

Withagen, Cees A.

**Working Paper**

## The Social Cost of Carbon and the Ramsey Rule.

CESifo Working Paper, No. 7359

**Provided in Cooperation with:**

Ifo Institute – Leibniz Institute for Economic Research at the University of Munich

*Suggested Citation:* Withagen, Cees A. (2018) : The Social Cost of Carbon and the Ramsey Rule., CESifo Working Paper, No. 7359, Center for Economic Studies and ifo Institute (CESifo), Munich

This Version is available at:

<https://hdl.handle.net/10419/191384>

**Standard-Nutzungsbedingungen:**

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

**Terms of use:**

*Documents in EconStor may be saved and copied for your personal and scholarly purposes.*

*You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.*

*If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.*

# The Social Cost of Carbon and the Ramsey Rule.

*Cees Withagen*

## **Impressum:**

CESifo Working Papers

ISSN 2364-1428 (electronic version)

Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH

The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute

Poschingerstr. 5, 81679 Munich, Germany

Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email [office@cesifo.de](mailto:office@cesifo.de)

Editors: Clemens Fuest, Oliver Falck, Jasmin Gröschl

[www.cesifo-group.org/wp](http://www.cesifo-group.org/wp)

An electronic version of the paper may be downloaded

- from the SSRN website: [www.SSRN.com](http://www.SSRN.com)
- from the RePEc website: [www.RePEc.org](http://www.RePEc.org)
- from the CESifo website: [www.CESifo-group.org/wp](http://www.CESifo-group.org/wp)

# The Social Cost of Carbon and the Ramsey Rule.

## Abstract

The objective of this paper is to critically assess the use simple rules for the social cost of carbon (SCC) employing a rudimentary form of the Ramsey rule. Two interrelated caveats apply. First, if climate change poses a serious problem, it is hard to justify an exogenous constant growth rate of consumption. Second, to derive the SCC one needs full knowledge of the entire future. Popular assumptions to get around this, such as assuming current GDP is optimal, are difficult to justify.

JEL-Codes: Q540.

*Cees Withagen*  
*Department of Spatial Economics*  
*School of Business and Economics*  
*Vrije Universiteit Amsterdam*  
*The Netherlands – 1081 HV Amsterdam*  
*cwithagen@feweb.vu.nl*

November 8, 2018

Acknowledgements go to Rob Aalbers, Erik Ansink, Simon Dietz, Christian Gollier, Sjak Smulders, Yacov Tsur, Aart de Zeeuw. The views of these persons need not coincide with those of the author.

## 1. Introduction

In a rudimentary form the Ramsey rule reads  $r = \rho + \eta g$ . Here,  $r$  is the discount rate,  $\rho$  is the pure rate of time preference,  $\eta$  is the elasticity of marginal utility, and  $g$  is the (per capita) consumption growth rate. The rule was derived by Ramsey (1928) as a necessary condition for optimality in a seminal model of economic growth. The Ramsey rule is often used to calculate the so-called Social Cost of Carbon (SCC), defined as the (monetized) current and future damage from emitting a marginal unit of CO<sub>2</sub> into the atmosphere. The reason for using the Ramsey rule for this purpose is that future damages need to be discounted, and the discount rate  $r$  is typically used for this purpose. It is calculated as the sum of an exogenously imposed pure rate of time preference and the product of the elasticity of marginal utility and the growth rate of consumption, both mostly taken as exogenous constants.<sup>1</sup> Tol (2016) surveys 211 estimates of the SCC, developed over the period 1982-2006 and argues that the vast majority of these estimates is based on the Ramsey rule. The policy relevance of the SCC lies in the fact that it can be interpreted as the Pigouvian tax to be imposed on CO<sub>2</sub> emissions. Since the level of the carbon tax and its development over time is a central issue in the debate on climate change and the way to fight climate change, the importance of the Ramsey rule is evident.

The objective of the present contribution is to investigate when the use of the Ramsey rule is justified and when not. The focus is on climate change policy. As mentioned before this is a popular area of using the Ramsey rule. But there are two interrelated caveats. First of all, if climate change poses a serious problem, then the use of the Ramsey rule to derive the appropriate interest rate may lead to errors, because as a consequence of the required non-marginal climate change projects, the growth rate of consumption is likely to change: Climate change policy is a non-marginal phenomenon. Dietz and Hepburn (2013) provide a nice overview of the literature, showing that the economics profession has been aware of the consequences of large projects for cost-benefit analysis (Dasgupta et al. (1972) and Starrett (1988)). They also provide a convincing example where valuing the reduction of global carbon emissions as if it were a marginal project, leads to serious errors. Second, we want to show that the by now popular custom of deriving ‘simple’ rules for the SCC (see Golosov et

---

<sup>1</sup> Of course many forms of uncertainty are pertinent to climate change and should be taken into account by modifying the Ramsey rule (see Gollier and Weitzman (2010) and Gollier (2012)). In this note we restrict ourselves to certainty. Uncertainty will not affect our basic argument.

al. (2014), Bijgaart et al. (2016), Rezai and Van der Ploeg (2015)) is hard to justify. In an optimal decentralized economy, the social cost of carbon can only be derived with full knowledge of the complete optimal future path of the relevant variables, including the interest rate, which is endogenous in optimal growth models. This has been argued before by Smulders (2012) in a general context where he argues that to know shadow prices it is necessary to know the future development of the economy. Nevertheless, in economic practice many empirical studies are performed to calculate the ‘right’ interest rate, based on just postulating a growth rate and an elasticity of marginal utility (see Werkgroep Discontovoet (2015) and Centraal Planbureau (2015) for the Netherlands, Cropper (2012), Committee for an Official Shadow Price of Carbon (2018) for France).

We will proceed as follows. In section 2 we outline the basic framework. Subsequently we provide a set of examples where the naive use of the Ramsey rule may lead to values of the SCC that are incorrect.

## 2. The basic model

In the present section we discuss a model that can be seen as a prototype model of the ‘Integrated Assessment Models’ used to evaluate climate policy. We keep the model as simple as possible, still capturing the essence of IAMs. Hence, it includes a climate module and describes the accumulation of capital. We consider a closed economy. The labor force  $L$  equals population and grows at an exogenous and constant growth rate  $\pi$ . Instantaneous welfare  $W$  depends positively on per capita consumption  $c = C/L$  and negatively on accumulated atmospheric CO2 concentration  $X$ , with initial concentration  $X_0$ . Instantaneous utility is discounted at a constant rate of pure time preference  $\rho$ . Total welfare is to be maximized:

$$\max \int_0^{\infty} e^{-\rho t} L(t) W(C(t)/L(t), X(t)) dt.$$

The economy’s aggregate production function is given by  $F(K, L, R + Z, X, t)$ , where  $K$  denotes man-made capital,  $R$  is the input from a non-renewable resource,  $Z$  is the use of a renewable resource that is perfectly substitutable with the non-renewable resource. The time argument  $t$  indicates the possibility of exogenous technical change. We also incorporate atmospheric CO2 that might negatively affect output. Emissions of CO2 are denoted by  $E$ . In

the model they are proportional to the use of fossil fuel, with factor of proportionality equal to unity. Atmospheric concentration decays at a rate  $\sigma$  per unit of time. This is a heroic assumption. But more realistic and therefore more complicated modelling of the climate module will reinforce our conclusions. The unit extraction cost of non-renewables depends on the remaining stock  $S$ . Extraction costs are represented by  $G(S)R$  where  $G$  is a decreasing function. Renewables are produced with a linear technology, requiring an amount  $b$  of output per unit of production of the renewable. This  $b$  may be declining over time. The optimal path of the economy is then derived from maximizing social welfare subject to the conditions described above, including the obvious non-negativity conditions.

$$(1) \dot{L}(t) = \pi L(t), L(0) = L_0,$$

$$(2) \dot{S}(t) = -R(t), S(0) = S_0,$$

$$(3) \dot{X}(t) = E(t) - \sigma X(t), X(0) = X_0,$$

$$(4) \dot{K}(t) = F(K(t), L(t), R(t) + Z(t), X(t), t) - C(t) - G(S(t))R(t) - b(t)Z(t) - \mu K(t), K(0) = K_0,$$

$$(5) E(t) = R(t),$$

$$(6) C(t) \geq 0, R(t) \geq 0, Z(t) \geq 0, E(t) \geq 0, X(t) \geq 0, S(t) \geq 0, K(t) \geq 0.$$

Taking account of (1) and (5) and setting  $L_0 = 1$  we can write the Hamiltonian of the system as

$$H(X, S, K, C, R, Z, \lambda, \tau, \kappa, t) = e^{(\pi-\rho)t} W(e^{-\pi t} C, X) + \lambda[-R] - \tau[R - \sigma X] \\ + \kappa[F(K, e^{\pi t}, R + Z, X, t) - C - G(S)R - b(t)Z - \mu K].$$

Here  $\lambda$  is the shadow price of the exhaustible resource,  $\tau$  is the shadow cost of atmospheric CO2 and  $\kappa$  is the shadow price of capital. The necessary conditions for the optimization entail the maximization of the Hamiltonian with respect to the instruments  $C$ ,  $R$ ,  $Z$  and  $E$ . Moreover, the shadow prices follow certain paths. This yields

$$(7) e^{-\rho t} W_c(e^{-\pi t} C, X) = \kappa,$$

$$(8) -\lambda - \tau + \kappa[F_{R+Z}(K, e^{\pi t}, R + Z, X, t) - G(S)] = 0 \text{ if } R > 0,$$

$$(9) F_{R+Z}(K, e^{\pi t}, R + Z, X, t) = b(t) \text{ if } Z > 0,$$

$$(10) -\dot{\lambda} = -\kappa G'(S)R,$$

$$(11) \quad \dot{\tau} = e^{(\pi-\rho)t} W_X(c, X) + \tau\sigma + \kappa F_X(K, e^{\pi t}, R + Z, X, t),$$

$$(12) \quad -\dot{\kappa} = \kappa[F_K(K, e^{\pi t}, R + Z, X, t) - \mu].$$

The social cost of carbon is the loss in welfare due to a marginal increase in the atmospheric concentration of CO2. It is equal to the negative of the shadow price of atmospheric CO2:  $\tau$ . We are also interested in the discount rate. It follows from (12) and (7) that

$$(13) \quad r \equiv F_K - \mu = -\dot{\kappa} / \kappa = \rho + \eta(c, X) \frac{\dot{c}}{c} + \mathcal{G}(c, X) \frac{\dot{X}}{X},$$

$$\text{where } c = C / L, \quad \eta(c, X) = -\frac{W_{cc}(c, X)c}{W_c(c, X)} \quad \text{and} \quad \mathcal{G}(c, X) = -\frac{W_{cX}(c, X)X}{W_c(c, X)}.$$

Next we derive an expression for the social cost of carbon. We have, in shorthand,

$$\dot{\tau} = e^{(\pi-\rho)t} W_X + \tau\sigma + \kappa F_X.$$

The solution reads

$$\tau(t) = -e^{\sigma t} \left( \int_t^\infty e^{-\sigma s} \{e^{(\pi-\rho)s} W_X(c(s), X(s)) + \kappa(s) F_X(K(s), e^{\pi s}, R(s) + Z(s), X(s), s)\} ds \right).$$

Taking into account the definition of the interest rate and (7), we have, in shorthand,

$$\tau(t) = -e^{\sigma t} \left( \int_t^\infty e^{-\sigma s} \{e^{(\pi-\rho)s} W_X(s) + W_c(0) e^{-\int_0^s r(v) dv} F_X(s)\} ds \right).$$

Here the social cost of carbon is expressed in utility terms. Dividing by  $W_c(t)$  yields

$$(14) \quad \frac{\tau(t)}{W_c(t)} = -e^{\sigma t} \left( \int_t^\infty e^{-\sigma s} \left\{ e^{(\pi-\rho)s} \frac{W_X(s)}{W_c(t)} + \frac{W_c(0)}{W_c(t)} e^{-\int_0^s r(v) dv} F_X(s) \right\} ds \right).$$

Let us consider expressions (13) and (14) in detail. Expression (13) has the flavor of the classical Ramsey rule  $r = \rho + \eta g$ . But (13) is much more general and contains elements that are often omitted in the derivation of simple rules.



First, since instantaneous welfare may directly depend on the stock of atmospheric CO<sub>2</sub>, for example due to increased health problems, there appears an additional term in the Ramsey

$$\text{rule: } \mathcal{A}(c, X) \frac{\dot{X}}{X}.$$

In most of the existing ‘simple rules’ literature not much attention is paid to justifying the usually made assumption of absence of CO<sub>2</sub> in the instantaneous welfare function. This neglects the existence of a large literature on how to model damages directly in the instantaneous welfare function (see e.g. Michel and Rotillon (1995)). The least one would expect is a sensitivity analysis with respect to alternative preference specifications.

Second, the elasticity of marginal utility of consumption,  $\eta(c, X)$ , may be a function of consumption as well as the CO<sub>2</sub> stock. Even with additively separable utility of consumption and disutility of atmospheric CO<sub>2</sub>, the elasticity does not need to be independent of the consumption rate.

Third, in employing the classical Ramsey rule to assume that the growth rate of consumption equals a constant stationary growth rate (see e.g. Rezai and Van der Ploeg (2016) and Van der Ploeg and Rezai (2018)) is not very plausible. In the simple model described, due to our assumption on the carbon cycle and the exhaustibility of fossil fuel, a steady state has a zero stock of atmospheric CO<sub>2</sub> and, most likely, no use of fossil fuel (or with use of fossil fuel going to zero)<sup>2</sup>. We are then in a state with green growth. However, that steady state is highly unlikely to prevail from the start, which is now. Interesting for policy makers in the present is how to make and steer the transition. Consequently, the relevant interest rate is not so much the interest rate corresponding with a steady state.

This brings us to a discussion of (14). Clearly, this is not a simple expression. In order to calculate the optimal social cost of carbon, we not only need to know *present* optimal consumption but also the entire *future* optimal path of all variables involved, regardless of whether atmospheric CO<sub>2</sub> does or does not play a direct role in welfare.<sup>3</sup> In order to find a simple rule heroic assumptions are made in the literature. For example Golosov et al. (2014) introduce specific functional forms for preferences and technology and claim that the optimal carbon tax is proportional to GDP. Rezai and Van der Ploeg (2016) employ slightly more

---

<sup>2</sup> With a more realistic carbon cycle atmospheric CO<sub>2</sub> will not equal zero in the steady state. But still it will take very long before the steady state is reached. See also section 3.3.

<sup>3</sup> It does play a role in e.g. an early paper by Van der Ploeg and Withagen (1990).

general functional forms and use the classical Ramsey and claim that the social cost of carbon tax is “almost” proportional to GDP. However, in both approaches the carbon tax is taken proportional to *actual* GDP and not to, as it should be, *optimal* GDP. Hence, together with the assumption of being in a steady-growth state, this may lead present-day policy makers to draw the wrong conclusions and implement suboptimal policies. Indeed, if climate change poses a serious problem, optimal input of fossil fuel is unlikely to equal current input. A similar objection concerns the simple rule in Bijgaard et al. (2016) who assume that actual consumption equals optimal consumption. A similar inconsistency appears in Nordhaus and Sztorc (2013), who seem to assume that actual current policy is optimal policy. Dietz and Hepburn (2013) convincingly show that evaluating projects on the assumption that they don’t have an effect on the economy in general equilibrium (such as consumption) may lead to suboptimal outcomes. They provide examples where in a general equilibrium approach, with endogeneity taken into account, projects may be rejected whereas they would be accepted otherwise.

### 3. Illustrative examples

In this section we present some examples, most of them known from the existing literature, of the difficulties of using simple rules. We first consider the original Ramsey model and some straightforward extensions. Then we discuss the effect of introducing non-renewable resources. Finally we go into the outcomes of a few analytical models that come close to the prototype model considered in the previous section.

#### 3.1 The original Ramsey model and some extensions.

The model developed by Ramsey (1928) is an optimal one sector growth model with one sector. The production function has only man-made capital as an input. There is no population growth, no technical change, no pure time preference, no emissions, no non-renewable resources. Hence, the problem reduces to

$$\max \int_0^{\infty} [U(C(t)) - U(C^*)] dt,$$

subject to

$$\dot{K}(t) = F(K(t)) - C(t) - \mu K(t), K(0) = K_0,$$

$$C(t) \geq 0, K(t) \geq 0.$$

Here  $C^*$  is defined by  $C^* = F(K^*) - \mu K^*$ ,  $F_K(K^*) = \mu$ .<sup>4</sup> The Ramsey rule reads

$$\eta(C(t)) \frac{\dot{C}(t)}{C(t)} = F_K(K(t)) - \mu = r(t).$$

It is a necessary condition for optimality. Ramsey shows that under mild conditions with respect to the utility function and the production function the economy converges to the steady state  $(K^*, C^*)$ . Obviously, if the actual capital stock  $K_0$  is not equal to  $K^*$ , the interest rate is not equal to zero and consumption is not the steady state consumption. Consumption will fall over time if and only if  $K_0 > K^*$ . It may also take infinitely long before consumption, and hence its growth rate, becomes constant. Extending this model with labor in the production function, growing at a constant rate  $\pi$ , allowing for Harrod technical progress at a rate  $\psi$ , for constant returns to scale in production and for a positive rate of pure time preference  $\rho$ , yields an optimal long run per capita consumption growth rate equal to  $\psi$ . The conclusions are again that the growth rate of per capita consumption is  $\psi$  forever only if we happen to start in the state corresponding with steady state growth. Hence, even if the elasticity of marginal utility is constant, assuming a constant interest rate and a constant per capita growth rate, is heroic.

### 3.2 Nonrenewable resources

Fossil fuels play a crucial role in climate change economics. However, their exhaustibility is seldom taken into account. This may give rise to insufficient attention for its consequences for consumption growth, and therefore the Ramsey rule. Stiglitz (1974) considered an optimal growth model in the vein of Ramsey, including, say, energy as a production factor, where energy comes from a non-renewable resource. He uses a Cobb-Douglas production function and a utility function with elasticity of marginal utility equal to unity. Withagen (1990) extended the model so as to include non-unitary elasticity of marginal utility. The economy's objective is to maximize

$$\int_0^{\infty} e^{-\rho t} e^{\pi t} \frac{1}{1-\eta} (C(t)e^{-\pi t})^{1-\eta} dt,$$

subject to

---

<sup>4</sup>This  $C^*$  is introduced in order for the objective functional to converge.

$$\dot{K}(t) = K^{\alpha_1}(t)R^{\alpha_2}(t)e^{\alpha_3(\varphi+\pi)t} - C(t) - \mu K(t), K(0) = K_0,$$

$$\dot{S}(t) = -R(t), S(t) \geq 0, S(0) = S_0.$$

For an optimum to exist the (long run) growth rate of fossil fuel use should be negative. In particular it is required that  $(1 - \alpha_1)(\rho - \eta\pi) > \alpha_3(\pi + \varphi)(1 - \eta)$ . Moreover, Withagen shows that the long run growth rate of consumption converges to  $g_C = \frac{(\pi + \varphi)\alpha_3 - \alpha_2(\rho - \eta\pi)}{\alpha_2\eta + (1 - \alpha_1 - \alpha_2)}$ .<sup>5</sup>The relevance of this result for the present discussion on the use of the Ramsey rule and SCC is that the consumption growth rate and the elasticity of marginal utility are difficult to disentangle: Postulating a given elasticity has an impact on the long run growth rate. The fact that this occurs in a very simple model with fossil fuel, does not make this issue a scientific curiosity. Exhaustibility of fossil fuel is pertinent in the real world and should be included in any IAM.

Another important finding of resource economics in the present context is due to Dasgupta and Heal (1974) who show that, even in the absence of technological progress, optimal consumption may be increasing for an initial interval of time and decreasing eventually. Hence, in that case, even with a constant elasticity of marginal utility, the social rate of discount is non-monotonic as well, and hence not constant. Moreover, whether or not there is a phase with increasing consumption depends on the level of the pure rate of time preference (see Benchechroun and Withagen (2011)). Hence, in this version of the Ramsey rule, the growth rate  $g$  is dependent on the rate of pure time preference  $\rho$ . Again, disentangling the growth rate and the rate of pure time preference is not warranted.

### 3.3. Models with climate change

There exist numerous papers on capital accumulation and pollution. Early contributions include Forster (1973) and Keeler et al. (1971). A recent paper that closely resembles the model of Section 2 was developed by Van der Ploeg and Withagen (2014). It focuses on the transition to a carbon-free economy. The maximization problem reads as follows.

---

<sup>5</sup> Note that for constant returns to scale and in the absence of fossil fuel in the production function ( $\alpha_2 = 0$ ) the growth rate is  $\pi + \varphi$ .

$$\int_0^{\infty} e^{-\rho t} W(C(t), X(t)) dt = \int_0^{\infty} e^{-\rho t} [U(C(t)) - D(X(t))] dt ,$$

where welfare is additively separable in utility from consumption and damages from accumulated CO2. The constraints are (1)-(6) with  $\pi = \sigma = 0$  and without technical progress in the production function and the development of renewables. Hence,

$$\dot{K}(t) = F(K(t), R(t) + Z(t)) - C(t) - G(S(t))R(t) - bZ(t) - \mu K(t), K(0) = K_0 .$$

Among the necessary conditions we have the Ramsey rule again:

$$F_K(K(t), R(t) + Z(t)) - \mu = \rho + \eta(C(t)) \frac{\dot{C}(t)}{C(t)} .$$

In the long run the economy will (asymptotically) converge to the carbon-free steady state, where, basically, we are back in the standard Ramsey model that was discussed as the first example. Without population growth and without technical progress, the rate of consumption will then be constant and the appropriate discount rate in that phase equals the rate of pure time preference. However, this should obviously not be the discount rate used on the transition path, because along the transition path optimal consumption can be increasing or decreasing. Actually, it is shown that if the economy is abundant in fossil fuel consumption will initially rise, overshooting the steady state carbon-free consumption rate, and eventually decrease towards the steady state. Simulations show that in such an economy the carbon tax might be monotonically increasing, but it can also be inverted U-shaped, depending on the question whether the economy is still in the developing stage or mature, in terms of capital. In any case, a simple rule exists, obviously, but it may be far from optimal.

#### 4. Conclusions

In this note it has been demonstrated that one should be careful in proposing simple rules based on specific assumptions with regard to the constituent elements of the Ramsey rule. The argument that policy makers want such rules, giving numbers, and preferably constant numbers, is not convincing unless the scientific policy advisors can make clear that the model they have in mind, justifies this choice. The existing rules make heroic assumptions: current GDP or consumption is optimal GDP or consumption. One could argue that the difference is not large, but that is hard to accept when it comes to climate change, which requires action in

the short run. Moreover, even if the difference is small, say *only* 1% of world GDP, one may wonder why the *price* of a simple rule would be billions of euros. Wouldn't it be better for policy makers to confront them with a set of scenarios, entailing the accumulation of atmospheric CO<sub>2</sub>, paths of capital accumulation, exhaustion of fossil fuel, consumption paths, consistent with each other, and the let the policy maker make a choice? Technically, the design of scenarios is relatively easy, given the enormous power we have in numerical calculations. One objection could be that preference of policy makers should be revealed *ex ante*, not *ex post*. However, we would like to end with a quote from Nobel Prize Winner Tjalling Koopmans: "Ignoring realities in adopting "principles" may lead one to search for a nonexistent optimum or to adopt an optimum that is open to unanticipated objections" (Koopmans, 1965). Indeed, if the policy maker would not understand what the ingredients of the model are, then it is better to confront her with entire time paths, rather than with optimal long run growth rates of e.g. discount rates or the social cost of carbon.

## References

Arrow, K., Cropper, M., Gollier, C., Groom, B., Heal, G., Newell, R., Nordhaus, W., Pindyck, R., Pizer, W., Portney, P., Sterner, T., Tol, R., and Weitzman, M.(2013): "Determining benefits and costs for future generations", *Science* 6144, pp. 349-350.

Arrow, K., Cropper, M., Gollier, C., Groom, B., Heal, G., Newell, R., Nordhaus, W., Pindyck, R., Pizer, W., Portney, P., Sterner, T., Tol, R., and Weitzman, M.(2012): "How should benefits and costs be discounted in an intergenerational context? The views of an expert panel", *Resources for the Future Discussion Paper* 12-52.

Benckroun, H. and Withagen, C. (2011): "The optimal depletion of exhaustible resources: A complete characterization", *Resource and Energy Economics* 33, pp. 612-636.

Bijgaart, I. van den, Gerlagh, R. and Liski, M. (2016): "A simple formula for the social cost of carbon", *Journal of Environmental Economics and Management* 77, pp. 75-94.

Centraal Planbureau (2015), *De discontovoet ontrafeld*, CPB Notitie.

Committee for an Official Shadow Price of Carbon (2018): "Nouvelle trajectoire de valeur tutélaire du carbone", *mimeo*.

Cropper, M. (2012): "How should benefits and costs be discounted in an intergenerational context?", *RFF Discussion Paper* 12-42.

Dasgupta, P., Marglin, S. and Sen, A. (1972), *Guidelines for Project Evaluation*, UNIDO, New York.

- Dasgupta, P. and Heal, G. (1974): “The optimal depletion of exhaustible resources”, *The Review of Economic Studies* 41, pp. 3-28.
- Dietz, S. and Hepburn, C. (2013): “Benefit-cost analysis of non-marginal climate and energy projects”, *Energy Economics* 40, pp. 61-71.
- Discount Rate Working Group (2015): “Report Working Group Discount Rate”, *mimeo*.
- Forster, B. (1973): “Optimal capital accumulation in a polluted environment”, *Southern Economic Journal* 39, pp.544-547.
- Gollier, C. (2012), *Pricing the planet’s future, The Economics of Discounting in an Uncertain World*, Princeton University Press.
- Gollier, C. and Weitzman, M. (2010) “How should the distant future be discounted when discount rates are uncertain?”, *Economics Letters* 107, pp. 350-353.
- Golosov, M., Hassler, J., Krusell, P. and Tsyvinski, A. (2014): “Optimal taxes on fossil fuel in general equilibrium”, *Econometrica* 82, pp. 41-88.
- Groom, B. and Maddison, D. (2018): “New estimates of the elasticity of marginal utility for the UK”, forthcoming in *Environmental and Resource Economics*.
- Keeler, E., Spence, M. and Zeckhauser, R. (1971): “The optimal control of pollution”, *Journal of Economic Theory* 4, pp. 19-34.
- Koopmans, T. (1965): “On the concept of optimal economic growth”, in *The Econometric Approach to development Planning, Pontificiae Academiae Scientiarum Scriptum Varia*, Amsterdam, North-Holland, pp. 225-287.
- Michel, P. and Rotillon, G. (1995): “Disutility of pollution and endogenous growth”, *Environmental and Resource Economics* 6, pp. 279-300.
- Nordhaus, W. and Sator, P. (2013): “DICE 2013R: Introduction and User’s Manual”, *mimeo*, website dicemodel.net.
- Ploeg, F. van der and Withagen, C. (1991): “Pollution control and the Ramsey problem”, *Environmental and Resource Economics* 1, pp. 215-236
- Ploeg, F. van der and Withagen, C. (2014): “Growth, renewables and the optimal carbon tax”, *International Economic Review* 55, pp. 283-311.

- Ploeg, F. van der and Rezai, A. (2018): “Simple rules for climate policy and integrated assessment”, *CEifo Working Paper 7207*.
- Ramsey, F. (1928): “A mathematical theory of saving”, *The Economic Journal* 38, pp. 543-559.
- Rezai, A. and Ploeg, F. van der (2016): “Intergenerational inequality aversion, growth, and the role of damages: Occam’s rule for the global carbon tax”, *Journal of the Association of Environmental and Resource Economics* 3, pp. 493-522.
- Rezai, A. and Ploeg, F. van der (2015): “Robustness of a simple rule for the social cost of carbon”, *Economics Letters* 132, pp. 48-55.
- Smulders, S. (2012): “An arrow in the Achilles’ heel of sustainability and wealth accounting”, *Environmental and Development Economics* 17, pp. 368-372.
- Starrett, D. (1988), *Foundations of Public Economics*, Cambridge university Press, Cambridge.
- Stern, N. (2007), *Stern Review: The Economics of Climate Change*, Cambridge University Press, Cambridge.
- Stiglitz, J. (1974): “Growth with exhaustible resources: Efficient and optimal growth paths”, *Review of Economic Studies, Symposium Issue*, pp. 139-152.
- Tahvonen, O. and Kuuluvainen, J. (1991), “Optimal growth with renewable resources and pollution”, *European Economic Review* 35, pp. 650-661.
- Tol, R. (2008): “The social cost of carbon: Trends, outliers and catastrophes”, *Economics: The Open Access E-Journal* 2, pp. 1-22.
- Werkgroep Discontovoet 2015 (2015), *Rapport Werkgroep Discontovoet 2015, mimeo*.
- Withagen, C. (1990): “Topics in resource economics”, in F. van der Ploeg (ed.), *Advanced Lectures in Quantitative Economics*, Academic Press, London, pp. 381-419.