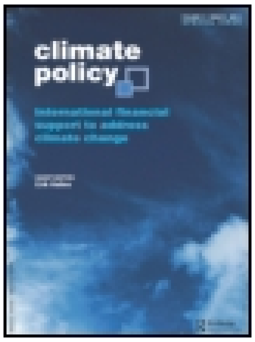

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RESEARCH ARTICLE

Integrating behavioural economics into climate-economy models: some policy lessons

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ABSTRACT

Various macroeconomic models have been proposed to study the effects of climate policies. But from many corners now, it has been argued that these models are inadequate as tools for policy analysis. In particular, extreme impacts of climate change, inherent uncertainty, and discounting have been widely discussed as flaws of current models. Surprisingly, unrealistic assumptions about individual behaviour, which ignore well-documented behavioural 'anomalies' and social interactions, have attracted little attention so far in the economic analysis of climate change impacts and policies. This article begins to address this gap by providing an overview of formal macro-behavioural models, designed to incorporate a variety of realistic behaviours, such as present bias, habit formation, loss-aversion, and social status into economic theory. We show that ignoring behavioural anomalies may undermine the effectiveness of climate policies, which we illustrate with examples of optimal pollution tax and the social cost of carbon. In addition, we study the probability of the rebound effect in each behavioural model. The rebound effect describes a situation where improvements in energy efficiency render a reduction in energy consumption less than proportional. We show that status concerns make the economy more conducive to the rebound effect compared to a model with fully rational agents. Models of habit formation and loss aversion can have the opposite effect.

POLICY RELEVANCE

Current models to assess climate policies may deliver biased insights owing to the omission of essential aspects of bounded rationality. The discounted utility framework, which describes how consumers trade current versus future consumption, is typically used to evaluate climate policies. Climate change economists have largely ignored alternative behavioural models, which integrate into economic theory realistic behaviours, such as: present bias, habit formation, loss-aversion, and social status. This is surprising in the light of evidence that virtually every assumption underlying the discounted utility model has been tested and found to be an invalid description of how people actually behave. We show with examples how well-established anomalies can undermine the effectiveness of climate policies.

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Bounded rationality; climate policy; energy efficiency; rebound effect

1. Introduction

It has been argued from many corners that a new approach to macroeconomics is needed for a robust policy analysis (Farmer & Foley, 2009; Schweitzer et al., 2009; Stiglitz & Gallegati, 2011). In particular, there is growing dissatisfaction with existing macroeconomic models used to assess climate policy (Dell, Jones, & Olken, 2013; Farmer, Hepburn, Mealy, & Teytelboym, 2015; Pindyck, 2013; Stern, 2016). The unrealistic and incomplete modelling of the physical impacts of climate change, the inherent uncertainty, and the sensitivity of model outcomes

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to the discount rate have been widely discussed in the literature. Far less attention has been paid to the behavioural assumptions of underlying models for climate policies. However, representative agent models, which are predominant in the economic studies of the impacts of climate change, are by their very nature ill-suited to address all relevant policy issues (Akerlof, 2002; Farmer & Foley, 2009; Stadler, 1994). In this article we provide an overview of the formal macro-behavioural models, which incorporate different realistic behaviours into economic theory. We discuss the implications of adopting these models for climate policies.

In the analysis of climate policies, the optimal growth path is derived from the discounted utility framework, which describes how consumers trade current versus future consumption. Climate change economists have largely ignored alternative behavioural models, especially shying away from utility functions which are non-standard, or where risk aversion, past consumption, and social comparisons play a role in the consumption-saving choice (an exception is Howarth, 2006). This is surprising in light of evidence that virtually every assumption underlying the discounted utility model has been tested and found to be an invalid description of how people actually behave (see Frederick, Loewenstein, & O'Donoghue, 2002 for an overview of the 'behavioural anomalies' related to intertemporal choice). In general, behaviours not complying with the standard model can be categorized as 'bounded or limited rationality', where agents' decisions are constrained by cognitive processes and the available information, and as 'other-regarding behaviour' where motives such as fairness, reciprocity, and self-identity affect decisions (Gsottbauer & van den Bergh, 2010). Several reviews summarize the findings from behavioural economics (Camerer, Loewenstein, & Rabin, 2004; Conlisk, 1996; Kahneman, Knetsch, & Thaler, 1986). To date, policy discussions have only focused on how to address behavioural failures related to environmental choices in a descriptive manner (e.g. Brekke & Johansson-Stenman, 2008; Gsottbauer & van den Bergh, 2010; Shogren & Taylor, 2008), but not in the macroeconomic assessment of climate policies.

From another perspective, interest in behavioural macroeconomics has grown in recent years (Akerlof, 2002; Driscoll & Holden, 2014). In particular, models of habit formation or 'keeping up with the Joneses' (Alvarez-Cuadrado, Monteiro, & Turnovsky, 2004; Shi & Epstein, 1993), hyperbolic discounting (Karp, 2005), recursive preferences and marginal impatience (Mausumi, 2003), as well as prospect theory (Foellmi, Rosenblatt-Wisch, & Schenk-Hoppe, 2011) have been addressed in the macroeconomic literature. These models have been successful in explaining: the excess smoothness of aggregate consumption (e.g. habit formation), underinsurance against probable small losses (e.g. prospect theory), or overconsumption and saving too little (e.g. hyperbolic discounting, and keeping up with the Joneses), where empirical evidence has contradicted the predictions of conventional models. In fact, mainstream economic models rule out phenomena such as insufficient or excessive savings, involuntary unemployment, or underinsurance. Since all of those decisions are the result of individual utility maximization, they must, in the absence of externalities, be optimal (Akerlof, 2002). On the other hand, behavioural economics recognizes that individuals may maximize a utility function that is different from their 'true welfare' (Bernheim & Rangel, 2009), which allows a study of how actual behaviours diverge from their rational predictions.

So far, no study has systematically examined the implications of different macro-behavioural models for climate policy. To fill in this gap, in this article, we discuss how different forms of bounded rationality affect the social cost of carbon (SCC), optimal pollution tax, and energy efficiency measures. Our aim is to show how different behavioural anomalies affect equilibrium outcomes in the Ramsey model. The Ramsey model is a model of optimal growth, which predominates in the analysis of climate policies. Our exercise can assist inexperienced, and possibly also experienced, researchers in understanding the available variety of behavioural anomalies, their possible formalizations in the Ramsey growth model, and their importance in deriving an optimal climate policy. We focus on the present bias, formation of habits, loss-aversion, and social status in the formal analysis. The choice of specific anomalies is motivated by the fact that although a large variety of behaviours have been discussed as relevant for climate policies, so far only a few anomalies have been shown to affect macroeconomic dynamics in theoretical and empirical analysis.

Shogren and Taylor (2008) argue that bounded rationality is a type of market failure, which needs to be corrected through public policy. We show that taxing pollution requires adjustments to correct behavioural failures if consumers are loss-averse or status-oriented. These corrections are not required for habit-oriented consumers. The rebound effect describes a situation where improvements in energy efficiency render a reduction in energy consumption less than proportional. We show that under status consumption, the economy is more conducive to the rebound effect. In particular, status concerns cause subjects to buy significantly more products, whose production requires additional energy, than rational consumers after improvements in energy efficiency. On the other hand, habit formation implies that consumers are less likely to increase their consumption after such improvements. Consequently, energy efficiency measures generate more energy savings in the habit formation model compared to the rational equilibrium. Under loss-aversion, the impact of energy efficiency on energy savings depends on the weight attached by consumers to the reference level of consumption, which they would like to attain.

This article bridges different aspects of the literature, including behavioural economics, integrated assessment modelling, and energy and environmental economics to study policy lessons for sustainability. We formulate specific suggestions on how to provide macro models with more behaviourally sounded foundations for the macroeconomic analysis of climate policies. The remainder of this article is as follows. In Section 2, we provide a brief overview of macro-behavioural models, and discuss their implications for the SCC. In Section 3, we incorporate the selected behavioural anomalies into the Ramsey model to study the optimal pollution tax and the probability of a rebound effect for each behavioural model. Section 4 concludes.

2. Integrating behavioural utility functions into the Ramsey model

The literature on the economic impacts of climate change has been dominated by two approaches: the Ramsey model with pollution externality, and integrated assessment models (IAM) with a climate module. The former model typically uses a one-commodity setting. Here, output is either consumed or saved, whereas savings are invested in capital accumulation. Economic activities are a source of pollution, which can be reduced by cleaning-up activities. In turn, IAMs combine geophysical stocks and flows with economic stocks and flows in different sectors. The accumulation of CO_2 emissions due to industrial activities affects the temperature, which in turn generates economic losses (damages). Most IAMs employ the Ramsey setting to derive optimal investments, consumption, and savings. (Other IAMs exist, where the accumulation of capital is not driven by optimization, but is based on an exogenous scenario, e.g. FUND (Tol, 2001). As simulations of exogenous scenarios rule out behavioural assumptions, in the discussion which follows, we discuss the implications of adopting realistic assumptions about individual behaviour in the Ramsey model.) The simplest version of the Ramsey model has three equations: (1) the Euler equation, which relates current to future consumption, (2) the capital accumulation equation, describing the dynamics of capital over time, according to which the economic outcome is either consumed or saved, whereas savings are invested in capital accumulation, and (3) the stock of pollutants or emissions accumulating in the atmosphere as a result of economic activities. The stock of emissions creates damage, which either reduces welfare directly, or lowers the productivity of output. These can be represented by (van der Ploeg & Withagen, 1991):

$$\dot{C}_{\mathrm{CR}} = \dot{c}_t = \eta(c_t)c_t(f'(k_t) - \theta - \delta), \tag{1}$$

$$\dot{k}_t = f(k_t) - c_t - \delta k_t - A, \tag{2}$$

$$\dot{S}_t = g(Y_t) - \sigma(A)S_t, \tag{3}$$

where $c_t$is consumption, k_t is capital, and S_t is pollution, $\eta(c_t) = -U_c/c_t Ucc$ denotes the instantaneous elasticity of intertemporal substitution, U_c is the first derivative of U on c, and U_{cc} is its second derivative, $f'(k_t)$ is the derivative of output with respect to capital, δ is the depreciation rate of capital, whereas θ is the discount rate. In Equation (3), the function g translates output $Y_t = f(k_t)$into pollution, $\sigma(A) > 0$ is the rate at which pollution S_t is dissolved by the environment, whereas A is the amount of total production devoted to cleaning-up activities. The three equations are sufficient to derive the optimal path of investments, as well as capital and savings on the optimal path.

Van der Ploeg and Withagen (1991) distinguish between stock and flow externalities arising from pollution. In particular, environmental damage can be caused by the flow of pollution $D_F(af(k_t))$, and additionally by the stock of pollutants due to greenhouse gases accumulated in the air $D_S(S)$. Accounting for both types of damages gives rise to the social welfare function: $U = \int_{t=0}^{\infty} \mathrm{e}^{-\theta t}[u(c_t) - D_F(af(k_t)) - D_S(S)]$. In some integrated assessment models, the accumulation of pollution affects welfare via its impact on output productivity in the formula: $Y_t = D_S(S)f(k_t)$ (see Nordhaus, 2011).

The model allows for two types of optimal policy analysis: of pollution tax which corrects the externality associated with the current flow of pollution ($D_F(af(k_t))$, and of the SCC measuring the discounted value of damages over time ($D_S(S)$). Below, we illustrate the basic idea behind the pollution tax, internalizing the flow externality in the classic Ramsey model, while in Section 3.1 we compare its value to optimal taxes in different behavioural models. We do not derive the optimal dynamic path for each behavioural model, leaving this for future research. As a result, we also do not compute the SCC for each behavioural model. This is because SCCs can only be derived in relation to a particular scenario that defines a reference path (Foley, Rezai, & Taylor, 2013), whereas our focus here is instead on the static analysis. This is motivated by the fact that we do not aim to exhaustively study the effects of adopting different behavioural functions for all environmental policies, but to illustrate, with relevant examples, how ignoring behavioural 'anomalies' may lead to an overestimation of environmental policy.

In the absence of stock damage, the modified Euler equation can be written as follows (using $U = \int_{t=0}^{\infty} e^{-\theta t}[u(c_t) - D_F(af(k_t))]$ in derivations):

$$\dot{C}_{ECR} = \dot{c}_t = \eta(c_t)c_t(f'(k_t)(1 - aD'_F(f(ak_t))/U'(c_t)) - \theta - \delta). \quad (4)$$

The environmental externality arises because individual households are too small to care about pollution as a by-product of production, and they therefore maximize the discounted utility from consumption $U = \int_{t=0}^{\infty} e^{-\theta t}u(c_t)$ ignoring the damages. In Figure 1, the market optimum lies in E_{CR}, at the intersection of $\dot{K} = 0$- and $\dot{C}_{CR} = 0$- curves. The market does not internalize the externality to consumers from pollution, which causes consumption and production to be above their socially optimal levels in E_{ECR}. The socially optimal outcome can be achieved by levying a tax on pollution $af(k_t)$ at a rate equal to $D'_F(af(k_t))$ (see van der Ploeg and Withagen (1991) for a discussion). Adopting alternative behavioural functions into the assessment of the optimal pollution tax does not affect the capital accumulation equation, only the Euler equation. This is because alternative behavioural models imply different values of $\eta(c_t)$ and $U'(c_t)$, which affects consumption, and therefore the size of the pollution externality, which we discuss in detail in Section 3.1.

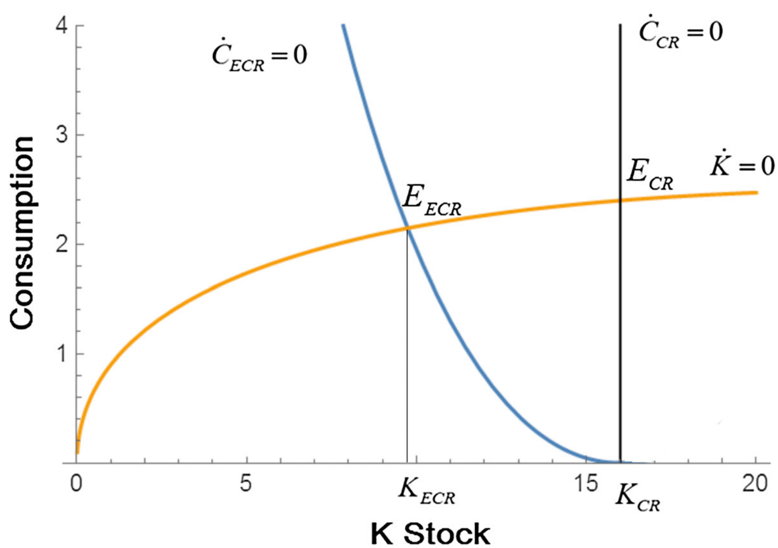


Figure 1. The classic Ramsey problem and the size of pollution externality.

Note: We use: $D_F(af(k_t)) = af(k_t)$, $f(k_t) = k_t^{\alpha}$, with parameter values: $a = 0.15$; $\alpha = 0.5$; $\theta = 0.025$; $\sigma = 0.5$; $\delta = 0.1$.

2.1. Behavioural models

In this section, we first discuss a recent line of research integrating models of bounded rationality into macroeconomic models and discuss their implications for the SCC. We focus on the models of keeping up with the Joneses, habit formation, prospect theory, and hyperbolic discounting, which have received the most attention in macroeconomic literature.

The model of keeping up with the Joneses relies on the idea that social comparison and status-seeking are important determinants of individual behaviour. In particular, people often imitate the consumption or leisure patterns of the 'Joneses' to keep up with their standard of living and signal their own wealth. A desire to keep up with the Joneses can be a source of a consumption or status externality, if agents do not take into account the effect of their spending on the utility of others. In the Ljungqvist and Uhlig (2000) model, an agent derives disutility from consuming less than average consumption:

$$u(c_t) = \frac{(c_t - xC_t)^{1-\sigma}}{1-\sigma} - An, \tag{5}$$

where c_t is the individual's consumption, C_t is average consumption across all agents, x captures the relative importance of average consumption, n stands for the population size, while A determines the relative importance of leisure. The authors show that agents consume too much compared to the first best solution. The consumption externality can be corrected with the optimal policy, which affects the economy countercyclically via procyclical taxes, i.e. 'cooling down' the economy with higher taxes when it is 'overheating' in booms and 'stimulating' the economy with lower taxes during recessions.

The idea of keeping up with the Joneses is a variation of the theme of habit formation. In the model of habit formation, current utility depends on a 'habit stock' formed by lagged expenditures, instead of average consumption. The basic idea here is that consumers dislike changes to their consumption levels. Habit formation has been shown to have important macroeconomic implications. In particular, it explains the excess smoothness of aggregate consumption (Campbell & Cochrane, 1995; Dynan, 2000; Lettau & Uhlig, 2000). This is due to the fact that habit formation makes agents more risk averse, which translates into a very low elasticity of substitution between labour and leisure (Lettau & Uhlig, 2000). Consequently, when technology shocks occur, workers work less but do not adjust their consumption as much. Formally, the utility function can be modified to account for the impact of habits on utility (Carroll, Overland, & Weil, 2000):

$$u(c_t) = \frac{(c_t/z_t^{\gamma})^{1-\sigma}}{1-\sigma}, \tag{6}$$

where γ measures the importance of habits z_t. The stock of habits evolves according to $\dot{z}_t = \rho(c_t - z_t)$, where the habit stock is a weighted average of past consumption, with the parameter ρ describing the relative weights of consumption at different times.

Many studies have documented the predictive failures of the expected utility theory. The expected utility (EU) theory states that the utility of a risky distribution of outcomes is a probability-weighted average of the outcome utilities. A consensus seems to emerge that the linear weighting in the EU theory works reasonably well except when the outcome probabilities are very low or very high (Camerer & Loewenstein, 2004), but otherwise prospect theory explains experimental choices more accurately than EU (Kahneman & Tversky, 1979). Prospect theory assumes a reflection of risk preferences at the reference point: people are risk-averse in the domain of gains and loss-averse in the domain of losses. As a result, the disutility of a loss is worse than the utility of an equivalent gain. Prospect theory has been applied successfully to explain asset pricing (Barberis, Huang, & Santos, 2001), tax evasion (Yaniv, 1999), and monetary policy (Surico, 2007). The theory has not achieved many macroeconomic applications yet. A notable exception, however, is Foellmi et al. (2011), who study consumption paths in a growth Cass–Koopmans–Ramsey model under prospect utility. The authors show that prospect theory can explain consumption smoothing beyond the standard model. This is because risk-averse agents are reluctant to reduce their consumption to achieve a higher steady state. As a result, loss aversion can cause the economy to remain in a steady state with low consumption and capital. The Euler equation under prospect utility differs from its standard formulation in a Ramsey model. In particular, it relies on past values of consumption, making consumption no longer time-separable. Prospect utility can be conceptualized as (Foellmi et al., 2011):

$$U(c_t, c_{t-1}) = (1-\beta)u(c_t) + \beta v(c_t - c_{t-1}), \tag{7}$$

where $u(c_t) = (c_t^{1-\rho} - 1)/(1-\rho)$; c_{t-1} is the value of consumption in the past period. The last component of the above equation equals:

$$v(c_t - c_{t-1}) = c_t - c_{t-1} \quad \text{for } c_t - c_{t-1} \geq 0, \tag{8}$$

$$v(c_t - c_{t-1}) = \varphi(c_t - c_{t-1}) \quad \textit{for } c_t - c_{t-1} < 0,$$

where $\phi > 0$ and $0 < \alpha < 1$.

The Euler equation depends on past values of consumption c_{t+2}, c_{t+1}, c_t and c_{t-1}:

$$u'(c_t) = \varphi f'(k_{t+1})u'(c_{t+1}) + \frac{\beta}{1-\beta}[-v'(c_t - c_{t-1}) + \varphi v'(c_{t+1} - c_t) + \varphi f'(k_{t+1})(v'(c_{t+1} - c_t) + \varphi v'(c_{t+2} - c_{t-1}))], \tag{9}$$

where ϕ is the discount rate.

By reducing current consumption an agent suffers additional utility loss $-v'(c_t - c_{t-1})$. However, the reference point is lower for the next period of consumption, which yields a gain of $\phi v'(c_{t+1} - c_t)$. If the loss aversion parameter ϕ is sufficiently strong, consumers are reluctant to change their consumption path ($c_{t-1} = c_t = c$) even if capital stock is below its steady state. High loss aversion makes individuals more concerned about current consumption than about possible gains in future consumption. As a result, prospect theory generates more extreme reductions in consumption during downturns.

Finally, empirical evidence questions whether the discount rate remains constant over time. According to the discounted utility framework (DU) in the Ramsey model, people discount future preferences independent of their consumption in any other period. Empirical research into intertemporal choice has documented the various inadequacies of the DU model as descriptive model of behaviour. For instance, the empirically observed discount rates are not constant, but appear to decline over time, which has been referred to as hyperbolic discounting (e.g. Harris & Laibson, 2001). Under hyperbolic discounting, the short-run discount factor applied to near-term consumption trade-offs, e.g. today and tomorrow, differs from the long-run discount factor, which is applied between tomorrow and the day after tomorrow, and so on. This assumption leads to time-inconsistent preferences (Stroz, 1955). As a result, a person who discounts the future hyperbolically will not carry out the consumption plans he makes today. Karp (2005) introduces hyperbolic discounting to study optimal abatement. The author shows the regulator may be unwilling to bear moderate costs today in order to prevent substantial damages in the distant future. However, the model does not account for capital accumulation. Recent research shows that if hyperbolic discounting provides the same present value for a constant infinite income stream as standard exponential discounting, then the equilibrium rate of economic growth is also the same under both discounting methods (Strulik, 2015). For this reason, we do not study equilibrium outcomes in the model with hyperbolic discounting in this article.

2.2. The social cost of carbon

Estimates of the SCC dioxide emissions are an essential part of any climate assessment. The SCC is equivalent to the Pigouvian tax that should be placed on emissions, and is equivalent to the discounted value of damages due to emissions over time. Formally, the SCC can be measured either by the discounted present value of the damages imposed on the economy by the emission of one tonne of carbon, or by the marginal cost of mitigating that emission.

Although it seems straightforward to derive the SCC, doing so raises many controversies. The value of the SCC is highly sensitive to the choice of the discount rate, specific forms of utility and production functions, and how damage translates into climate loss. For instance, different economists favour different values of the discount rate, which leads to radically different policy prescriptions (for a discussion see Goulder & Roberton, 2012). Consequently, the estimates of the SCC vary from \$10 to \$200 per tonne of CO_2 (Pindyck, 2013). Tol (2008) reviews 211 estimates of the SCC, confirming that a lower discount rate implies a higher estimate. In addition, the estimates of the SCC depend on how the damage is specified (see Ackerman & Stanton, 2012). It is beyond the scope of this article to summarize all the recent debates, which has already been done elsewhere (e.g. Pindyck, 2013; van den Bergh & Botzen, 2015). Instead, here we ask the question of how behavioural anomalies affect the SCC.

The SCC is sensitive to how the economy responds to output shocks, which in the context of climate policies can be thought of as climatic events destroying part of the capital stock. Alternative behavioural models have different implications for the adjustment path following the shock. A model incorporating habit formation predicts a greater immediate reduction in capital after the productivity shock, and slower adjustments towards the equilibrium afterwards (Carroll et al., 2000). In this context, the stronger the habits are, the more severe and persistent the effect of a shock on savings and growth are expected. As a consequence, incorporating habits into the analysis of the SCC would generate higher than existing estimates. Also, adopting prospect theory in the growth models for climate policies would result in higher estimates of the SCC compared to the classic Ramsey model. Loss aversion makes individuals more concerned about current consumption than possible gains in future consumption. This generates substantial reductions in consumption during economic downturns, which would increase climate damages after output shocks. In particular, loss-averse consumers are reluctant to change their consumption path regardless of whether capital is above or below its optimal value (Foellmi et al., 2011). So far, adjustments following the shock have not been studied in the growth model with hyperbolic discounting or status-oriented consumers, which constitutes an important topic for future research.

3. Environmental policy in different behavioural models

Here, we integrate social status, habit formation, and loss aversion into the Ramsey model to derive the optimal pollution tax in Section 3.1 and then examine the probability of the rebound effect in different behavioural models in Section 3.2.

3.1. The optimal pollution tax in different behavioural models

How does integrating behavioural utility functions into the Ramsey model affect the individual and social optimums? If realistic behaviours are closer to the truth, would ignoring them undermine the effectiveness of climate and energy policies? Formally, alternative behavioural models affect the optimal path of consumption and investments via their impact on the Euler equation. This is because each model implies different values for the instantaneous elasticity of intertemporal substitution $\eta(c_t)$ and $U'(c_t)$. Table 1 summarizes the values of $\eta(c_t)$ and $U'(c_t)$ for different behavioural models, and their implications for the optimal pollution tax. In particular, (+) in the table indicates that the flow externality is greater under the behavioural model compared to the model with fully rational agents, whereas (–) indicates the opposite.

Table 1. The flow externality under different behavioural models.

Model	Utility functions	$\eta(c_t)$	$U'(c_t)$	The size of externality flow compared to a rational-agent model
A model with rational agents	$u(c_t) = \frac{c_t^{1-\rho}}{1-\rho}$	$\frac{1}{\rho}$	$c_t^{-\rho}$	
Keeping up with Joneses	$u(c_t) = \frac{(c_t - xC_t)^{1-\sigma}}{1-\sigma}$	$\frac{1-x}{\rho}$	$((1-x)c^t)^{-\rho}$	+
Habit formation model	$u(c_t) = \frac{(c_t/z_t^{\gamma})^{1-\sigma}}{1-\sigma}$	$\frac{1}{\rho+\gamma(1-\rho)}$	$\frac{(1-\gamma)(c_t^{1-\rho})^{1-\gamma}}{c_t}$	–
Prospect theory	$u(c_t) = (1-\beta)\frac{c_t^{1-\rho}}{1-\rho} + \beta v(c_t - c_{t-1})$	$\frac{1-\beta+\beta c_t^{\rho}}{\rho(1-\beta)}$	$\beta + (1-\beta)c_t^{-\rho}$	+

Note: (+) larger than under the rational-agent model; (–) smaller than under the rational-agent model.

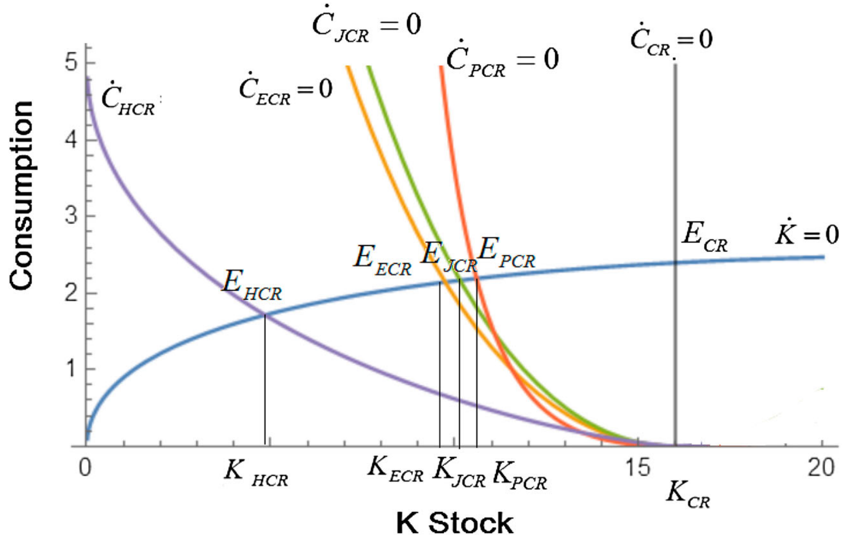


Figure 2. Steady states under different behavioural utilities and flow externality.

Note: We use in derivations the specific functions: $D_F(af(k_t)) = af(k_t)$, $f(k_t) = k_t^{\alpha}$, with parameter values: $a = 0.15$; $\alpha = 0.5$; $\theta = 0.025$; $\sigma = 0.5$; $\delta = 0.1$; $\phi = 1$; $\beta = 0.9$; $\gamma = 0.1$; $\rho = 0.5$, $x = 0.001$.

Figure 2 compares the social optimums for keeping up with the Joneses (E_{JCR}), habit formation (E_{HCR}), prospect theory (E_{PCR}); and also for rational agents (E_{ECR}). Bounded-rational agents – similarly to fully rational agents – ignore the impact of pollution. Therefore, they consume up to E_{CR}, which is exactly the amount consumed by rational agents in the classic Ramsey problem, regardless of the type of biases involved in the decision-making process. However, the socially optimal outcomes differ under alternative behavioural models, which implies that the optimal policy needs to be adjusted to correct not only for market failures but also for behavioural failures.

If the parameters describing the strengths of different anomalies equal zero, behavioural models are equivalent to the model with fully rational agents. Increasing the weight attached to the consumption of others in the model with status-oriented consumers, shifts the social optimum rightwards in Figure 2. A similar effect occurs after increasing the weight attached to the reference consumption (β) under prospect utility, which raises consumption and capital in the social optimum. As with the classic Ramsey problem of the pollution externality, imposing a tax on pollution equal to $D'_F(af(k_t))$brings the economy to the social optimum in both models: with loss-averse and status-oriented agents. However, in the presence of behavioural externalities, the social optimums are characterized here by 'overconsumption' compared to the rational model. Thus, the planner needs to correct for the behavioural failures on top of correcting the flow externality so as to bring the economy to E_{ECR}. The need for high environmental taxes in the face of relative consumption effects has been already acknowledged by Howarth (2006). The author shows that, in a one-sector growth model with exogenous population growth and technological change, private consumption generates a negative externality by raising the standards of living that other members of society must attain to achieve a given level of satisfaction. On the other hand, habitual consumers tend to consume too little compared to the 'rational' optimum. As a result, imposing a tax on pollution equal to $D'_F(af(k_t))$ would bring the economy to E_{HCR} state, whereas a lower tax level would be sufficient to achieve a rational equilibrium.

3.2. *The macro-behavioural assessment of energy efficiency measures*

Interest has arisen in recent years about the impact of bounded rationality on energy savings (e.g. Allcott, Mullainathan, & Taubinsky, 2014; Gillingham, Newell, & Palmer, 2009). It has been long recognized that policy measures, implemented with the aim of encouraging energy savings in production and consumption, can generate results opposite to those expected. This phenomenon is known as the rebound effect (e.g. Brookes, 2000; Sorrell, 2007). The effect goes back to Jevons (1865), who suggested that improvements in the efficiency of coal-fired steam engines would result in more coal consumption, ultimately offsetting the benefits from increased efficiency. It has been argued that the most effective way to discourage rebound may be through carbon pricing since the policy influences all potential energy-savings decisions (Baranzini, van den Bergh, Carattini, Howarth, & Padilla, 2016). However, this may be difficult to implement politically, especially in the form of nationally distinct taxes (van den Bergh, 2015).

Bounded rationality implies that individuals are unaware of the energy-intensities of their everyday actions and the indirect consequences of any energy conservation decisions (van den Bergh, 2011). Consequently, energy savings from reducing the frequency of, or quitting, specific activities can be offset by individuals shifting to other energy-intensive activities. Alternatively, behavioural failures such as loss aversion and present bias can prevent consumers from investing in energy-efficient technologies even if the lifetime energy savings exceed the lifetime costs of the investment. This is because consumers often undervalue energy savings if these savings are realized in the long term (Allcott et al., 2014; Greene et al., 2008).

To examine how improving energy efficiency in macroeconomic models would affect the probability of the rebound effect, we consider the following model:

$$U = \int_{t=0}^{\infty} \mathrm{e}^{-\theta t}[u(c_t) - D_F(ae_t)], \tag{10}$$

$$\dot{k}_t = f(k_t, e_t) - c_t - \delta k_t - p_e e_t, \tag{11}$$

where output is described by the Cobb–Douglass production function with constant returns to scale $f(k_t, e_t) = k_t^{\alpha 1}(\tau e_t)^{\beta 1}$, and the following inputs: energy e_t and capital k_t; whereas τ is energy efficiency; and $D_F(ae_t)$ is a damage function describing how energy translates into welfare loss. Firms employ inputs for production in proportion to their marginal productivity $k_t/\alpha_1 = p_e \tau e_t/\beta_1$, where p_e is the price of energy, while we set the price of capital to 1 for reasons of simplicity. After substituting $e_t = (\beta_1/p_e\tau\alpha_1)k_t$ to (10) and (11),

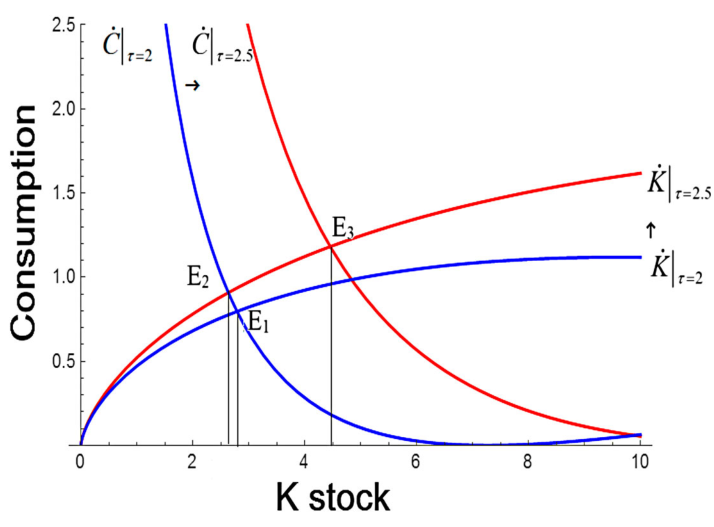
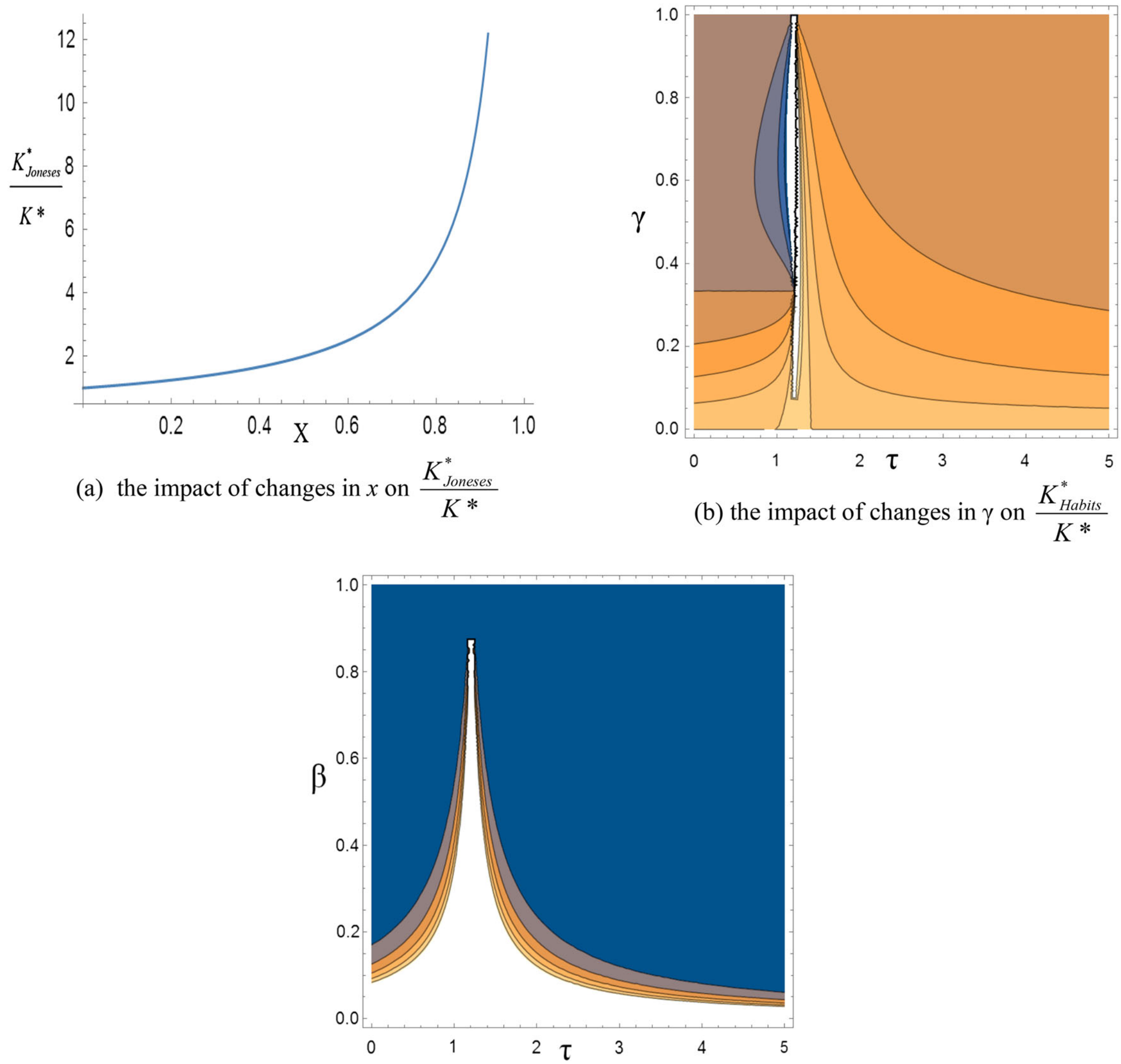


Figure 3. The effect of improved energy efficiency in the classic Ramsey model.

Note: We use parameter values: $a = 0.5$; $\alpha 1 = 0.5$; $\beta 1 = 0.35$; $\theta = 0.025$; $pe = 1.1$; $\delta = 0.1$; $\rho = 0.5$. (a) the impact of changes in x on $K^*_{Joneses}/K*$, (b) the impact of changes in γ on $K^*_{Habits}/K*$, and (c) the impact of changes in β on $K^*_{Loss-aversion}/K*$.



(a) the impact of changes in x on $\frac{K^*_{Joneses}}{K^*}$

(b) the impact of changes in γ on $\frac{K^*_{Habits}}{K^*}$

(c) the impact of changes in β on $\frac{K^*_{Loss-aversion}}{K^*}$

Figure 4. The effect of improved energy efficiency under different behavioural anomalies compared to the rational-agent model in the classic Ramsey model.

Note: We use parameter values: $a = 0.5$; $\alpha 1 = 0.5$; $\beta 1 = 0.5$; $\theta = 0.025$; $pe = 1.1$; $\delta = 0.1$; $\rho = 0.5$.

we derive the Euler equation as:

$$\dot{c}_t = \eta(c_t)c_t\left(f'(k_t) - \theta - \delta - \frac{\beta_1}{\alpha_1 \tau} - \frac{a(\beta_1/\alpha_1 \tau p_e)D'(ae_t)}{U'(c_t)}\right). \tag{12}$$

Figure 3 illustrates the effect of improvements in energy efficiency in the classic Ramsey model to the steady state. The individual optimum can be identified at the intersection of the $\dot{K} = 0$- and $\dot{C} = 0$- curves. An increase in τ shifts the curve $\dot{K} = 0$upwards, which reduces capital in the steady state from E_1 to E_2. Simultaneously, an increase in τ shifts the $\dot{C} = 0$- curve rightwards, increasing capital to E_3, and thus also the energy use. The net effect of improved energy efficiency on energy use depends on different parameter values, especially on the value of the elasticity of the substitution of inputs in production.

How do improvements in energy efficiency affect energy use in different behavioural models? To answer this question, we compare capital in the equilibrium of each behavioural model to its steady-state value in the rational-agent model. Energy use is proportional to capital in the equilibrium $E* = (\beta_1/p_e\tau\alpha_1)K*$. Therefore, changes in capital because of improvements in energy efficiency are indicative of corresponding changes in energy use. Formally, we look at the following ratios: $K^*_{Joneses}/K*$, $K^*_{Habits}/K*$, $K^*_{Loss-aversion}/K*$. If any of these indicators are greater than 1 it implies that more energy is used in the corresponding behavioural model compared to the rational-agent model for a given value of τ, which implies a higher probability of the rebound effect.

Figure 4 illustrates how the discussed ratios change depending on τ and the parameters describing the strength of different behavioural anomalies, namely the weights attached to consumption by other people (x), to habits (γ) and reference consumption (β). As we shall see, energy and capital use are always larger in the model with status-oriented consumers compared to the rational equilibrium, which implies a greater risk of the rebound effect. This is due to the fact that the ratio $K^*_{Joneses}/K* = 1/(1-x)$ is above 1 for $0 < x < 1$, while its value does not depend on τ.

In Figures 4(b)–(c), the area coloured in white indicates the range of parameters for which the ratio of capital in behavioural models compared to the rational equilibrium is greater than 1. In Figure 4(b), this area is very small, which suggests that in the model with habitual consumers, the probability of the rebound effect is negligible. Only for a very small range of values of τ, around 1.2 in Figure 4(b), do habits generate greater energy use than the rational-agent model. In turn, Figure 4(c) illustrates that, in prospect theory, the chances of a rebound effect are higher in the loss-aversion model compared to rational-agent model (i.e. $K^*_{Loss-aversion}/K* > 0$) for a larger range of parameter values. Here, the lower the value of β, the more likely the rebound effect is. In turn, for larger values of β, agents attach a greater weight to the reference consumption. They are therefore less willing to change their consumption path after improvements in energy efficiency, which implies a smaller consumption effect (a shift from E_2 to E_3 in Figure 3) than the rational model, reducing the probability of the rebound effect.

4. Conclusions

Macroeconomic models for climate policies have been much criticized for inadequately dealing with uncertainty, technological change, and the impacts of climate change. However, assumptions about agents' behaviours have been scrutinized far less often. This is surprising since the discounted utility model, which underlines the analysis of environmental policies in nearly all climate models, has been found to provide an inadequate description of how people actually behave.

Many behavioural anomalies have been identified in the literature as relevant to climate policy. If the behavioural-macro models are closer to the truth, environmental policy needs to correct not just for market failures but also for behavioural failures. However, so far the implications of behavioural anomalies for environmental policy have been discussed mostly in a descriptive manner. This is because many of the realistic behaviours are difficult to incorporate into the formal growth model (e.g. cooperation and crowding-in effects), or require a modelling setting with many agents (trust, fairness concerns). In this article, we take a different approach and study how behavioural anomalies affect environmental policy in the Ramsey model. We focus on status concerns, habit formation, and loss aversion, whose relevance for macroeconomic dynamics have already been established, and examine how the size of the behavioural externality depends of the strength of different anomalies.

In the Ramsey model with pollution externality, the social optimum can be achieved by imposing a Pigouvian tax on pollution (energy) equal to the marginal damage. We show that this tax is insufficient in models where consumers are status oriented and want to imitate the consumption of their neighbours (the Joneses) or where they are loss-averse. Loss aversion and status concerns may lead to 'overconsumption' compared to the first best solution. As a consequence, a pollution tax alone is unable to reach the social optimum, and an additional tax to correct behavioural failures is required. This is not the case in the model with habit formation, where agents consume less than the rational equilibrium.

We argued that adopting behavioural models to assess the SCC would generate very different estimates from the existing ones. The reason for this is that macro-behavioural models provide distinct perspectives on how economic agents behave in response to shocks to output productivity or capital destruction due to climatic events. According to prospect theory, agents may be unwilling to adjust their consumption after a shock, which would leave the economy in a steady state with low capital. Also, the more habitual consumers are, the slower adjustments are made towards the steady state because of capital destruction. Therefore, if these behavioural-macro models are closer to the truth, larger losses due to productivity or capital shocks are expected, which would result in higher estimates of the SCC.

In this article, we discuss different channels through which bounded rationality can affect policies aimed at improving energy efficiency. On the one hand, such improvements reduce energy use in production. On the other, the consumption effect implies that consumers can afford to buy more products, which become cheaper after improvements in energy efficiency are made. We show that with status concerns the consumption effect dominates, causing energy use to always be above its rationally optimal level. As result, the probability of the rebound effect is higher here compared to the rational-agent model. This suggests a need for a consumption tax to correct the behavioural failure. In turn, the probability of the rebound effect under habit formation is very low, as consumers are less likely to adjust their consumption levels, following improvements in energy efficiency. This means there is a small probability of a rebound effect. Finally, under loss aversion, the probability of the rebound effect depends on the weight, which consumers attach to the 'reference' consumption. The more important the reference consumption is for them, the less willing consumers are to change their consumption path after improvements in energy efficiency, which translates into a lower probability of a rebound effect.

The analysis proposed in the article is far from exhaustive. We focused on anomalies, which can undermine the effectiveness of climate policies. However, there are a number of realistic behaviours that can help reduce pollution. For instance, cooperation has received much attention in the last few decades (e.g. Dawes & Thaler, 1988; Fehr & Gächter, 2000; Fehr & Schmidt, 1999). Recent evidence suggests that people may behave cooperatively with respect to climate change (Carattini, Baranzini, & Roca, 2015; Ostrom, 2009; Tavoni & Levin, 2014). If people cooperate to reduce greenhouse gas emissions, a model that does not account for other-regarding preferences may overestimate climate damages. In addition, the impact of environmental policy on intrinsic motivation may affect the policy lessons, depending on whether these policies crowd-out or crowd-in environmental motivations. A carbon tax may signal the importance of climate-friendly behaviour, causing crowding-in (see Antweiler & Gulati, 2016; Davis & Kilian, 2011; Li, Linn, & Muehlegger, 2014; Rivers & Schaufele, 2015) or it may crowd-out environmental motivations if consumers perceive the policy as a signal that a lot has already been done to curb emissions. These issues constitute an important topic for future research. First, these behaviours need to be integrated into macroeconomic models, before they can guide environmental policy. All in all, current models to assess climate policies may deliver biased insights due to the omission of essential aspects of bounded rationality. Integrating bounded rationality into macroeconomic models of climate policy constitutes an important topic for future research, which can improve information about effective climate policies.

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