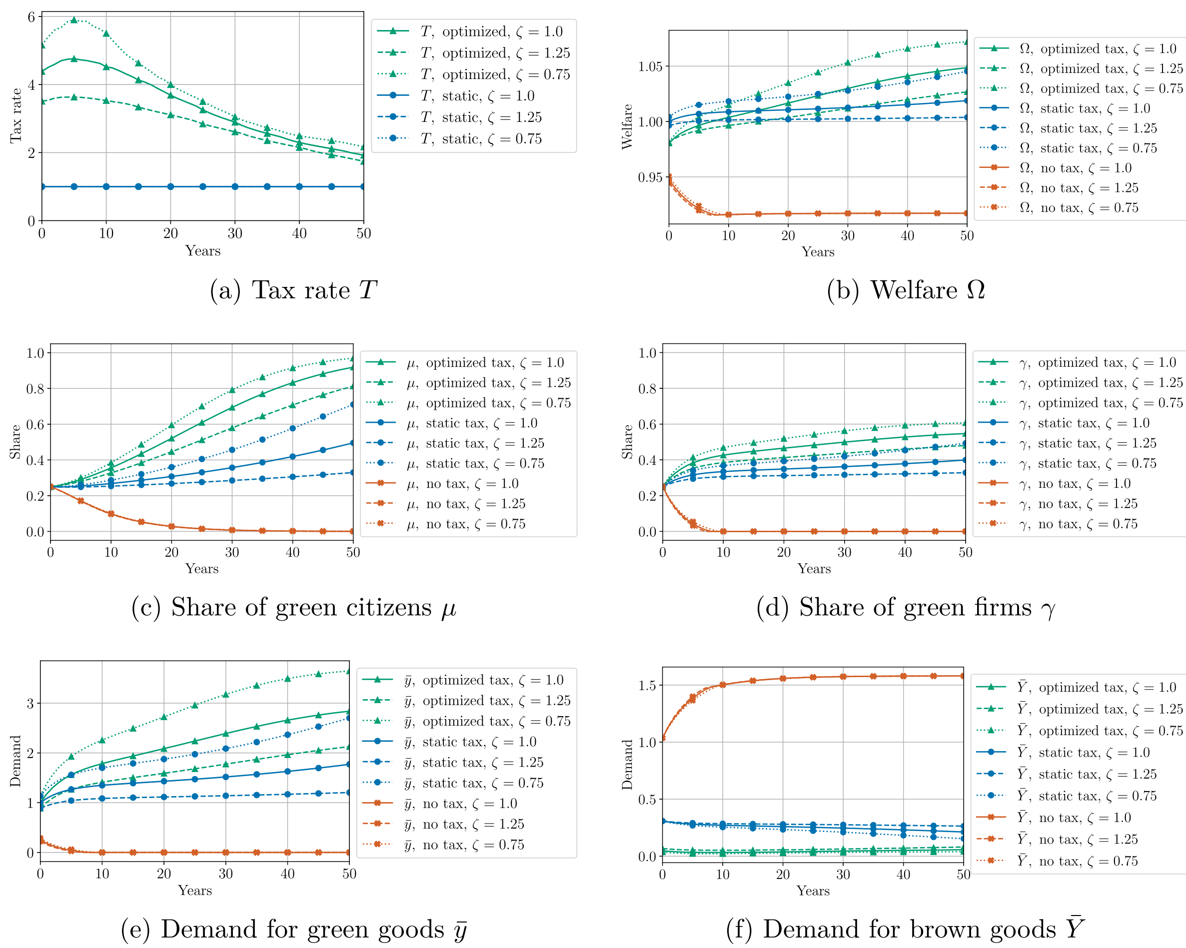


Fig. 12. Change in green marginal costs ζ.
Note: Tax rate, welfare, and demand are normalized by their initial value with a static tax and the basecase parameters.

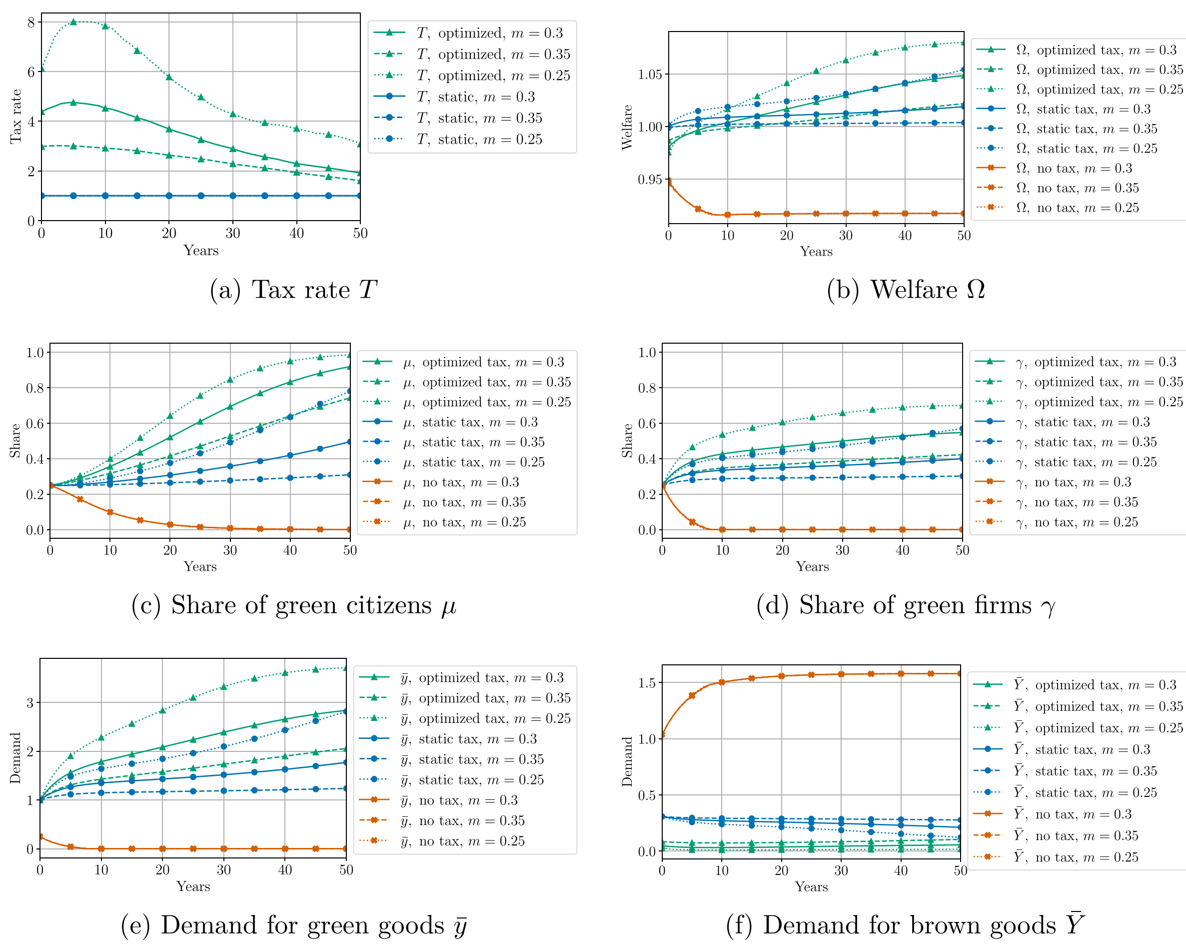
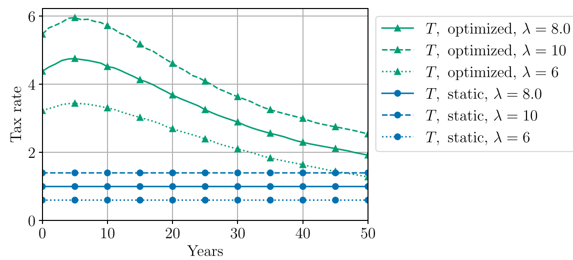
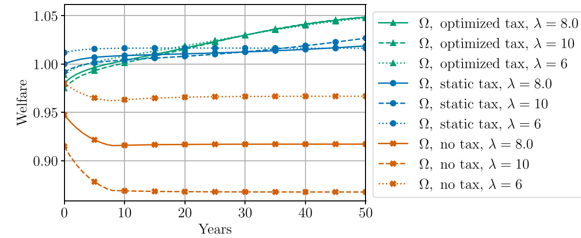


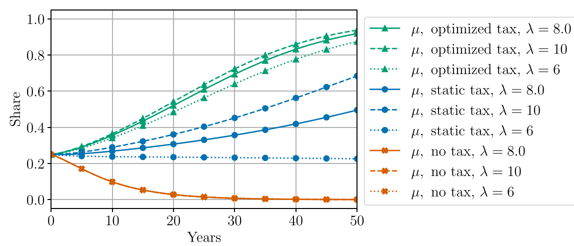
Fig. 13. Change in green fixed costs *m*.
Note: Tax rate, welfare, and demand are normalized by their initial value with a static tax and the basecase parameters.



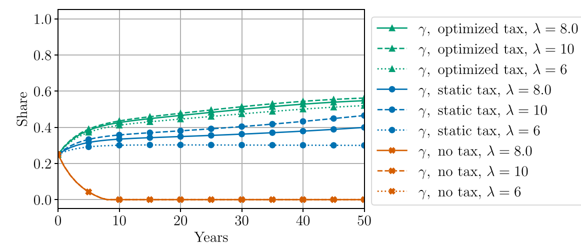
(a) Tax rate T



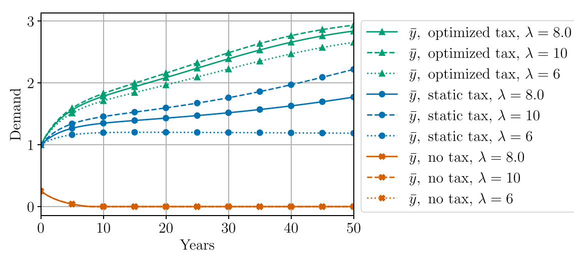
(b) Welfare Ω



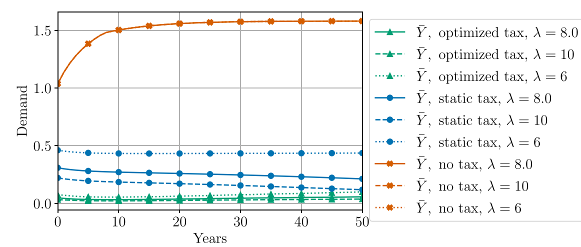
(c) Share of green citizens μ



(d) Share of green firms γ



(e) Demand for green goods $\bar{y}$



(f) Demand for brown goods $\bar{Y}$

Fig. 14. Change in externality λ. Note: Tax rate, welfare, and demand are normalized by their initial value with a static tax and the basecase parameters.

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