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Endogenous preferences and environmental policy

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Abstract:

This paper investigates environmental policy in the presence of endogenous preferences. The optimal time trajectory is achieved if and only if the consumer is perfectly time-consistent. The suboptimal trajectories do not only differ from the optimal path during the transition between two equilibria, but also the new stationary states differ. A key difference is more pollution in the suboptimal equilibrium. If the consumer is less than perfectly time-consistent, the standard Pigou tax can be complimented with taxes and subsidies to implement the optimal time trajectory. If this option is unavailable to the regulator, a second-best option is a single tax that is above the Pigouvian level. The results in this paper indicate that the integrated assessment models used by the Intergovernmental Panel on Climate Change (IPCC) to derive optimal emission paths may recommend too high carbon emissions.

Keywords: Regulation, Endogenous preferences, habits.

JEL classification: H23, H31, D15, Q54.

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Sammendrag

Preferansene og vanene som bestemmer dagens handlinger er i mange tilfeller avhengige av tidligere valg. I denne artikkelen undersøker jeg hvordan vaner og endogene preferanser påvirker utformingen av miljøpolitikk. Et viktig funn er at den optimale prisen på utslipp gjerne er høyere enn den marginale miljøskaden utslippene forårsaker når preferansene er endogene. Dette skyldes at prisen på utslipp nå har to effekter: (i) internalisere miljøskaden fra produksjon, og (ii) påvirke fremtidige preferanser via dagens konsum. Mens (i) alene leder til den vanlige Pigou-skatten vil en eventuell tilstedeværelse av (ii) innebære at den optimale skatten er heves ytterligere. Lavere konsum av et forurensende gode i dag kan en også redusere ønsket eller avhengigheten av å konsumere dette godet i fremtiden. Det synes rimelig å vente at mekanisme (ii) kan være relevant for tema som kjøttkonsum, transport og en del fritidsaktiviteter, og mindre relevant i andre tilfeller. Resultatene indikerer at en bør være forsiktige med å subsidiere forurensende goder. Årsaken er at subsidiene ikke bare fører til økt forurensing i dag, men også økt etterspørsel etter de forurensende godene i fremtiden. Resultatene i dette paperet trekker i retning av at IAM modellene brukt av FN's klimapanel foreslår for høye utslipp av klimagasser.

1 Introduction

The standard approach in intertemporal economic models is to maximize the present value of the sum (or integral) of a given utility function over the time horizon. Whereas the arguments in the utility function may change over time, the functional form and its parameters remain constant. The assumption of a constant utility function is arguably at odds with our intuition that preferences and current decisions depend on previous experiences and choices.[1]

In this paper I investigate environmental policy in the presence of endogenous and time-inconsistent preferences. Endogenous preferences have a substantial impact on the model dynamics, because current actions influence future preferences and thereby utility. The foresighted consumer will take this into account when determining current actions. The optimal time trajectory is achieved if and only if the consumer is perfectly time-consistent. The reason is that endogenous preferences put a shadow price on consumption, and these shadow prices depend on the valuation of the future. The suboptimal trajectories do not only differ from the optimal path during the transition phase between two equilibria, but also the consumption levels in the new stationary states differ. A key difference is more pollution in the suboptimal equilibrium. The optimal tax scheme requires a combination of taxes and subsidies (unless the consumer is perfectly time-consistent), which may not be available to the regulator. In the case of environmental policy, a second-best option is a single tax that is above the Pigouvian level (to compensate for the lack of subsidies to substitute goods under the optimal tax scheme).

The results in this paper indicate that models used to derive optimal paths towards the low-emission society, without taking endogenous preferences into account, may recommend too high emissions. This is not without relevance as, e.g., the integrated assessment models (IAM) used by the Intergovernmental Panel on Climate Change (IPCC) to derive optimal paths towards the low-emission society feature fixed preferences (IPCC, 2014; Rogelj et al., 2018).

This paper is relevant when current consumption affects future preferences (e.g., habit formation or changes in tastes). Whereas this is arguably the case for, e.g., food consumption, drugs, leisure activities, health and musical tastes, it may be less important for other issues. To fix thoughts, parts of the analysis are framed in a setting where red meat consumption declines over time to reduce emissions of greenhouse gases.[2] This is arguably

[1] "It is nonsense to assume that successive consumptions are independent; the normal condition is that there is strong complementarity between them" (Hicks, 1965, p. 261).

[2] Atkin (2013) firmly rejects the hypothesis of no habit formation (i.e., Atkin rejects the hypothesis that preferences do not depend on past relative prices) in the case of food consumption in India.

an important example: A recent UN climate change report (IPCC, 2019) estimates that, by 2050, dietary changes involving less red meat consumption could free up several million square kilometres of land and reduce global CO2 emissions by up to eight billion tons per year, relative to business as usual. This is roughly equal to the emissions that where avoided in 2018 through global use of nuclear power, assuming nuclear power plants replace fossil fueled power plants (Nature, 2019). Another case is the transport sector. For example, you may start to like cycling to work if you use a bicycle instead of a car or public transport for a period of time. A third example could be the choice between polluting leisure activities (e.g., shopping or long-distance travel) and other less polluting leisure activities (e.g., music or outdoor life). The issue of endogenous preferences may be particularly relevant in contexts where the time horizon is long, like the case of climate change.

There is a small literature on endogenous preferences and environmental policy. Mattach et al. (2018) show (in a static model) that, when the introduction of a carbon tax changes consumers' values, the target-compatible carbon price must be adjusted by the size of this effect. This paper differs from Mattach et al. (2018) in several ways. In particular, the present paper has a dynamic model and preferences are determined by the consumer's own consumption choices in previous periods. Mattauch and Hepburn (2016) discuss normative issues with regulation and climate policy in a setting where policy measures influence people's preferences.

Gorman (1967) examines conditions for a stable long-run equilibrium when preferences are endogenous. Bowles (1998) reviews models and evidence concerning impact of economic institutions on preferences, and discusses some implications for economic theory and policy analysis.[3] Van den Bijgaart (2018) studies consumption in the presence of endogenous habits and determines the path of taxes or subsidies that implements first-best consumption, both when goods are produced competitively and when they are produced by monopolists. Van den Bijgaart (2018) does not consider environmental policy and examines a process for habit formation that differs from the endogenous preferences in the present paper.

Whereas framed in a very different setting, the model mechanisms discussed in the present paper relates to the literature on rational addiction; see, e.g., Becker and Murphy (1988), Chaloupka (1991) and Becker (1996). There are many differences between the present paper and the rational addiction literature. In particular, the present paper features an environmental externality and models markets for several goods that are linked by the utility function and the budget constraint. The interaction between the different markets is important for the results. Moreover, whereas the rational

[3] Dasgupta et al. (2015) and Ulph and Ulph (2021) examine how social interactions affect consumer preferences and behavior in a setting with environmental damage. Perino (2015) shows that climate campaigns can create leakage effects if coverage of cap-and-trade schemes are incomplete.

addiction literature tends to focus on the case where the consumer rationally internalizes the addiction caused by consumption of drugs, the present paper focuses on the case where the consumer fails to internalize the endogenous preference formation. In this respect, Nobel Laureate George A. Akerlof states the following regarding endogenous preferences and consumer foresight: "Standard economic analysis is based upon the Benthamite view that individuals have fixed utilities which do not change. Stigler-Becker and Becker-Murphy have gone so far as to posit that these utilities do change, but that individuals are forward looking and thus foresee the changes that will occur. A more modern view of behavior, based on twentieth-century anthropology, psychology, and sociology is that individuals have utilities that do change and, in addition, they fail fully to foresee those changes or even recognize that they have occurred." (Akerlof, 1991, p. 17). I refer to Kahneman and Tversky (1979), Kahneman et al. (1991) and Cartwright (2011) for further discussion on perfectly informed and rational human behavior.

Endogenous preferences have so far received limited attention in the literature on environmental economics and climate change, but the results in the present paper are somewhat similar to the mechanisms that occur in the case of convex investment costs, a private discount rate that is above the social discount rate, and long-lived capital (see Storrøsten, 2020). A contribution to the environmental economics literature given by the present paper is that the optimal emission tax is above marginal environmental damage in cases where preferences are determined by earlier consumption and experiences. This implies that emissions will be above the optimal emissions level with standard Pigouvian taxes in these cases.

The analytical analysis is in Section 2. Endogenous preferences and time-inconsistent behavior have important effects on the consumer's intertemporal optimization whether a negative environmental externality is present or not. I therefore present the model without a negative externality first, and then introduce the externality in Section 2.1. Section 3 presents a stylized numerical illustration. It is primarily included to ease the understanding of the model dynamics. Section 4 concludes.

2 Theoretical analysis

Consider a partial equilibrium model with two goods x and d and $t \in T = \left\{1, 2, ..., \overline{t}\right\}$ time periods. The representative consumer has a constant elasticity of substitution (CES) utility function given by:

$$u\left(\cdot\right) = \left(\alpha x_t^{\rho} + \left(1-\alpha\right) d_t^{\rho}\right)^{\frac{1}{\rho}}, \tag{1}$$

in period t. Here the α's represent the value of consumption shares and the substitution elasticity between the two goods is $1/\left(1-\rho\right)$. Assume that d_t

is a composite good consisting of goods y_t and z_t such that:

$$d_t = \left(\beta_t y_t^{\theta} + (1-\beta_t)\, z_t^{\theta}\right)^{\frac{1}{\theta}}, \tag{2}$$

where β_t is value of consumption share in period t and the elasticity of substitution is $1/(1-\theta)$. We assume $\rho, \theta \neq 0$, $\rho, \theta < 1$ and $\alpha, \beta \in (0,1)$. The utility function $u(\cdot)$ given by equations (1) and (2) is a standard nested CES function, except for the time dependence of the consumption share parameter β_t.

In the following we will focus on the case where y_t and z_t are substitutes, but the formal analysis remains the same whether y_t and z_t are substitutes or complements. x_t is a composite good that represents all the other goods in the consumption bundle.

I let β_t be endogenous to capture endogenous preferences in the sense that the more of a given good you consume today, the more of that good you will prefer to consume in the future. As argued in the introduction, endogenous preferences will be relevant for some goods (e.g., food preferences, transport and recreational activities) and less important for other goods. In this paper, we will consider goods for which endogenous preferences is relevant for the value share β_t in the lower CES nest in equation (2). Let β_t be determined by the following process:

$$\beta_t = f(B_t), \tag{3}$$

where $f(\cdot)$ is an increasing function ($\partial f/\partial B_t \equiv f_B \in (0,1)$) satisfying $\lim_{B_t\to 1} f(B_t) < 1$ and $\lim_{B_t \to 0} f(B_t) > 0$ with:

$$B_{t+1} = B_t + \nu\left(\frac{y_t}{y_t+z_t} - B_t\right),\ B_0 = \overline{B}. \tag{4}$$

Here $v \in [0,1]$ and $\overline{B} \in (0,1)$ are constants. We define $\beta_0 = \overline{\beta} = f(\bar{B})$. The shape on $f(\cdot)$ determines how previous consumption choices affect the value of consumption share parameter β in equation (2). The restrictions on $f(\cdot)$ capture the assumption that the more of a given good you consume today, the more you will want to consume that good in the future. The difference equation (4) specifies the process for the function argument B_t in equation (3). The current value of B_t equals the previous value, B_{t-1}, plus a 'correction term'. The speed of the correction process is determined by ν. Specifically $B_t = y_{t-1}/(y_{t-1}+z_{t-1})$ for all $t \in T$ if $v = 1$, whereas $B_t = \overline{B}$ for all $t \in T$ if $v = 0$. Note that equation (4) implies that B_t converges towards $y_s/(y_s+z_s)$ when $v > 0$ and $y_s/(y_s+z_s)$ is constant ($s \in T,\ s > t$). The utility function in period $t \in T$ can be written (cf., equations 1, 2 and 3):

$$u(x_t, y_t, z_t; B_t) = \left(\alpha x_t^{\rho} + (1-\alpha)\left(f(B_t) y_t^{\theta} (1-f(B_t)) z_t^{\theta}\right)^{\frac{\rho}{\theta}}\right)^{\frac{1}{\rho}}. \tag{5}$$

The utility function (5) in itself remains constant, only consumption levels and the state variable B_t changes over the time horizon.

I assume that the goods x_t, y_t and z_t are supplied by competitive firms with constant returns to scale production technology. Hence the consumer prices in period t are given by $p_{gt} = s_g + \tau_{gt}$, where $g = \{x, y, z\}$ and s_g and τ_{gt} are marginal production costs and taxes on good g in period t, respectively.[4] Further, disposable income is given by $m_t = \overline{m} - \tau_{mt}$, where $\overline{m}$ is (finite) income and τ_{mt} is a lump-sum tax. A negative value on τ_{gt} indicates a subsidy to consumption, whereas $\tau_{mt} < 0$ indicates a lump sum transfer. The consumer's budget constraint is given by:

$$m_t \geq p_{xt}x_t + p_{yt}y_y + p_{zt}z_t. \tag{6}$$

Non-satiation in the CES utility function (5) implies that the budget constraint (6) must be binding in all periods.

The consumer maximizes the present value of utility over the whole time horizon, given perfect information about current and future prices and taxes. Traditional exponential discounting implies that human preferences are time-consistent. As pointed out by O'Donoghue and Rabin (1999, p. 103), casual observation, introspection, and psychological research all suggest that the assumption of time consistency is counterfactual. Specifically, it ignores the human tendency to grab immediate rewards and to avoid immediate costs. For example, suppose a person is given two choices. First, choose between one apple today and two apples tomorrow. Second, choose between one apple in one year and two apples in one year plus one day. While some people may be tempted to select one apple today on the first choice, no one would select one apple in a year in the second choice. Yet if the rate of discount is exponential and time consistent, the choices are formally identical.[5]

In this paper I will assume that the impatience described above is suboptimal. Specifically, I assume that optimal climate policy must be time-consistent. Whereas this is reasonable in the case of environmental regulation, and particularly in the case of climate change which will affect the earths' population several generations into the future, it may be more questionable applied to other issues (like musical tastes or recreational habits).[6]

Present-biased time-inconsistent preferences can be modelled using hyperbolic discounting. In this paper, I use a form developed by Phelps and

[4]It is equivalent whether the taxes are placed on the consumer or the producer in this model.

[5]This example is taken from Thaler (1981, p. 202), who refers to it as "Strotz's famous dynamic inequality" (see Strotz, 1955-56). See also Loewenstein (1992) on exponential discounting in economics.

[6]Exponential (and time-consistent) discounting has been criticized for putting very low values on future welfare (Karp, 2005). In this respect, note that the important driver in the present paper is just that the less than perfectly time-consistent consumer does not fully internalize the endogenous preference formation (the results are valid $\delta = 1$), and Proposition 2 and Corollary 2 are derived for a myopic consumer).

Pollak (1968) and later used by, e.g., O'Donoghue and Rabin (1999). The intertemporal utility function with hyperbolic discounting is given within the square brackets in equation (7) below. Here $\gamma \in [0,1]$ represents a bias for the present (if $\gamma < 1$), whereas $\delta \in (0,1]$ represents the standard exponential time consistent discounting. Note that, as seen from period s, the discount factor applied from period s to period $s+1$ is $\gamma\delta$, whereas the discount factor from period $s+1$ to $s+2$ is δ. Further, $\gamma = 0$ and $\gamma = 1$ yields myopic and time-consistent preferences, respectively.[7]

The consumer solves the following discrete dynamic optimization problem:

$$V = \max_{x,y,z}[u(x_1, y_1, z_1; B_1) + \gamma \sum_{t=2}^{\bar{t}} \delta^{t-1} u(x_t, y_t, z_t; B_t)], \tag{7}$$

subject to equations (3), (4), (5) and (6). In this model the only reason why current decisions in period t have influence over the subsequent periods $t+s$ ($s = 1, 2, ..., \bar{t} - t$) is the process for endogenous preferences (cf. equations 3 and 4).[8] Hence time inconsistency, as measured by γ, only affects the total value of discounted welfare (V in equation 7) via the endogenous preferences. I will focus on the two extremes: the myopic consumer with $\gamma = 0$ and the time-consistent consumer with $\gamma = 1$.[9] The path of the time-consistent consumer coincides with the solution obtained by a social planner that maximizes social welfare.

The competitive equilibrium is characterized by the following Lemma:

Lemma 1. *The interior solution competitive equilibrium for the time-consistent consumer ($\gamma = 1$) solving (7) is characterized by equations (3),*

[7] O'Donoghue and Rabin (1999) differentiate between two types of time-inconsistent consumers ($0 < \gamma < 1$): Sophisticates and Naifs (see also Strotz, 1955-1956, and Pollak, 1968). The sophisticates realize that their future selves will be time-inconsistent and continue procrastinating unpleasant actions. The Naifs, on the other hand, (wrongly) believe that they will be time consistent and fully rational in future time periods. The present paper assumes Naifs, but the distinction is less important as I focus on the extreme cases $\gamma = \{0, 1\}$.

[8] I.e., there are no capital stocks, endogenous growth or similar characteristics of dynamic models.

[9] I do this because (i) these two cases capture the most interesting results (i.e., market-failure when $\gamma = 0$ and no need for regulation when $\gamma = 1$), and (ii) the intermediate cases $0 < \gamma < 1$ yield time inconsistent trajectories with re-optimization in each period which significantly complicates the analytical analysis (see Appendix A).

(4), (6) and:

$$u_{x_t} - \lambda_t p_{xt} = 0, \tag{8a}$$

$$u_{y_t} - \lambda_t p_{yt} + \frac{\mu_t v z_t}{\delta^{t-1}(y_t + z_t)^2} = 0, \tag{8b}$$

$$u_{z_t} - \lambda_t p_{zt} - \frac{\mu_t v y_t}{\delta^{t-1}(y_t + z_t)^2} = 0, \tag{8c}$$

$$\delta^{t-1} f_{B_t} u_{\beta_t} + \mu_t (1 - v) = \mu_{t-1}^i, \tag{8d}$$

$$\mu_{\bar{t}} = 0. \tag{8e}$$

For the myopic consumer ($\gamma = 0$), the interior solution competitive equilibrium solving (7) is characterized by equations (3), (4), (6), (8a), (8b) and (8c) with $\mu_t \equiv 0$ for all $t \in T$.

Proof. See Appendix A.

The intermediate cases with $\gamma \in (0, 1)$ yield time-inconsistent solutions involving re-optimization in each time period, see the proof of Lemma 1 in Appendix A. The derivatives u_{g_t} in equations (8a), (8b) and (8c) are the marginal utilities of the utility function (5) in time period t w.r.t. good $g_t = \{x_t, y_t, z_t\}$. They are all positive. Further, u_{β_t} in equation (8d) is the derivative of the utility function (5) in period t w.r.t. the endogenous value share parameter β_t. It can be written $u_{\beta_t} = \left(y_t^\theta - z_t^\theta\right) X_t$, where X_t is positive (see the proof of Lemma 1 in Appendix A for the exact expressions for X_t and the derivatives in Lemma 1). λ_t is the shadow price on the budget constraint (6). It is the rate at which the optimal value of the objective function (denoted V in equation 7) changes following a marginal increase in disposable income m_t. Note that λ_t is strictly positive given our utility function (5), finite disposable income m_t and $p_{gt} > 0$ (for all g and t). The adjoint (or co-state) variable μ_t is the first order approximate change in the value function V in (7) caused by a marginal increase in the state variable B_t. It can be interpreted as a shadow price on B_t. Equation (8e) is the transversality condition associated with a free terminal value on the state variable $B_{\bar{t}}$ (which determines $\beta_{\bar{t}}$ via equation 3).

The solution to the myopic consumer's optimization problem in any period $t \in T$ is identical to that of a static maximization problem where utility (given by equation 5) is maximized subject to the budget constraint (6). We have $\mu_t \equiv 0$ for all $t \in T$ for the myopic consumer. Whereas the fully rational time-consistent consumer type may be most familiar in economics, the myopic consumer may be at least as good an approximation to actual behavior in this particular setting (where the only dynamic element is the endogenous preferences).[10]

[10] In a discussion of G. Becker's book "Accounting for tastes" (1998) and the theory of rational addiction, Elster (1997, p. 754) writes: "The only place I can find for motivated preference change is in the context of weakness of will".

Suppose there is a one-time change in consumer prices at time $s > 1$ such that the rate $p_{zt}/p_{yt} > p_{z1}/p_{y1}$ for all $t \geq s$ (e.g., an increase in p_{zt} or a decrease in p_{yt}). Moreover, assume that we at time $t = 1$ are in a stationary state and let $v \in (0, 1)$. Then a (at least marginally) higher rate y_1/z_1 today increases future utility. The reason is that the utility from a higher rate y_t/z_t ($t > 1$) in the future, caused by the one-time change in consumer prices, increases in the current rate y_1/z_1 due the endogenous preference formation process. This is captured in Lemma 1 with $\mu_1 > 0$, which pulls in the direction of more consumption of y_1 (cf., equation 8b) and less consumption of z_1 (cf., equation 8c). It follows that the rate y_t/z_t will increase monotonously over time, before stabilizing on a new and higher stationary state level. Conversely, we would have $\mu_1 < 0$ if prices changed such that the rate y_t/z_t decreased monotonously over time, pulling in the opposite direction of consumption of y_1 and z_1. Note that the consumer is willing to accept a lower utility level in the current period in order to increase the utility in future time periods, and that the adjustment starts before the actual price change takes place (given $\gamma > 0$).

Lemma 1 implies the following result:

Proposition 1. *Suppose consumption of y changes at least once over the time horizon and let preferences be endogenous. Then the optimal time trajectory will not be realized in competitive equilibrium unless the consumer is perfectly time consistent (i.e., unless $\gamma = 1$).*

Proof. *See Appendix A.*

It is the combined presence of time-inconsistency and endogenous preferences that causes suboptimal behavior in Proposition 1. Endogenous preferences in itself does not cause suboptimal outcomes if the consumer is able to perfectly internalize how current actions affects future preferences, and thereby utility.

Suppose the consumer is time-inconsistent. Then it is possible for the regulator to induce the optimal time trajectory by changing the consumer prices with taxes and subsidies. The time trajectory for the taxes can be complicated, however, especially when $0 < \gamma < 1$. Let superscripts *'opt'* and *'myo'* refer to the equilibrium values for the time-consistent (optimal path) and myopic type of consumer, respectively (as given by Lemma 1). Further, let τ_{ht}^{opt} denote a tax on variable $h = \{y, z, m\}$ in period t. Then we have the following result:

Proposition 2. *Suppose preferences are endogenous. Then the following taxes and subsidies is required to induce the optimal trajectory in the case of* *a myopic consumer* ($\gamma = 0$)*, :*

$$\tau_{yt}^{myo} = \left(\frac{\lambda_t^{opt}}{\lambda_t^{myo}} - 1\right) s_y - \frac{\mu_t^{opt} v z_t^{opt}}{\lambda_t^{myo} \delta^{t-1} \left(y_t^{opt} + z_t^{opt}\right)^2},$$

$$\tau_{zt}^{myo} = \left(\frac{\lambda_t^{opt}}{\lambda_t^{myo}} - 1\right) s_z + \frac{\mu_t^{opt} v y_t^{opt}}{\lambda_t^{myo} \delta^{t-1} \left(y_t^{opt} + z_t^{opt}\right)^2},$$

$$\tau_{mt}^{myo} = -\tau_{yt}^{myo} y_t^{myo} - \tau_{zt}^{myo} z_t^{myo},$$

Suppose $\lambda_t^{opt} \approx \lambda_t^{myo}$*.*[11] *Then the expressions for the consumption taxes simplify to:*

$$\tau_{yt}^{myo} \approx -\frac{\mu_t^{opt} v z_t^{opt}}{\lambda_t^{myo} \delta^{t-1} \left(y_t^{opt} + z_t^{opt}\right)^2}, \tau_{zt}^{myo} \approx \frac{\mu_t^{opt} v y_t^{opt}}{\lambda_t^{myo} \delta^{t-1} \left(y_t^{opt} + z_t^{opt}\right)^2}$$

Proof. *See Appendix A.*

Note that net tax income, $-\tau_{yt} y_t - \tau_{zt} z_t$, is added to m_t as a lump sum transfer (or lump sum tax if tax income is negative). This lump sum transfer ensures that the scheme in Proposition 2 is revenue neutral (the tax income is transferred back to the representative consumer). Remember that s_y and s_z are the production costs of goods y and z, respectively.

A caveat with Proposition 2 is that the optimal tax scheme is very information intensive. As such, it may be argued that there is an inconsistency in the analysis behind Proposition 2. That is, whereas the consumer is time-inconsistent, the regulator behaves time-consistent, and is well enough informed to implement taxes that correct for the time-inconsistent behavior of the consumers as given in Proposition 2. A more modest implication of Proposition 2 is that, at least, care should be taken when subsidizing goods or services which have negative externalities related to them; i.e., when doing the opposite of the policy suggested by Proposition 2. The reason is that this will make it more difficult to reduce consumption of these goods later due the endogenous preference formation process (see also Section 2.1). Proposition 2 may also provide a possible rationale for non-uniform rates on taxes that are primarily implemented for generating state revenues, like the value added tax (VAT).[12]

[11] We typically have $\lambda_t^{opt} > \lambda_t^{myo}$, because the rational consumer perfectly maximizes welfare V (in 7), whereas the myopic consumer does not take the endogenous β_t into account. The possible exception is in the period after a price change has been announced, but before it has been enacted (e.g., periods $1, 2, ..., 7$ in the numerical simulation), where the time-consistent consumer sacrifices current utility to increase future welfare.

[12] There are several examples on sumptuary taxes implemented to mitigate use of certain goods deemed harmful to society and individuals, like alcohol, tobacco, gambling, and

2.1 Environmental policy and endogenous preferences

Consider the case where consumption or production of good z causes a negative externality, where marginal damage is ϕ_t per unit of z_t produced and consumed. For example, z may be consumption of red meat, y vegetables and fish, and x a basket of all the other goods.[13] A rough calculation suggests that the US retail price of beef would increase with around 35 percent if emissions related to production of beef were priced at the Biden administration's social cost of carbon (see Appendix A).

Propositions 1 and 2 have the following corollary in the case of environmental policy:

Corollary 1. *Suppose preferences are endogenous. Then the optimal time trajectory will not be realized in competitive equilibrium with a tax equal to environmental damage (ϕ_t) unless the consumer is perfectly time consistent ($\gamma = 1$). In the case of a myopic consumer ($\gamma = 0$), the following taxes implement the optimal trajectory:*

$$\begin{aligned}
\varphi_{yt}^{myo} &= \tau_{yt}^{myo}, \\
\varphi_{zt}^{myo} &= \phi_t + \tau_{zt}^{myo}, \\
\varphi_{mt}^{myo} &= -\varphi_{yt}^{myo} y_t^{myo} - \varphi_{zt}^{myo} z_t^{myo},
\end{aligned}$$

where τ_{yt}^{myo} and τ_{zt}^{myo} are given in Proposition 2.

Proof. *See Appendix A.*

The optimal time trajectory can be achieved with a Pigou tax if and only if the consumer is perfectly time-consistent. Otherwise, the optimal time trajectory requires a tax above the Pigouvian tax level on the dirty good z, and a subsidy on consumption of the clean good y.

We need three taxes to correct for the single externality of environmental pollution caused by production or consumption of z in Corollary 1.[14] This is because the endogenous preferences create additional externalities in the consumer's optimization problem (unless $\gamma = 1$). A numerical illustration of the optimal taxes in Corollary 1 is graphed in Figure 1 in Section 3.

As compared with a standard Pigou tax, the price on the polluting good z is higher and the price on the substitute good y is lower under the optimal

vehicles emitting excessive pollutants (e.g., in the Scandinavian countries). There are also examples of tax breaks on goods deemed to have a positive effect on society, like the reduced UK rate of VAT on certain energy-saving products like isolation.

[13] A study by the U.N. Food and Agriculture Organization (Gerber et al., 2013) estimated that total annual emissions from animal agriculture (production emissions plus land-use change) were about 14.5 percent of all human emissions. Beef and cattle milk production accounted for 41 and 20 percent of the sector's emissions, respectively. See also Wolf et al. (2017) and https://www.nature.com/articles/d41586-019-02409-7.

[14] The Tinbergen Rule states that the regulator needs one instrument per target variable.

tax scheme. Hence, the optimal time trajectory involves less pollution than the suboptimal path that is implemented by a standard Pigou tax (assuming a myopic consumer). The optimal tax system changes the preferences so that consumers prefer relatively more of the clean good y, and less of the polluting good z. This preference change is completely endogenized by the time-consistent consumer type ($\gamma = 1$).

Suppose that x is red meat and y is fish and vegetables (and that red meat is relatively emission intensive as compared to fish and vegetables). In this case, Corollary 1 suggests that the regulator should tax consumption of red meat above the Pigouvian level, whereas consumption of fish and vegetables should be subsidized. One could also consider other ways to motivate consumption of fish and vegetables, e.g. advertising. Another example, taken from the transport sector, could be tolls and cheaper public transport tickets. Better cycle path networks and public transport offers are also examples of measures that can make more people travel in an environmentally friendly way.[15]

Corollary 1 suggests that models used to derive the optimal path for carbon emissions without taking endogenous preferences into account suggests too high carbon emissions, given that preferences are endogenous as modelled in this paper. In this respect, it is noteworthy that the integrated assessment models (IAM) used by the IPCC to derive optimal paths towards the low-emission society feature fixed preferences (see IPCC, 2014). Whereas this is probably fine for the lion share of sectors modelled by these IAMs, it may be problematic regarding, e.g., food consumption, travel and certain luxury polluting goods.

Assume that the regulator only has access to a tax on the z-good associated with the negative externality. Then we have the following:

Corollary 2. *Suppose preferences are endogenous. Then the second-best tax on good z_t is above marginal environmental damage (ϕ_t), unless the consumer is perfectly time consistent ($\gamma = 1$).*

Proof. *See Appendix A.*

Corollary 2 states that a tax above the Pigouvian level may be a second-best alternative to the tax scheme in Corollary 1, if the optimal scheme is unavailable to the regulator.[16] Whereas welfare will be lower with only a single instrument, as compared with the optimal scheme in Corollary 1, the second-best tax may improve the outcome as compared with a standard

[15] The examples with advertising and infrastructure differ from the subsidy s_y in Corollary 1, but the generalization is straightforward. The point with the subsidy is to increase current consumption of y (and reduce z). Other measures that accomplishes this will have the same effect on future preferences.

[16] Mattauch and Hepburn (2016) point out that optimal levels of greenhouse gas emissions and the design of policies to reduce emissions are affected by preference endogeneity.

Pigou tax. The second-best tax tends to be above the first-best optimal tax on the polluting good z, because it needs to compensate for the lack of subsidy to consumption of the substitute good y. Even though the second-best tax can in principle fully control the price ratio p_{zt}/p_{yt}, a too high tax on z will increase the disturbance caused by the tax in the upper CES nest (cf., equation 1).

Corollaries 1 and 2 indicate that care should be taken when subsidizing goods that cause environmental damage, such as beef production.[17] The reason is that the cost of reducing consumption of the z-good may be larger due to the endogenous preference formation process. That is, if consumption of z has to decline in the future, because of pollution, it may be harder do so because current subsidies cause the consumers to get used to enjoying the polluting z-good.

3 Numerical illustration

In this section I present a very stylized numerical model to shed some light on the dynamics of the system of equations presented in Lemma 1. The simulation solves the model consisting of equations (1) to (7) with $\alpha = 0.3658$, $\overline{\beta} = 1/2$, $\rho = \theta = 1/2$, $\nu = 1/4$, $\delta = 0.9873$, $\gamma = \{0, 1\}$ and $\bar{t} = 500$ (approximating the infinite horizon solution for the first 100 time periods). The model is calibrated such that the initial budget shares of x, y, and z at time $t = 0$ are 0.4, 0.3 and 0.3, respectively. These budget shares corresponds roughly to the shares of US food consumption if z is meats, y is fish, fruits and vegetables, and x is the rest (including cereals, dairy, oils and fats). As such, the numerical illustration may be loosely interpreted as continuing the example from Section 2.1. A difference is that the negative externality is zero for the first seven time-periods (I do this because it emphasizes that it is optimal to start the changes in consumption even before the price change or externality occurs when endogenous preferences are present). The reader may interpret one time period as one quarter, in which case the quarterly discount factor is equivalent to a yearly discount rate of 5 percent. Under this interpretation the new habits are largely ingrained after a couple of years, which is somewhat faster than indicated by the results in Atkin (2013) for food consumption in India.

[17] Significant subsidies are handed out to the meat industry. For example, American governments spend 38 USD billion each year to subsidize meat and dairy, but only 0.04 percent of that (17 USD million) to subsidize fruits and vegetables (https://meatonomics.com/2013/09/28/10-things-i-wish-all-americans-knew-about-the-meat-dairy-industries/). Nearly a fifth of the EU's total budget goes to support livestock farms across Europe, the majority of which are climate-intensive (https://www.theguardian.com/environment/2019/may/22/eu-ignoring-climate-crisis-with-livestock-farm-subsidies-campaigners-warn).

Let the economy at time $t = 0$ be in a stationary state, such that we would have $\beta_t = f\left(\overline{B}\right)$ if consumer prices and disposable income m_t remained constant for all $t \in T$. We examine the optimal consumption patterns in the case of an anticipated one-time 35 percent increase in the supply cost of good z in time period $t = 8$ (the supply cost increases because the negative externality is internalized in the production cost).[18] All other parameters remain constant. We also derive the first- and second-best taxes in the case of a myopic consumer. For ease of exposition most results are presented in percentage changes from the initial stationary state level at time $t = 0$ (i.e., before the numerical model starts running). Some changes occur in the first period $t = 1$ under first- and second-best taxes, so the time trajectories do not all start at zero in period 1.

Figure 1 (left) graphs the optimal consumption patterns of the three goods ('opt'). This path can be implemented by the optimal tax scheme given in Corollary 1 if the consumer is myopic ($\gamma = 0$), or by a standard Pigou tax if the consumer is time-consistent ($\gamma = 1$). Hence, the graphs denoted 'opt' refer to both the consumption paths of a perfectly rational and time-consistent consumer facing a Pigou tax, and the path of a myopic consumer facing the optimal tax scheme in Corollary 1. Figure 1 also graphs the consumption paths of a myopic consumer facing a Pigou tax ('pig'), and a myopic consumer facing a second-best tax ('SB') (i.e., the tax on z that maximizes welfare V in equation (7) given that the regulator is unable to put taxes on the goods x and y, see Section 2.1).

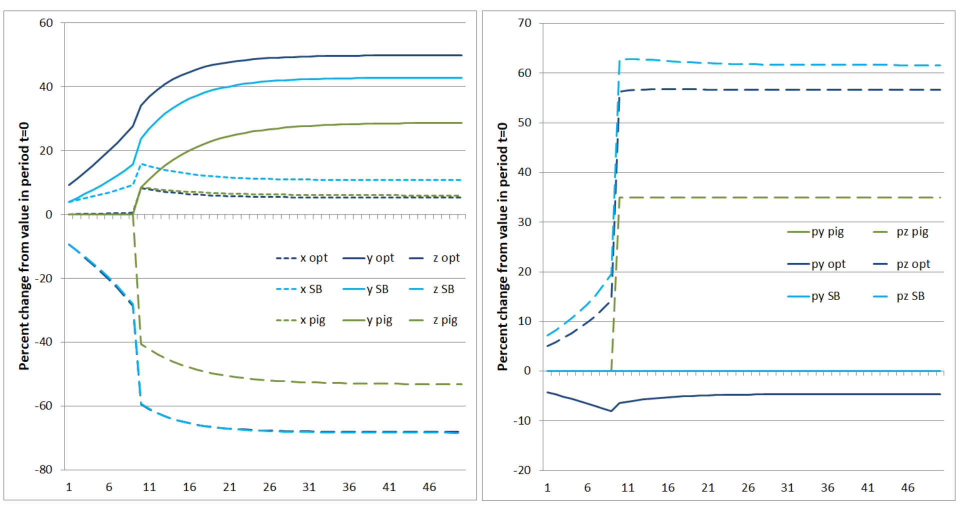

Figure 1: Consumption levels (left) and undiscounted prices including taxes (right). First 50 time periods. Some graphs overlap

[18]Hence the supply cost of z depends on t in the numerical simulation, and satisfies $s_{zt} = s_z$ for $t < 8$ and $s_{zt} = s_z(1 + 0.35)$ for $t \geq 8$.

Substantial changes in consumption levels occur along the optimal trajectory before the price change takes place in period $t = 8$. In contrast, the myopic consumer does not change consumption patterns before the price change is implemented in period $t \geq 8$ under Pigou taxation. The differences between the trajectories are not limited to the transition, but also the new stationary state is influenced; i.e., the new stationary state features markedly less consumption of z_t and higher consumption of y_t along the optimal path than the trajectory for a myopic consumer facing a standard Pigou tax.[19]

We also observe that consumption levels are quite close to the optimal trajectory in the case of a second-best tax on z only. The difference between welfare under the second-best tax and the optimal tax scheme increases in α (the share of the composite good x in the utility function (1)), and approaches zero as α approaches zero; i.e., as the model converges towards the case with two goods y and z only.

Figure 1 (right) graphs the optimal tax scheme and the second-best tax scheme in the case of a myopic consumer. It also graphs the standard Pigou tax. The producer prices are constant and equal to marginal cost, so the changes in consumer prices in Figure 1 are all caused by the taxes. Note that the second best tax is slightly higher than the optimal tax τ_z^{opt}, because it has to compensate for the lack of subsidy to the substitute good y. The change in the price p_y is zero under the second-best and Pigou tax schemes. The price p_x is constant under all the tax schemes.

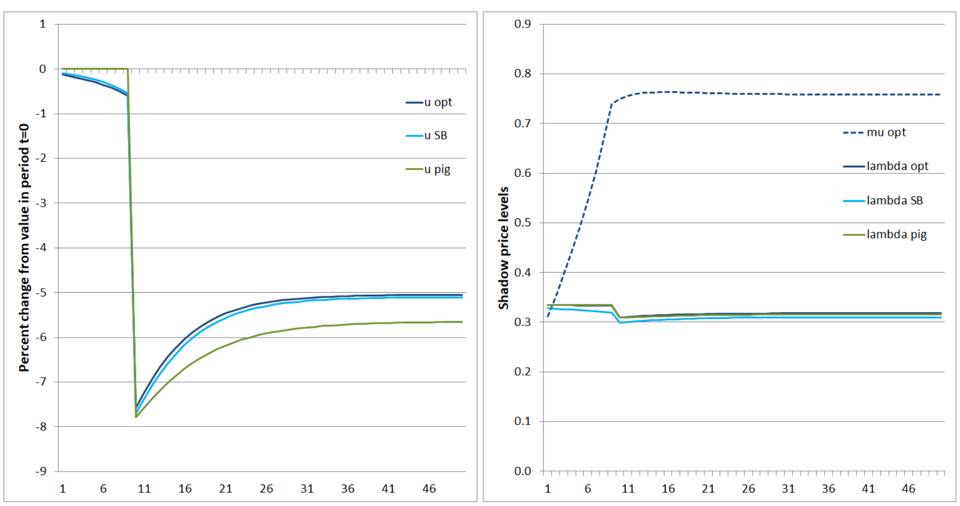

Figure 2: Utility levels (left) and shadow prices right). Undiscounted values. First 50 time periods

Figure 2 (left) plots the changes in utility levels under the three tax

[19] Around period $t = 450$ the difference starts a gradual decline, but it remains non-zero even in the final period $t = 500$ (because the preferences formation process in equation (4) is sluggish when $v < 1$).

regimes. The net tax revenue is recycled back to the consumer, but utility declines because of the negative externality (modelled equivalently with an increase in the supply cost of good z when $7 < t$). The optimal and second-best paths trade-off utility in the early periods to increase utility later along the trajectory.

Figure 2 (right) graphs the shadow price μ on the endogenous preferences state variable B along the optimal path, and the shadow prices on the budget constraints under the three tax regimes, λ. The shadow prices on the budget constraints decline in period $t = 8$ because a marginal increase in monetary endowment gives the consumer less goods, and thereby utility, after period $t = 7$. The undiscounted shadow price (μ) remains constant until the model values are affected by the end of the time horizon in period $t = 500$. The undiscounted shadow prices on the budget constraints (λ) remain constant for all time periods after the new preferences have been ingrained.[20] Note that Figure 2 graphs the undiscounted values (discounted shadow prices and utility decline over time).

4 Concluding remarks

I have examined the effects of endogenous and time-inconsistent preferences in a dynamic model with environmental policy. The optimal time trajectory is achieved by a standard Pigou tax if and only if the consumer is perfectly time-consistent. Suboptimal trajectories differ from the optimal path during the transition phase and in the new stationary state. The tax scheme that can induce the optimal trajectory requires a combination of taxes and subsidies. If only a tax on the polluting good is available, a second-best option may be a tax above the Pigouvian level. A key implication of the present paper is that the optimal tax on carbon emissions may be above the social cost of carbon.

The results in this paper do not hinge on time-inconsistent preferences per se. The important point is that endogenous preferences cause an externality unless the consumer perfectly internalizes the endogenous preference formation. In particular, it can be shown that a too high discount rate (i.e., that the consumers operate with a discount factor that is above the social discount rate) leads to very similar results as the presence of time-inconsistent behavior.

A caveat with the present analysis is that it is demanding to estimate how important endogenous preferences are in matters concerning environmental policy, also with regard to the magnitude of the mechanisms identified in this paper.[21] Also, while hyperbolic discounting may provide a better descrip-

[20] Very small changes in all shadow prices is present as the endogenous preferences parameter B_t adjusts.

[21] See Laporte et al. (2017) for some challenges in estimating the related rational addic-

tion of intertemporal choice than exponential discounting, researchers have demonstrated patterns of choice that seem anomalous also from the framework of hyperbolic discounting; see e.g. Loewenstein and Prelec (1992), Loewenstein and Thaler (1989) and Roelofsma (1996). Last, regulation in a setting where the government can influence people's preferences raises some ethical issues. This discussion is beyond the scope of the present paper. I refer to Mattauch and Hepburn (2016) for more on this topic in a setting with environmental policy.

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Appendix A: Proofs and calculations

Proof of Lemma 1: The maximization problem (7) can be solved as an optimal control problem over discrete time with mixed constraints (it is mixed because of the budget constraint (6)). Note that whereas B_t (and, hence, β_t, cf. equation (3)) depends on the pair (x_{t-1}, y_{t-1}), B_t is independent of (x_t, y_t) (cf. equation (4)). We define the Lagrangian function:

$$L(x_t, y_t, z_t; B_t) = H(x_t, y_t, z_t; B_t) + \lambda(m_t - p_{xt}x_t - p_{yt}y_y - p_{zt}z_t),$$

where $H(\cdot)$ is the Hamiltonian associated with the problem (7) s.t. equation (3) and λ is the Lagrange multiplier associated with the problem (7) s.t. equation (6). A social planner that maximizes welfare (V in equation 7) face the budget constraint $m_t = s_x x_t + s_y y_y + p_{zt}z_t$, which is identical to the consumer's budget constraint (6) when all taxes are zero (the firms supply the goods at marginal cost s_g). Hence, the Lagrangian above, with $\gamma = 1$, also solves the time-consistent social planner's problem.

Let $\gamma\delta > 0$. Then the Hamiltonian is given by:

$$H_t = \begin{cases} \gamma\delta^{t-1}u\left(x_t, y_t, z_t; B_t\right) + \mu_t\left(B_t + \nu\left(\frac{y_t}{y_t+z_t} - B_t\right)\right), \forall t < \bar{t}, \\ u\left(x_t, y_t, z_t; B_t\right), t = \bar{t}, \end{cases}$$

where μ_t is the adjoint (or co-state) variable associated with the state variable B_t. We observe that the marginal utility of the goods $g = \{x, y, z\}$ satisfies $\lim_{g\to 0}\left(\partial u\left(\cdot\right)/\partial g\right) = \infty$ for our assumptions about the parameters entering the CES utility function (5) (see expressions for the partial derivatives below). Hence we will have an interior solution. We further observe that non-satiation in the CES utility function implies that the budget constraint will hold with strict equality.

The necessary conditions for solving the mixed constraints problem (7) s.t. equations (3) and (4) are:

$$\begin{aligned} \frac{\partial L_t}{dx_t} &= \gamma\delta^{t-1}\left(\frac{\partial u}{\partial x_t} - \lambda_t p_{xt}\right) = 0, \\ \frac{\partial L_t}{dy_t} &= \gamma\delta^{t-1}\left(\frac{\partial u}{\partial y_t} - \lambda_t p_{yt}\right) + \frac{\mu_t v z_t}{\left(y_t + z_t\right)^2} = 0, \\ \frac{\partial L_t}{dz_t} &= \gamma\delta^{t-1}\left(\frac{\partial u}{\partial z_t} - \lambda_t p_{zt}\right) - \frac{\mu_t v y_t}{\left(y_t + z_t\right)^2} = 0, \\ 0 &= m_t - p_{xt}x_t - p_{yt}y_y - p_{zt}z_t, \\ \mu_{t-1} &= \frac{\partial L_t}{dB_t} = \gamma\delta^{t-1}\frac{\partial u_t}{\partial f_t}\frac{\partial f_t}{\partial B_t} + \mu_t\left(1 - v\right), \\ \mu_T &= 0, \end{aligned} \tag{9}$$

The last line is the transversality condition associated with a free state variable β_T. The above system of equations with $\gamma = 1$ constitutes Lemma 1. Note that the system of equations (9) with $\gamma = 1$ characterizes the socially optimal path (together with equations (3), (4) and (6)). Define the following variables:

$$A_t = \left(\left(1-\alpha\right)\left(z_t^{\theta}\left(1-\beta_t\right) + y_t^{\theta}\beta_t\right)^{\frac{\rho}{\theta}} + x_t^{\rho}\alpha\right)^{\frac{\rho-1}{\rho}} > 0 \tag{10}$$

$$D_t = \left(z_t^{\theta}\left(1-\beta_t\right) + y_t^{\theta}\beta_t\right)^{\frac{\theta-\rho}{\theta}} > 0$$

Then the derivatives in the above system of equations (and Lemma 1) are given by:

$$\begin{aligned}\frac{\partial u}{\partial x_t} &= x_t^{\rho-1}\frac{\alpha}{A_t} > 0 \\ \frac{\partial u}{\partial y_t} &= y_t^{\theta-1}\beta_t\frac{1-\alpha}{A_t D_t} > 0 \\ \frac{\partial u}{\partial z_t} &= z_t^{\theta-1}\left(1-\alpha\right)\frac{1-\beta_t}{A_t D_t} > 0 \\ \frac{\partial u}{\partial \beta_t} &= \left(y_t^{\theta} - z_t^{\theta}\right)\frac{1-\alpha}{\theta A_t D_t} \lesseqgtr 0\end{aligned} \tag{11}$$

Lemma for the time-inconsistent consumer ($0 < \gamma < 1$*)*: When $\gamma \in (0, 1)$ the system of equations (9) is time-inconsistent. That is, if solved in period s, the values for the variables in future periods $t > s + 1$ will be changed because the consumer re-optimize in period $s + 1$. (The reason is that the discounting between two periods $s + 1$ and $s + 2$ is δ as seen from period s, and $\gamma\delta$ as seen from period $s + 1$.) Suppose we are in period $s \in T$. Then Lemma 1 gives the solution to the problem (7) with $\gamma \in (0, 1)$ for x_s, y_s and z_s, but not for periods $t > s$. Therefore, solving (7) with $\gamma \in (0, 1)$ over the whole time horizon $t \in T$ requires us to solve $\bar{t}$ problems (of which $\bar{t} - 1$ is dynamic and the last in period $\bar{t}$ is static). Suppose we are in some period $s \in T \setminus \{\bar{t} - 1\}$. Then we observe from the system of equations (9) that a larger γ will have very similar effects on (x_s, y_s, z_s) as a larger discount factor δ. But the consumption path for the periods $t > s$ will be affected differently by γ and δ due to the inconsistent time preferences.

Lemma for the myopic consumer ($\gamma\delta = 0$*):* The myopic consumer solves (7) subject to the budget constraint (6), which is a simple static optimization problem. The associated Lagrangian is:

$$L^{myo} = \left(\alpha x_t^{\rho} + (1-\alpha)\left(\beta y_t^{\theta} + (1-\beta)\, z_t^{\theta}\right)^{\frac{\rho}{\theta}}\right)^{\frac{1}{\rho}} + \lambda\left(m_t - p_{xt}x_t - p_{yt}y_t - p_{zt}z_t\right)$$

The necessary conditions for optimum are given by:

$$\begin{aligned}\frac{\partial L}{\partial x} &= \frac{\partial u}{\partial x} - \lambda p_x \leq 0 \\ \frac{\partial L}{\partial x} &= \frac{\partial u}{\partial y} - \lambda p_y \leq 0 \\ \frac{\partial L}{\partial z} &= \frac{\partial u}{\partial z} - \lambda p_z \leq 0 \\ 0 &\leq m_t - p_x x - p_y y - p_z z\end{aligned}$$

which must hold with strict inequality in optimum, because of non-satiation in the CES utility function and $\lim_{g\to 0}(u_g) = \infty$. Note that this system of equations is equal to the the system consisting of the first order conditions w.r.t. x_t, y_t and z_t in (9) with $\mu_t \equiv 0$ and the budget constraint (6). In this case β_t is still determined by equations (3) and (4), but this process is treated as exogenous by the myopic consumer.

Proof of Proposition 2: Lemma 1 with $\gamma = 1$ characterizes the socially optimal path. The taxes necessary for the myopic consumer's consumption path, denoted τ_{yt}^{myo}, τ_{zt}^{myo} and τ_{mt}^{myo}, to equal that of the time-consistent consumer must solve:

$$-\lambda_t^{opt} p_{yt}^{tc} + \frac{\mu_t^{opt} v z_t^{opt}}{\delta^{t-1}\left(y_t^{opt} + z_t^{opt}\right)^2} = -\lambda_t^{myo} p_{yt}^{myo},$$

$$-\lambda_t^{opt} p_{zt}^{opt} - \frac{\mu_t^{opt} v y_t^{tc}}{\delta^{t-1}\left(y_t^{opt} + z_t^{opt}\right)^2} = -\lambda_t^{myo} p_{zt}^{myo},$$

$$\overline{m} - \tau_{mt}^{myo} - \tau_y y_t - \tau_z z_t = \overline{m},$$

where we have $p_{yt}^{opt} = s_y$, $p_{zt}^{opt} = s_z$, $p_{yt}^{myo} = s_y + \tau_y$ and $p_{zt}^{myo} = s_z + \tau_z$ (no taxes for the time-consistent consumer, $\tau_y^{opt} = \tau_z^{opt} = \tau_{mt}^{rat} = 0$). This ensures that the partial derivatives in Lemma 1 is equal for the myopic and the time-consistent consumer types. Rearranging yields Proposition 2.

Proof of Corollary 1: Let the social cost of good z equal the supply cost s_z plus a negative externality ϕ. Then socially optimal trajectory still solves Lemma 1, but with $p_{zt} = s_z + \phi$. Corollary 1 then follows directly from Proposition 2.

Proof of Corollary 2: This is the same case as in Corollary 1, except for the additional constraint that $\tau_{yt}^{myo} = 0$. This extra constraint does not change the sign on $\tau_{zt}^{myo} > 0$, because the term $f_{B_t} u_{\beta_t}$ in equation (8d) does not change sign. The economic intuition is that a (marginally) larger value on β increases future utility, which again implies that a larger value on B_1 increases future utility. Hence, the shadow price on B_1 (i.e., μ_1) is positive, because higher consumption of y_1 (or lower consumption of z_1) increases future utility.

Price of beef and CO2 emissions: The retail price of 100 percent ground beef in 2020 was 3.95 USD per pound (https://www.statista.com/statistics/236776/retail-price-of-ground-beef-in-the-united-states/). Average emissions per kg beef is 60 kilograms (https://www.forbes.com/sites/davidrvetter/2020/10/05/got-beef-heres-what-your-hamburger-is-doing-to-the-climate/?sh=7ae7b0da5206). The Biden administrations estimate of the social cost of carbon is 51USD per

$\bar{t}$	s_x, s_y, s_z	δ	γ	v	α	β_0	m	ρ, θ	$\phi_t(t \leq 7)$	$\phi_t(t > 7)$
500	1	0.98726	0 or 1	0.2	0.3658	0.5	3.33	0.5	0	0.35

Table 1: Parameters in the numerical illustration.

ton (https://www.scientificamerican.com/article/cost-of-carbon-pollution-pegged-at-51-a-ton/). The very rough calculation is as follows: Price of one kg beef = 3.95/0.4536 (US average 2020 retail price per kg beef) + 60*51/1000 (CO2 cost per kg beef) = 11.79.

Appendix B: The numerical model

The simulation solves the model consisting of equations (1) to (7) with the values given in Table 1. For the $f(\cdot)$ function I used the cumulative Cauchy distribution with scale/shape parameter equal to 0.7. I also imposed non-binding upper and lower bounds on β (equal to 0.75 and 0.5) to ease the numerical computation. The numerical model is solved in GAMS (numerical software, GAMS version 24.8.3). Partly as a nonlinear optimization problem (NLP) using the Conopt solver, and partly as a mixed complementarity problem (MCP) using the Path solver. The GAMS code is available from the author on request.