Energy Policy 39 (2011) 2208–2212

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Communication

When do increasing carbon taxes accelerate global warming? A note on the green paradox

Ottmar Edenhofer [a,b], Matthias Kalkuhl [a,*]

[a] Potsdam Institute for Climate Impact Research, PO Box 601203, 14412 Potsdam, Germany
[b] Technische Universität Berlin, Strasse des 17. Juni 135, 10623 Berlin, Germany

ARTICLE INFO

Article history:
Received 6 October 2010
Accepted 11 January 2011
Available online 5 February 2011

Keywords:
Climate policy
Resource taxes
Supply-side dynamics

ABSTRACT

The "green paradox" by Hans–Werner Sinn suggests that increasing resource taxes accelerate global warming because resource owners increase near-term extraction in fear of higher future taxation. In this note we show that this effect does only occur for the specific set of carbon taxes that increase at a rate higher than the effective discount rate of the resource owners. We calculate a critical initial value for the carbon tax that leads to a decreased cumulative consumption over the entire (infinite) time horizon. Applying our formal findings to carbon taxes for several mitigation targets, we conclude that there is a low risk of a green paradox in case the regulator implements and commits to a permanently mal-adjusted tax. This remaining risk can be avoided by emissions trading scheme as suggested by Sinn—as long as the emission caps are set appropriately and the intertemporal permit market works correctly.

1. Introduction

The green paradox of Sinn (2008) analyzes possible responses of intertemporally profit maximizing fossil resource owners to climate policy, which are omitted by many existing studies on climate policy instruments. The focus on the dynamics of fossil fuel supply leads to important implications regarding the effectiveness and robustness of policy instruments. By examining several tax schemes, Sinn concludes that "measures to reduce carbon demand, ranging from taxes on fossil fuel consumption to the development of alternative energy sources […] will not mitigate the problem of global warming" (Sinn, 2008, p. 388). The analysis of Sinn is in particular based on a formal examination of increasing ad-hoc[1] *cash-flow* taxes for resource owners within a Hotelling model. Increasing cash-flow taxes raise the value of resources extracted in the present relative to the resources extracted in the far-distant future. As such taxes, for Sinn's model assumptions, always exhaust the entire stock within infinite time, such a relative up-valuation of early extracted fossil resources leads to higher near-term extraction compared to the zero-tax case. Thus, increasing cash-flow taxes accelerate extraction and worsen global warming (the "green paradox"). Therefore, Sinn proposes several other policies like decreasing cash-flow taxes, constant unit taxes, *in-situ* subsidies, emissions trading, or capital source taxes which slow down and postpone extraction.

In this note, we focus on the impact of increasing *unit* taxes on resource extraction instead of cash-flow taxes because the economic and political debate mainly centers on CO_2 or carbon taxes as unit taxes which are not linked to actual prices of fossil resources (e. g. IPCC, 2007, pp. 755–756; Nordhaus, 2008; Stern, 2008; Edenhofer et al., 2010). As it turns out, the denomination 'increasing taxes' has a very different meaning and incentive effect for unit and cash-flow taxes. This comes from the intertemporal dynamics of the resource extraction model which generates increasing resource prices due to increasing scarcities. We use basically the same model as Sinn (2008) and extend the original model by a formal analysis of unit taxes. While Sinn focuses only on a pure *timing effect* of policies (i.e. a pure intertemporal reallocation of resource extraction without affecting the cumulative amount of extraction), we will also take into account a *volume effect* (i.e. a lower cumulative amount of extraction within an infinite time horizon).

2. The effect of increasing resource taxes

In order to keep the analysis simple, we assume constant extraction costs $c \geq 0$ and focus on the tax and price dynamics of the standard Hotelling problem for a competitive resource industry as presented in Sinn (2008). There, resource owners maximize profit according to:

$$\max \int_0^\infty (1-\upsilon(t))(p(t)-c)q(t)e^{-rt}dt$$
$$\dot{S}(t) = \frac{dS(t)}{dt} = -q(t)$$
$$S(0) = S_0$$

* Corresponding author. Tel.: +49 331 288 2528; fax: +49 331 288 2640.
E-mail address: kalkuhl@pik-potsdam.de (M. Kalkuhl).

[1] The tax is ad-hoc because it is not derived from an optimality or efficiency criterion.

0301-4215/$ - see front matter © 2011 Published by Elsevier Ltd.
doi:10.1016/j.enpol.2011.01.020

where $p(t)$ is the resource price, $q(t)$ the resource extraction, r the interest rate, $S(t)$ the resource stock in the ground and $0<S_0<\infty$ the initial stock size. The resource price is determined by the demand function $q(p)$ with $q'(p)=(\partial q(p))/\partial p<0$ and $q(p)>0$ for all $p>0$.[2] In contrast to Sinn's increasing cash-flow tax $\upsilon(t)=1-\psi_0 e^{\sigma t}$ with $\sigma \leq 0$ we will in the following consider the unit tax $\tau(t)=\tau_0 e^{\theta t}$ which increases at a constant rate θ. The maximization problem, hence, reads:

$$\max \int_0^\infty (p(t)-\tau(t)-c)q(t)e^{-rt}dt$$
$$\dot{S}(t)=-q(t)$$
$$S(0)=S_0$$

By setting up the Hamiltonian (in the following, we suppress the explicit time-dependency of the variables p, q, τ, λ and S)

$$H=(p-\tau-c)q+\lambda\dot{S}$$

we obtain as first-order conditions:

$$\lambda=p-\tau-c$$
$$\dot{\lambda}=r\lambda$$

These lead to the Hotelling rule

$$r=\frac{\dot{p}-\dot{\tau}}{p-\tau-c}=\frac{\dot{p}-\dot{\tau}+r\tau}{p-c}=\frac{\dot{p}+(r-\theta)\tau}{p-c} \tag{1}$$

and to the transversality condition

$$0=\lim_{t\to\infty}\lambda S e^{-rt}=\lim_{t\to\infty}(p-\tau-c)Se^{-rt}$$

The resource price cannot be lower than the sum of the tax and the extraction costs, $p\geq\tau+c$. We define τ_0^* as the initial tax level where a pure tax-and-extraction-cost-price would equalize cumulative demand with the entire resource stock, i.e.[3]

$$\int_0^\infty q(\tau_0{}^* e^{\theta t}+c)dt=S_0 \tag{2}$$

Proposition 1. (*a*) *If* $\tau_0\leq\tau_0^*$, *the entire resource stock will be depleted in infinite time,* i.e. $S_\infty:=\lim_{t\to\infty}S=0$.

(*b*) *If* $\tau_0>\tau_0^*$, *the stock will not be exhausted in infinite time, i.e.* $S_\infty>0$; *we say the tax provokes a volume effect.*

Proof. Solving the inhomogeneous linear differential equation (1) for the resource price p with $p_0{:}=p(0)$, we obtain:

$$p=\tau_0 e^{\theta t}+(p_0-\tau_0-c)e^{rt}+c \tag{3}$$

The transversality condition reads:

$$(p_0-\tau_0-c)S_\infty=0 \tag{4}$$

The final size of the resource stock S_∞ is characterized by the cumulative demand $q(p)$ with the consumer price p given by (3):

$$S_\infty=S_0-\int_0^\infty q(\tau_0 e^{\theta t}+(p_0-\tau_0-c)e^{rt}+c)dt \tag{5}$$

(*a*): Suppose that $S_\infty>0$. Then the transversality condition (4) implies that $(p_0-\tau_0-c)=0$. Hence, final resource stock equation (5) reads:

$$S_\infty=S_0-\int_0^\infty q(\tau_0 e^{\theta t}+c)dt\leq S_0-\int_0^\infty q(\tau_0{}^* e^{\theta t}+c)dt=0$$

as $\tau_0\leq\tau_0^*$, $q'(p)<0$ and τ_0^* is according to (2) the stock-depleting tax level. This is, however, a contradiction to the assumption $S_\infty>0$.

(*b*): If $\tau_0>\tau_0^*$, with Eq. (5) follows:

$$\begin{aligned} S_\infty &= S_0-\int_0^\infty q(\tau_0 e^{\theta t}+(p_0-\tau_0-c)e^{rt}+c)dt>S_0 \\ &\quad -\int_0^\infty q(\tau_0{}^* e^{\theta t}+(p_0-\tau_0-c)e^{rt}+c)dt \\ &\geq S_0-\int_0^\infty q(\tau_0{}^* e^{\theta t}+c)dt=0 \end{aligned}$$

as $\tau_0>\tau_0^*$, $p_0\geq\tau_0+c$, $q'(p)<0$ and τ_0^* is the stock-depleting tax level. □

Hence, if the initial resource tax level is set higher than τ_0^*, the cumulative extraction will always be reduced and the stock will be prevented from exhaustion, i.e. $S_\infty>0$.

From (3) and (4) follows immediately:

Corollary 1. *If* $\tau_0>\tau_0^*$, *the resource price will be completely determined by the tax and the extraction costs:* $p=\tau_0 e^{\theta t}+c$. *The resource owners reap zero profits.*

In case the tax provokes a volume effect, the carbon tax reflects the scarcity rent for the de facto resource stock $S_0' := S_0-S_\infty$. In contrast, if the initial resource tax level was set equal or below τ_0^*, there would be no volume effect of the tax and the entire resource stock would be exhausted despite an increasing resource tax, i.e. $S_\infty=0$.

With respect to the time path of the resource extraction, we can now distinguish three cases concerning the term $r-\theta$ in (1):

(1) the carbon tax grows at the discount rate;
(2) the carbon tax grows at a rate lower than the discount rate; and
(3) the carbon tax grows at a rate higher than the discount rate

Table 1 summarizes the different cases and their implications which are discussed in detail in the following.

Case 1: *The carbon tax grows at the discount rate.* If $\theta-r=0$, the increasing tax will not influence the relative time path of the resource price and, hence, resource extraction. If the initial tax level τ_0 is equal or below τ_0^* as defined by (2), the resource tax will simply absorb the scarcity rent without any distortions (Dasgupta and Heal, 1979, p. 364). The initial consumer price p_0 is at the level that equalizes the total resource stock with the cumulative demand over an infinitive time horizon. If, in contrast, the initial tax level τ_0 is above τ_0^*, the consumer price for resources will equal the tax and is at each point in time strictly higher than in the no-tax case. Thus, a unit tax that increases with the discount rate has no timing effect—but it can have a substantial volume effect in decreasing demand and conserving the resource stock. With such a unit tax, a green paradox cannot occur.

Case 2: *The carbon tax grows with a rate lower than the discount rate.* If $\theta<r$, the resource tax will have a clear timing effect. The price path in (1) is flattened and, thus, extraction is postponed to the future. Whether the cumulative amount of the extracted resources is affected, however, depends on the initial tax level. If it was set equal or below τ_0^*, the entire resource stock would be depleted. In contrast, if the initial tax level was set above τ_0^*, the resource tax would decrease the cumulative demand below the initial stock size. In this case, the resource stock will not be completely depleted. In any case, the tax postpones carbon

[2] Sinn's model assumptions imply a positive demand for fossil resources for arbitrarily high resource prices—i. e. there is no backstop-technology as a perfect substitute. Several working papers which relax this assumption and consider the impact of backstop energy and/or subsidies on backstop energy have recently been published (i.e. Gerlagh, 2010; Grafton et al., 2010; Van der Ploeg and Withagen, 2010). However, we neglect this modification because our aim is to concentrate on the impact of carbon taxes within the original Sinn (2008) model.

[3] In a recent working paper, Hoel (2010) provides a similar definition describing a ''large'' tax that reduces cumulative extraction below a certain threshold. We differ from Hoel by assuming an exponential tax because we focus in the following on the initial tax level and the tax growth rate as two relevant variables for policy choices.

Table 1
Assessment of resource unit taxes with respect to the zero-tax case. r—effective discount rate of the resource owners; θ—rate of the tax increase, τ_0—initial tax level. Impact on damages: "–" denotes a reduction of damages; "+" an increase of damages.

	Tax increases at discount rate $\theta = r$		**Slowly increasing tax** $\theta < r$		**Fast increasing tax** $\theta > r$	
	τ_0 small ($T0 \le T0^*$)	τ_0 large ($T0 > T0^*$)	τ_0 small ($T0 \le T0^*$)	τ_0 large ($T0 > T0^*$)	τ_0 small ($T0 \le T0^*$)	τ_0 large ($T0 > T0^*$)
Timing effect	None	None	Postpone extraction	Postpone extraction	Accelerate extraction	Accelerate extraction
Volume effect	None	Conservative	None	Conservative	None	Conservative
Green paradox	None	None	None	None	Yes	Ambiguous
Impact on damages compared to zero-tax case	None	–	–	–	++	±
		Volume effect	Timing effect	Timing and volume effect	Timing effect	Timing vs. volume effect

extraction and therefore reduces climate damages by the timing affect and – if $\tau_0 > \tau_0^*$ – additionally by the volume effect.

Case 3*: The carbon tax grows with a rate higher than the discount rate.* If $\theta > r$, the resource tax will have a clear timing effect. The price path is steepened according to (1) and, thus, extraction is accelerated. The volume effect, however, depends once more on the initial tax level. An initial level below τ_0^* does not decrease the cumulative extraction. Climate damages increase compared to the zero-tax case because the resources are extracted too early. This is the case for the classical green paradox as described in Sinn (2008). If, in contrast, the tax level is above τ_0^*, the cumulative extraction will be lowered and the stock will be prevented from exhaustion. In this case, we have two driving forces on climate damages with an antithetic impact. While the volume effect leads to lower long-term extraction, near-term extraction could actually increase due to the timing effect. The higher the initial tax level, the stronger is the volume effect and, thus, the timing effect diminishes. In principle, every value of S_∞ could be achieved if the initial tax level was set appropriately high.

In a related study, Hoel (2010) argues that a carbon tax of 179 $/t$CO_2$ (656 $/tC) will definitely reduce carbon emissions from the beginning and that such immediate emissions reduction are likely to occur for carbon taxes higher than 367 $/tC. Due to the heterogeneity of fossil resources in extraction costs and demand, it is difficult to calculate exactly the critical initial tax level leading to sufficient lower (cumulative) extraction. In the following, we will therefore focus on the timing effect of carbon tax proposals and their impact on resource extraction.

3. The role of the discount rate

The previous considerations revealed that the green paradox does only occur for a special subset of increasing ad-hoc carbon taxes, namely where the initial tax level is low and the growth rate of the tax is higher than the effective discount rate of the resource owners for the entire time horizon.

At this point, it is important to emphasize that the discount rate resource owners actually use is decisive—and not one based on normative considerations about the choice of an appropriate social discount rate. The latter is important to quantify and evaluate costs and benefits of mitigation and to determine optimal mitigation targets (the "normative" approach). However, when determining optimal carbon taxes the incentive effect of policies has to be considered which relies on a correct modeling of the behavior of economic actors (the "descriptive" approach). In this sense, integrated assessment models need a careful and explicit interpretation depending on their specific research question.[4]

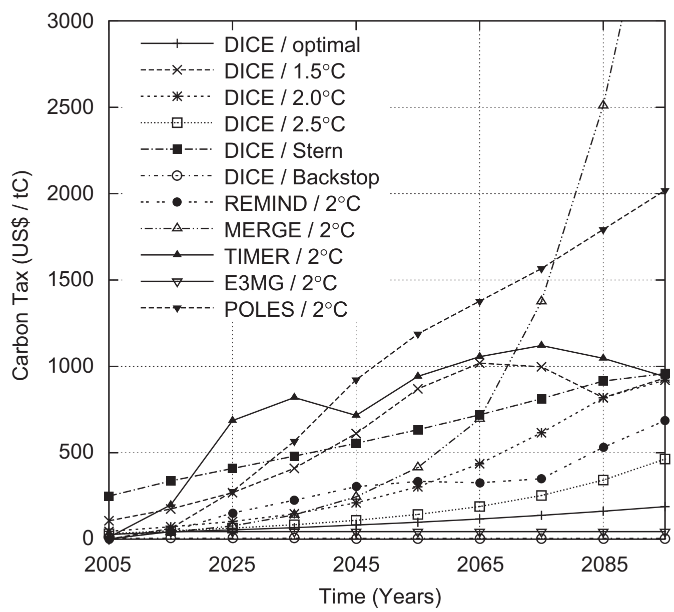

Fig. 1. Carbon taxes in 2005-US$ per ton of carbon as calculated for several temperature scenarios by the integrated assessment models DICE-2007 (Nordhaus, 2008, pp. 92–93), REMIND, MERGE, TIMER, E3MG and POLES (Edenhofer et al., 2010).

What carbon taxes do integrated assessment models suggest? In general, carbon taxes are very sensitive to many parameters concerning the climate system, damages and technological progress (Edenhofer et al., 2006). Fig. 1 shows carbon taxes calculated by several models. Table 2 gives also the initial tax level and growth rate of the respective exponential carbon taxes which are approximated to the models' taxes. Even for ambitious mitigation targets (450 ppm) most of the taxes have moderate growth rates between zero and three percent and are lower than the risk-free interest rates within these models. Only in the MERGE model the tax growth rate is with 5.8% on a very high level.

Resource owners discount their resource rent usually at the market interest rate which differs with respect to region and risk of financial assets. While the long-run rate of return of UK or US government bonds is about 1.5%, long-run rates of private equity are around 6–7% (Stern, 2008). Sinn (2008) argues that resource owners may add an additional risk premium if the ownership of their resources in the ground is insecure due to (geo)political instability—an analogous argument will hold if futures markets

[4] Although social planer models can – according to the welfare theorems – mimic market dynamics if no externalities and market failures exists, both models lead to different results in second-best worlds. This is, for example, relevant if the discount rate of a social planner differs from the rate of private households (see Heal (2009) for the debate on normative vs. positive discounting).

Table 2
Initial tax level τ_0 and tax growth rate θ for the approximated exponential carbon tax $\tau=\tau_0 e^{\theta t}$. The approximation of Fig. 1 models' ten-year taxes (from 2015 to 2095) is calculated by linear regression of the log-values with the least square method. The R^2 values measure how good the approximated tax fits to the models' tax. The last column shows – when available – the average discount rate r (return on capital) which applies in the models.

	τ_0	θ (%)	R^2	r (%)
DICE-2007				
Optimal (586 ppm CO_2)	37,2	1.9	0,994	5.5
1.5 °C (420 ppm CO_2)	209.2	2.1	0,774	5.5
2 °C (465 ppm CO_2)	54.2	3.3	0,992	5.5
2.5 °C (544 ppm CO_2)	36.0	2.8	0,999	5.5
Stern review (404 ppm CO_2)	316,0	1.3	0,985	5.5
Low-cost backstop (340 ppm CO_2)	5.0	−0.2	0,999	5.5
REMIND 2 °C (450ppm CO_2-eq.)	72.1	2.6	0,802	5
MERGE 2 °C (450 ppm CO_2-eq.)	23.9	5.8	0,999	5
TIMER 2 °C (450 ppm CO_2-eq.)	375.6	1.4	0,530	NA
E3MG 2 °C (450 ppm CO_2-eq.)	43.5	0.0	0,525	0
POLES 2 °C (450 ppm CO_2-eq.)	121.6	3.7	0,790	8

for fossil resources are incomplete. Adelman (1986) estimated that effective discount rates of OPEC countries exceed 25% partly due to poor diversification of OPEC's economies and other political economy aspects—while in industrialized countries discount rates are estimated to be around 10%. Even if these numbers differ from current discount rates, it is very likely that discount rates of resource owners exceed market interest rates significantly.

4. Policy implications

So far, we focused on the incentive effect of an arbitrarily set carbon tax. An optimal carbon tax as calculated by Kalkuhl and Edenhofer (2010) follows a complex dynamics and requires a precise understanding of the damages of global warming. While such an optimal tax does not provoke an accelerated extraction, the consideration of second-best taxes as done by Sinn (2008) and by this paper gives important hints on the robustness of carbon taxes. As the mere possibility of an accelerated resource extraction exists in case the carbon tax is (and permanently remains) mal-adjusted, this instrument could be perceived too risky to prevent dangerous climate change. An emissions trading scheme as suggested by Sinn (2008) can avoid this risk—as long as the emission caps are set appropriately and the intertemporal permit market works correctly.

As an alternative to a global cap-and-trade scheme, Sinn (2008) proposes a capital income tax harmonization within OECD countries as a robust fool-proof instrument. Extraction is always slowed down because such a tax reform lowers the effective discount rate of resource owners. This instrument, however, is in practice not capable to achieve ambitious mitigation targets: Firstly, capital tax rates cannot be set very high as they lead to distortions in investment decisions implying lower welfare. Second, capital taxes cannot reduce cumulative extraction, i.e. they cannot provoke a volume effect (see Appendix for proof).

By the specific choice of resource and capital tax instruments, Sinn (2008) completely rules out the volume effect. This is a strong limitation: The volume effect could become relevant if policy makers commit to concentration targets or cumulative carbon emissions in order to prevent the crossing of tipping points in the climate system (see WBGU, 2009 for the carbon budget proposal). An optimal carbon tax under such a carbon budget grows at the discount rate and the initial tax level is set such that cumulative extraction equals the carbon budget (see Kalkuhl and Edenhofer (2010) for a formal analysis). However, a mal-adjusted tax can again provoke an accelerated extraction and an emissions trading scheme may be the superior alternative.

5. Conclusion

By implementing carbon (unit) taxes in Sinn's (2008) model, we have shown that an accelerated resource extraction due to increasing carbon taxes (green paradox) is limited to specific conditions: The initial tax level has to be lower than a certain threshold and the tax has to grow permanently at a rate higher than the discount rate of resource owners. We showed that a prominent set of carbon taxes for several mitigation targets is not at high risk to provoke a green paradox. However, in order to avoid the small risk of a green paradox, quantity instruments might be preferable if they are implemented appropriately and markets work correctly. The capital income tax proposed by Sinn can be useful to slow down extraction, but it is not capable to achieve low stabilization targets. If regulators nevertheless rely on carbon taxes (i.e. due to political constraints) the initial tax level should be high enough and the long-run tax-growth rate equal or below market interest rates.

Acknowledgments

We wish to thank Kai Lessmann, Brigitte Knopf and two anonymous reviewers for their constructive support.

Appendix

Introducing a constant capital tax $\kappa<1$ changes the effective discount rate of resource owners' maximization problem to $\tilde{r}=r(1-\kappa)$. The resulting Hotelling rule is then:

$$r(1-\kappa)=\frac{\dot{p}}{p-c} \tag{A1}$$

Solving the differential equation (A1) for $p(t)$ gives:

$$p=(p_0-c)e^{r(1-\kappa)t}+c \tag{A2}$$

Putting (A2) into the transversality condition $0=\lim_{t\to\infty}(p-c)\,Se^{-r(1-\kappa)t}$ yields:

$$0=\lim_{t\to\infty}(p_0-c)S$$

Hence, either the entire resource stock has to be exhausted (i.e. $\lim_{t\to\infty}S(t)=0$) or the resource price equals always the extraction costs, i.e. $p=c$ due to (A2). The latter condition, however, contradicts the stock clearing condition because with positive demand, the cumulative demand exceeds the initial resource stock:

$$\int_0^\infty q(p)dt=\int_0^\infty q(c)dt=\infty>S_0.$$

References

Adelman, M.A., 1986. Oil producing countries' discount rates. Resources and Energy 8, 309–329.

Dasgupta, P.S., Heal, G.M., 1979. Economic Theory and Exhaustible Resources. Cambridge University Press, Cambridge, London, New York.

Edenhofer, O., Lessmann, K., Kemfert, C., Grubb, M., Koehler, J., 2006. Technological change: exploring its implications for the economics of atmospheric stabilization. In: Edenhofer, O., Carraro, C., Koehler, J., Grubb, M. (Eds.), Endogenous Technological Change and the Economics of Atmospheric Stabilisation. The Energy Journal, vol. 27; 2006 (Special Issue I).

Edenhofer, O., Knopf, B., Leimbach, M., Bauer, N. (Eds.), 2010. The Energy Journal, Volume 31; 2010 (Special Issue 1).

Gerlagh, R., 2010. Too much oil. CESifo Economic Studies Advance Access published on June 21. doi:10.1093/cesifo/ifq004.

Grafton, R.Q., Kompas, T., Long, N.V., 2010. Biofuels subsidies and the green paradox. CESifo Working Paper Series 2960, CESifo Group Munich.

Heal, G., 2009. Climate economics: a meta-review and some suggestions for future research. Review of Environmental Economics and Policy 3 (1), 4–21.
Hoel, M., 2010. Is there a green paradox? CESifo Working Paper Series 3168, CESifo Group Munich.
IPCC, 2007. Climate Change 2007: Mitigation. Cambridge University Press, Cambridge, UK.
Kalkuhl, M., Edenhofer, O., 2010. Prices vs. quantities and the intertemporal dynamics of the climate rent. CESifo Working Paper Series, 3044 CESifo Group Munich.
Nordhaus, W.D., 2008. A Question of Balance: Weighing the Options on Global Warming Policies. Yale University Press, New Haven, USA.
Sinn, H., 2008. Public policies against global warming: A supply side approach. International Tax and Public Finance 15, 360–394.
Stern, N., 2008. The economics of climate change. American Economic Review 98 (2), 1–37.
Van der Ploeg, F., Withagen, C.A., 2010. Is there really a green paradox? CESifo Working Paper Series 2963, CESifo Group Munich.
WBGU, 2009. Solving the climate dilemma: the budget approach. WBGU, Berlin.