

Frontiers of Climate Change Economics*

Gerard van der Meijden[‡]

Vrije Universiteit Amsterdam

Frederick van der Ploeg[‡]

University of Oxford

Cees Withagen[§]

IPAG Business School Paris

July 17, 2017

Abstract

The economics of climate change is an active field of research. The contributions to a Special Issue are put in context of the literature, and it is suggested that second-best issues such as carbon leakage and the Green Paradox need to be complemented with a political economy analysis of why certain instruments are politically infeasible and with intra- and intergenerational analyses of the impact of climate policy. A case is also made for more empirical work on the gradual and catastrophic damages of global warming.

JEL codes: Q51, Q52, Q54, Q58

Keywords: Climate change, green paradox, carbon leakage, political economy, distribution, tipping points, climate damage estimates

*We gratefully acknowledge financial support from FP7-IDEAS-ERC Grant No. 269788. We also thank the Tinbergen Institute for the organisation of the 11th Tinbergen Institute Conference “Combating Climate Change: The Political Economy of Green Paradoxes”, Amsterdam, 21-22 April 2016, at which all of the papers in this Special Issue were originally presented.

[‡]Department of Spatial Economics, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands, e-mail: g.c.vander.meijden@vu.nl. Also affiliated with Tinbergen Institute

[‡]Department of Economics, Manor Road Building, Manor Road, Oxford, OX1 3UQ, United Kingdom, email: rick.vanderploeg@economics.ox.ac.uk. Also affiliated with St. Petersburg State University, 7/9 Universitetskaya nab., St. Petersburg, 199034 Russia, Vrije Universiteit Amsterdam, Tinbergen Institute, CEPR and CESifo.

[§]Email: c.a.a.m.withagen@vu.nl. Also affiliated with Vrije Universiteit Amsterdam, Tinbergen Institute, and CESifo.

1 Introduction

Important contributors to climate change are the greenhouse gas emissions by mankind at home, in factories, in the office and on the road and in the air. Greenhouse gases mix immediately once in the atmosphere, so that it does not matter whether emissions take place in China, India, Africa, Europe or the Americas. Global warming can therefore be characterised as a global externality. A key concept in the economics of climate change is the social cost of carbon (SCC). The SCC is the present value of all present and future damages to aggregate economic production caused by the global warming induced by emitting one ton of carbon today. There is a whole industry of trying to assess these damages and also a literature on what kind of ethical and risk considerations drive the rate used to discount these damages.

The main point is, however, that if the global warming externality is the only market failure on the planet (and it clearly is not), the policy makers of the world should ensure that carbon is priced uniformly throughout the planet at a level equal to the SCC (Chichilnisky and Heal, 1994). This carbon price can be realised through a uniform global carbon tax or through a worldwide system of trade carbon permits as this is the most efficient way of curbing emissions. Van der Ploeg and Withagen (2014) and Golosov et al. (2014) show how the optimal SCC is calculated in general equilibrium and is the key driver of phasing out fossil fuel and phasing in renewable energy.

Such a worldwide system of pricing carbon can only be sustained if rich countries in the world compensate the poor countries with lump-sum transfers. Since after decades of climate summits such a system of global carbon pricing and lump-sum transfers is still not in place, one has to consider second-best arrangements where only part of the world prices carbon, or at different rates (cf. Chichilnisky and Heal, 1994; D'Autume

et al., 2016). This leads to the inevitable problem of international carbon leakage. Even those countries that try to price carbon, have to face the political realities that policy makers tend to commit to *future* climate policies and to procrastinate. They also tend to prefer the carrot of a renewable energy subsidy to the stick of an effective and credible carbon price. This leads to Green Paradox effects. Both leakage and Green Paradox effects render climate policy less effective than they would have been otherwise.

In this Special Issue to mark the completion of an Advanced Instigator Grant of the European Research Council, Kverndokk et al. (2017), Gronwald et al. (2017) and Mulatu (2017) deal with and add new insights into these two key reasons for frustration of first-best climate policies. These papers are discussed and put in context in Section 2. Another reason why climate policy is frustrated in practical policy making is, for example, that carbon prices often hit the poorest people of society hardest and thus politicians have little appetite to implement carbon pricing. Section 3 discusses two papers in the Special Issue that deal with politics of climate policy. Carattini et al. (2017) study voting on energy taxes which helps to understand of public resistance environmental policy measures. Dao et al. (2017) deal with the intricate issues of how to tackle intergenerational distributional consequences of climate policies. Section 4 discusses in some detail the emerging literature on tipping points and catastrophes including the contribution by Tsur and Zemel (2017) to the Special Issue. Section 5 discusses the estimation of damages from climate change including the contribution of Howard and Sterner (2017). Section 6 concludes with a brief agenda for future research.

2 Carbon Leakage and the Green Paradox

Climate policies may suffer from *interregional* and *intertemporal* carbon leakage. Interregional carbon leakage occurs if only a subset of regions in the world introduces climate policies. There are two channels through which this effect operates. First, polluting firms may relocate to regions with less stringent climate policies. Second, climate policies reduce fossil demand in policy-active regions, leading to a lower price for fossil fuels on the world market. As a result, demand and emissions in the policy inactive regions go up. Estimates of the size of this carbon leakage effect vary from 5 to over 30 percent of the reduction in policy active regions (Burniaux and Martins, 2012; Böhringer et al., 2017), but there are also extreme examples of negative leakage rates (Elliott and Fullerton, 2014) and a leakage rate of 130 percent (Babiker, 2005).

Intertemporal leakage occurs if, due to the implementation of ‘gradually greening’ policies’ (such as announced future carbon taxes or subsidies for renewable energy) owners of fossil fuels increase their current supply in anticipation of a reduction in future demand. Because this front-loading of fossil supply causes an acceleration of climate change, intertemporal carbon leakage is also known as the Green Paradox (cf. Sinclair, 1994; Sinn, 2008, 2012; Van der Ploeg and Withagen, 2015). A *Weak* Green Paradox is said to occur when current emissions increase upon the introduction of these (suboptimal) climate policies, whereas a *Strong* Green Paradox arises when the present discounted value of climate damages increases as well (cf. Gerlagh, 2011). If extraction costs of fossil fuels depend positively on cumulative extraction, climate policy increases the amount of fossil fuels that is left in the crust of the earth which can have a positive effect on welfare and might lead to a strong Green Paradox not occurring (e.g. Hoel, 2012; Van der Ploeg and Withagen, 2012a). Van der Ploeg (2016b) has shown that

the weak Green Paradox effect is especially strong if the price elasticity of the demand for fossil fuel is large relative to that of the supply of fossil fuel. Furthermore, using duality theory, it can be shown that whether there is a strong Green Paradox effect with an adverse effect on welfare or not depends on whether the price elasticity of demand exceeds that of supply or not.

Recently, Eichner and Pethig (2011), Van der Meijden et al. (2015), and Van der Ploeg (2016b) have shown that general equilibrium effects are likely to mitigate weak Green Paradox effects. The reason is that the front-loading of fossil supply increases current output relative to future output, which positively affects global savings and therefore drives down the interest rate. According to the Hotelling rule, a lower interest rate implies more conservative extraction, counteracting the Green Paradox effect. In the literature, several other channels that mitigate the Green Paradox have been investigated. First, Hart and Spiro (2011) show empirically that scarcity rents on fossil fuels have been very low, which limits the potential for a Green Paradox. Second, a dirty backstop alongside fossil and clean renewable resources attenuates the Green Paradox (Van der Ploeg and Withagen, 2012b; Michielsen, 2014). Third, fossil and renewable energy are used simultaneously due to increasing marginal production costs of renewables (Grafton et al., 2012) or imperfect substitution between fossil and renewable resources (Michielsen, 2014), which mitigates the Green Paradox as well.

In this issue, three new directions on adverse effects of well-intended climate policy are explored. First, Kverndokk et al. (2017) analyse carbon leakage and Green Paradox effects induced by energy efficiency improvements. Second, Gronwald et al. (2017) focus on the effects of the existence of opposition to increasing renewables capacity beyond its current level. Third, Mulatu (2017) provides new empirical evidence for

carbon leakage due to the pollution haven effect. These contributions are discussed in the following subsections.

2.1 Feedback effects of energy efficiency improvement

The article of Kverndokk et al. (2017) in this issue examines rebound (to be defined below), carbon leakage and Green Paradox effects resulting from policy-induced energy efficiency improvements. Kverndokk et al. (2017) construct a detailed, numerical model of the international oil market, named Petrol2. Demand for energy comes from seven regions with each seven different demand sectors and the model distinguishes six different energy goods: oil, gas, electricity, coal, biomass and biofuels. Oil supply is modelled in detail, by taking into account the cartel-fringe structure of the international oil market and the scarcity rent associated with the finite availability of oil. The cartel consists of the ‘OPEC-Core’ countries Saudi Arabia, Kuwait, United Arab Emirates and Qatar, which belong to the Gulf Cooperation Council and have larger oil reserves and lower extraction costs than most other OPEC countries. Kverndokk et al. (2017) calibrate and simulate the model to analyse the ‘feedback’ effects of different scenarios of energy efficiency improvement, which they decompose into a *direct* and *indirect* rebound effect, a carbon leakage effect, and a Green Paradox effect. The rebound effects emerge within the sector that experiences the efficiency improvement. The direct rebound effect consists of an increase in the demand for an energy source that, at a given price level, has become relatively cheaper due to the efficiency increase. The indirect rebound effect consists of an increase in demand as a result of a price drop induced by the increase in efficiency. Carbon leakage, on the contrary, occurs outside the sector that has experienced the efficiency improvement. The model considers both

intersectoral and international carbon leakage. In the benchmark scenario in which efficiency improves in the transport sectors in all regions by 30 percent (gradually over time until 2050), the direct and indirect rebound effects are 47 and 10 percent of the initial decrease in emissions due to the efficiency improvement, respectively. The carbon leakage effect amounts to 13 percent, but can increase to over 35 percent in other scenarios in which only major oil consuming regions experience energy efficiency improvements. Furthermore, there is a small weak Green Paradox (i.e., intertemporal carbon leakage) effect in all investigated scenarios. Especially the large carbon leakage number shows the importance of complementing policies aimed at energy efficiency improvements with measures such as carbon pricing, to mitigate negative feedback effects.

2.2 Constraints on increasing the share of renewable energy

An expansion of renewable energy capacity beyond its current level often faces substantial technological and political constraints, for example because of land use restrictions in producing biofuels or local resistance to increasing the number of wind turbines in case of renewable electricity generation. In their contribution to this Special Issue, Gronwald et al. (2017) investigate the consequences of a capacity-constrained backstop technology for energy use and for the effects of climate policies (cf. Wang and Zhao, 2013). They show that relatively cheap fossil fuels are used first in the decentralised market equilibrium, then follows a regime of simultaneous use of fossil fuel and relatively expensive and capacity-constrained renewable energy until depletion, after which demand completely shifts to renewables. For plausible parameter values, both a subsidy for renewable energy and an increase in the backstop capacity cause a weak Green

Paradox. Moreover, a capacity increase induces a strong Green Paradox and may even cause a welfare loss if climate damages are large enough. The reason is that an increase in renewables capacity causes an inward shift of the future residual fossil demand function, which makes it attractive for fossil owners to front-load fossil extraction. As a result, initial fossil supply goes up and depletion may occur sooner. Both effects increase the present value of climate damages. A renewables subsidy also boosts initial fossil use, but increases the duration of the simultaneous use regime as well, which postpones depletion and thus makes a strong Green Paradox less likely to occur. These results indicate that, as in the case of energy efficiency improvements, subsidies for renewables use and policies that extend renewables capacity should be complemented by carbon pricing to counteract adverse Green Paradox effects.

2.3 Carbon leakage through pollution havens

The pollution haven hypothesis states that more stringent environmental regulations (mostly in the developed world) induce polluting industries to relocate to countries with relatively lax environmental regulations (typically in the less developed world). However, empirical evidence for this hypothesis is mixed. Complicating issues in this literature are selecting decent and internationally comparable measures of environmental regulation and its enforcement, finding data that is available over a large number of countries and years, and endogeneity of environmental policy and pollution intensity. In his contribution to this Special Issue, Mulatu (2017) addresses these problems. He uses an environmental stringency indicator from the Global Competitiveness Report, and employs a novel three-dimensional dataset (containing data from 23 different industries and 64 countries over the period 2002-2006), that allows him to correct

for unobserved heterogeneity by including time-invariant location and industry fixed effects, and location- and industry-invariant time fixed effects in his empirical analysis. Furthermore, Mulatu (2017) instruments for environmental stringency and uses a lagged pollution intensity variable to handle endogeneity issues. His results show that environmental policy has a significant impact on the pattern of UK outbound Foreign Direct Investment (FDI): a one standard deviation decrease in environmental stringency (which is about the stringency difference between France and Greece) increases FDI in relatively polluting industries by 28 percent. The evidence that Mulatu (2017) finds for the pollution haven hypothesis may provide a reason to complement more stringent environmental policies with a border adjustment tax on the carbon content of imports (cf. Fischer and Fox, 2012; Böhringer et al., 2017).

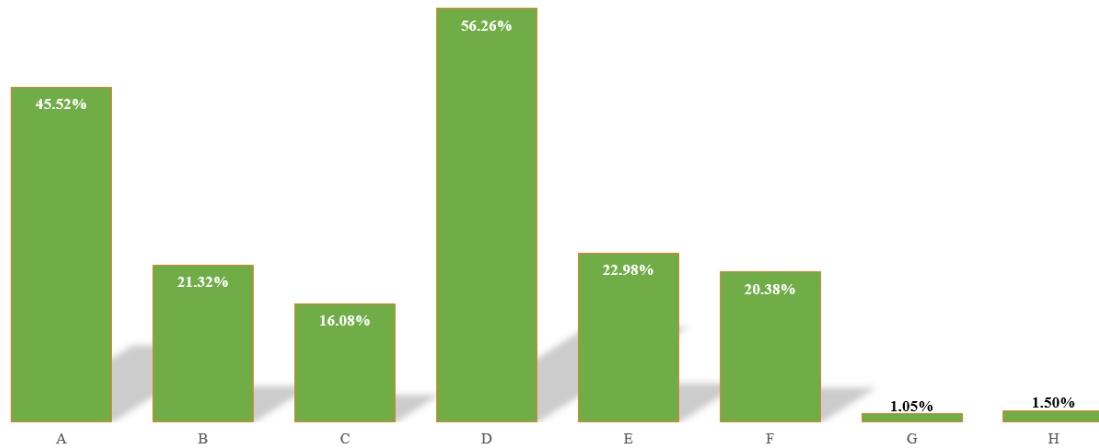
3 Distributional Effects and Political Economy

Although additional measures may be required to enhance clean innovation and encourage technology transfer, a ‘first-best’ approach always has carbon pricing at its core (Fischer et al., 2017). Moreover, as argued in Section 2, carbon pricing is also required to mitigate leakage and Green Paradox effects. Still, citizens around the world strongly prefer subsidies for renewable energy and support for clean R&D over carbon pricing policies, as shown in Figure 1, which contains the outcome of a global citizen consultation from 2015 involving 10,000 citizens in 76 countries.

The figure shows that only 21 percent of all respondents have indicated carbon pricing as one of their preferred policy instruments, compared to 46 percent for supporting green R&D and 56 percent for subsidising clean energy.¹

¹ Respondents were asked to indicate one or two preferred options.

Figure 1: Preferred policy instruments



Which of the following approaches do you prefer for making large-scale cuts in greenhouse gas emissions?

- A. Support for R&D of low-carbon technology, for example research into effective car batteries
- B. Carbon pricing, for example through taxes on carbon emissions, or emissions trading schemes
- C. Cutting fossil fuel subsidies
- D. Subsidisation of low-carbon energy, such as wind, solar power, marine energies, geothermal energy
- E. Legislation of new standards, for example to improve the energy efficiency of cars or buildings and appliances
- F. New socioeconomic institutions and practices, such as investment in public transportation systems or consumption of locally produced food
- G. No large-scale cuts should be made
- H. Don't know / don't wish to answer

Note: The total amount of all answers can be higher than 100 percent, since participants could choose two answer options. *Source:* <http://climateandenergy.wviews.org>.

The theoretical literature on the political economy of environmental policy implementation typically emphasizes lobbying by the fossil sector (cf. Oates and Portney, 2003). The Special Issue contains two contributions that approach political economy considerations from a different perspective.

3.1 Climate policies and voting behaviour

First, Carattini et al. (2017) provide empirical explanations for the lack of public support for energy and carbon taxes. They analyse voting behaviour in a real ballot in Switzerland on replacing the current value-added tax (VAT) with an energy tax in a revenue-neutral way. About 2.2 million Swiss people voted on March 8, 2015. The proposal was rejected by 92 percent of the voters. Carattini et al. (2017) used the VOX Survey by the Swiss Centre of Expertise in the Social Sciences (in which a representative

sample of 1500 persons is interviewed within a month after the ballot), to assess the determinants of the observed voting behaviour. They conclude that the chances of the rejected initiative would have been much higher if tax revenues had been earmarked for environmental purposes instead of used for replacing the VAT. Furthermore, distributional concerns, worries about the loss of competitiveness of firms, and perceived environmental ineffectiveness were among the most important reasons for rejection.

At the same time, Carattini et al. (2017) conducted a choice experiment in which they considered a carbon tax with four different rates (60, 90, 120 and 150 CHF/tCO₂) and five different types of revenue recycling (income tax rebates, VAT rebates, lump sum transfers, social redistribution, and environmental earmarking). Furthermore, they informed the participants in the choice experiments about the expected outcomes of each alternative, in terms of the energy price, emission abatement, overall economic effects, and distributional consequences (on the basis of simulations of a general equilibrium model). Providing this information about expected outcomes leads to different results compared to the ballot and the literature. First, revenue-neutral designs (for example lump sum recycling) can become popular, provided that revenues are recycled in a progressive way (i.e., such that income inequality goes down). Second, although it is typically found that environmental earmarking reduces the resistance to environmental taxes (as it increases the perceived environmental effectiveness), the outcome of the choice experiment shows that providing information on the expected environmental effectiveness of carbon taxes reduces the need for environmental earmarking. Third, support for green taxes declines linearly with the tax rate.

The results in Carattini et al. (2017) are also interesting for policymakers. They imply that providing detailed information on the expected effectiveness and (*intra-*

generational) distributional implications of environmental tax reforms with the general public, reduces the widespread resistance to environmental taxes. We now discuss opposition resulting from *intergenerational* redistribution.

3.2 Intergenerational redistribution

The burden of climate change policies mainly falls on current generations, whereas the benefits of lower climate damage accrue to future generations. Therefore, policy makers often face problems with finding political support for climate measures. In their contribution to this Special Issue, Dao et al. (2017) propose a scheme of bilateral climate damage mitigation contracts between successive generations to overcome this political barrier. They examine the implementation of a social contract, according to which agents of the each young generation give up a share of their labor income to be invested in abatement technology that lowers the pollution stock in the next period. In exchange for this payment, the young generation receives a transfer when retired. This transfer, in turn, is financed from labor income of the next young generation, who benefits from a lower pollution level.

Dao et al. (2017) assume that households derive utility from consumption according to a logarithmic utility function and that damages from the stock of carbon are proportional to output, where the factor of proportionality is an exponential function of the carbon stock. As a result, the climate gain from the social contract depends on the absolute level of income, whereas the utility loss from mitigation depends on the income share spent on mitigation. Therefore, the social contract can only be Pareto-improving as long as the income level is large enough. As a result, if the implementation of an initially Pareto-improving contract is delayed for too long, pollution may have

increased by too much, pushing the income level below the threshold implying that a Pareto-improving contract is no longer feasible.

Without a commitment device, the social contract proposed by Dao et al. (2017) can only be sustained over time if it is self-enforcing, requiring that the return to participating in the contract exceeds the return to private savings. Typically, this implies that the economy needs to be dynamically inefficient: the growth rate of the economy should exceed the rate of interest (Anderberg and Balestrino, 2003; Cigno, 2006). However, Dao et al. (2017) model the benefit during retirement as a subsidy to capital income rather than as a lump-sum transfer. As a result, a simultaneously Pareto-improving and self-enforcing contract may exist even in a dynamically efficient economy. The reason is that under such a social contract, investment in the transfer scheme and investment in physical capital become complementary.

The insights obtained by Dao et al. (2017) are useful for overcoming political barriers in implementing climate policies: if the use of debt policy to redistribute gains from public abatement between generations (cf. Bovenberg and Heijdra, 1998, 2002; Heijdra et al., 2006) is restricted, for whatever reasons, social contracts between successive generations could be used instead. But one should make sure to design them in such a way that participation is self-enforcing in dynamically efficient economies, for example by using subsidies to capital income for the old, rather than lump-sum ‘green pensions’ as proposed by Von Below et al. (2016).

4 Tipping Points and Catastrophes

Apart from the ‘smooth’ global warming damages arising from small and moderate temperature increases, optimal climate policies should also take into account the exis-

tence of tipping points that, once crossed, trigger feedback effects and may cause severe climate catastrophes. Alternatively, climate policy has to deal with tipping points whose hazard increases with global warming so that tipping points are postponed if global warming is curbed. Examples of these are a weakening of the Atlantic conveyor belt, a release of methane from permafrost in Siberia, or the melting of ice sheets in Greenland which will reduce the reflection of solar radiation (cf. Lenton and Ciscar, 2013). The existence of climate tipping points warrants precautionary capital accumulation to be better prepared for the catastrophe (e.g. Van der Ploeg and de Zeeuw, 2017). Furthermore, if the risk of triggering those feedback effects increases with the stock of atmospheric carbon, the optimal carbon price becomes higher (e.g. Van der Ploeg, 2014).

4.1 Multiple climate tipping points

When taking into account that crossing one tipping point increases the risk of also crossing other climate tipping points, the optimal carbon price adjustment is larger than the sum of the individual components (cf. Van der Ploeg, 2016a). Lemoine and Traeger (2016) allow for interdependencies of different catastrophes and show that the optimal carbon price almost doubles (from 6 US\$ to 11 US\$ per tonne CO₂). Cai et al. (2016) even find an almost eightfold increase in the optimal carbon price (from 15 US\$ to 116 US\$ per tonne CO₂), which lowers the probability of crossing one or more tipping points from 46 to 11 percent.

4.2 Other catastrophes lurking in the background

Climate-related disasters are not the only catastrophes that mankind has to deal with. We are facing multiple catastrophic threats from different sources, like nuclear and bio-terrorism, mega viruses and asteroids hitting the Earth. Even if these disasters occur independently of each other Martin and Pindyck (2015) have shown that in deciding which of them to avert, simple cost-benefit rules may lead us astray. The reason is that policies to avert these catastrophes are not marginal: they will have a significant impact on the overall economy. Averting one catastrophe will change the level and marginal utility of consumption, and therefore the willingness to pay for averting the other catastrophes. Hence, even if the benefits of averting each individual catastrophe exceed the costs, it may not be optimal to avert them all. Nor is it necessarily optimal to start averting the catastrophe with the largest benefit-cost ratio first and to sequentially decide whether or not to avert the next one.

In their contribution to this Special Issue, Tsur and Zemel (2017) extend Martin and Pindyck's analysis of coping with multiple catastrophic threats by introducing an intertemporal dimension and endogenous catastrophe hazard rates. They assume that the hazard rate (i.e., the instantaneous probability that a catastrophe occurs) of each catastrophe depends positively on a specific pollution stock. Pollution stocks increase over time due to emissions and decrease because of natural decay and abatement efforts. Hence, by investing in different types of abatement, society can reduce the different stocks of pollution associated with different catastrophes (and therefore the hazard rates of these catastrophes) over time. As a result, efforts to reduce the probability of catastrophes occurring can be spread over time, implying that the instantaneous investment levels become smaller, although the cumulative investment levels to avert

catastrophes (or reduce their hazard rates) are substantial. Nevertheless, Tsur and Zemel (2017) show that the main result of Martin and Pindyck (2015)—that because of non-marginal costs a comprehensive approach is needed rather than dealing with each catastrophe in isolation—remains valid if abatement efforts can be smoothed over time. In the setting of Tsur and Zemel (2017) with endogenous hazards, this result is even true for marginal, i.e., non-catastrophic, threats, whereas in the analysis of Martin and Pindyck (2015) the usual cost-benefit rules apply (so each threat can be dealt with in isolation) in situations with marginal threats. Furthermore, where the marginal willingness to pay to avert a single catastrophe depends positively on the ‘background risk’ (of other catastrophes occurring) in Martin and Pindyck (2015), Tsur and Zemel (2017) obtain an ambiguous effect. They show that in their framework the presence of other threats may either increase or decrease the long run abatement efforts of a specific catastrophic threat relative to the policy adopted if this threat would be considered in isolation, depending on the size of the catastrophic damages. Intuitively, if damages from each threat are large, abatement is high and consumption is low in equilibrium. Therefore, marginal utility of consumption is high, implying that it is optimal to reduce abatement efforts if an additional catastrophic threat is added. Conversely, if damages are relatively small, abatement is low and consumption is high in equilibrium. As a result, marginal utility of consumption is low, implying that the optimal response to an additional threat is to increase abatement efforts per catastrophic source.

The results of Martin and Pindyck (2015) and Tsur and Zemel (2017) imply that we should not be fixated on climate change alone. Climate policy should be determined while taking into account the presence of other catastrophic threats lurking in the background, such as the outbreak of a worldwide virus, nuclear and bio-terrorism, or

asteroids hitting the Earth. Although Tsur and Zemel (2017) focus on the steady-state equilibrium, their model can also be used to derive transitional dynamics enabling us to think about the chronological sequence of averting catastrophes: When to start and when to stop investing in mitigating each particular catastrophic threat?

5 Climate Damage Estimates

The marginal cost to society of burning an additional ton of carbon, the SCC, is a crucial input in the process of designing climate policies. Therefore, policy makers need reliable estimates for this measure of climate damage. The most common approach to estimating the SCC is to build ‘Integrated Assessment Models’ (IAMs), which integrate a detailed climate and an economic module and allow for interactions between these two subsystems (i.e., economic activity generates carbon emissions that lead to climate change, and, conversely, climate change affects the economy, for example because of output losses due to lower agricultural productivity).

IAMs can be used to examine the effects of different climate policies, as well as to determine the socially optimal carbon emission path and to calculate the discounted value of welfare losses due to the emission of an additional ton of carbon: the SCC. Since the 1990s, a plethora of IAMs has been developed, such as the Dynamic Integrated model of Climate and the Economy, DICE, (cf. Nordhaus, 1994), the Framework for Uncertainty, Negotiation and Distribution, FUND, (cf. Tol, 1995), and Policy Analysis of the Greenhouse Effect, PAGE, (cf. Plambeck and Hope, 1996). The U.S. government’s Interagency Working Group (IWG) bases its SCC estimate on these three IAMs (cf. Interagency Working Group on Social Cost of Carbon, 2010, 2013).

Apart from IAMs, other methods have been used in the literature to estimate the

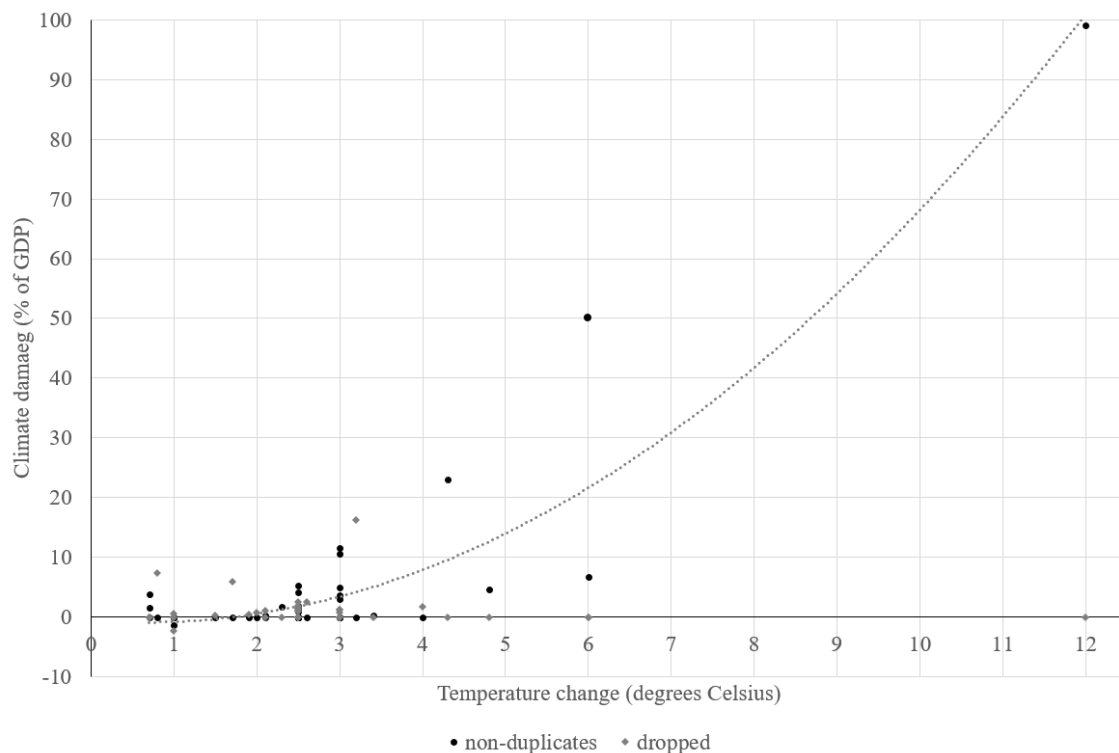
SCC. These include cross-sectional empirical analyses that make use of differences in climate between different regions of the world (Burke et al., 2015), panel data regressions that exploit changes in the weather patterns over time (the ‘New Climate-Economy Literature’, cf. Dell et al., 2014), and expert elicitation (Pindyck, 2016). Uncertainty in the response of temperature to changes in the atmospheric carbon concentration (due to feedback effects and tipping points, as discussed in Section 4) and uncertainty about the economic impact of increased temperatures severely complicate estimation of the SCC (Pindyck, 2013). Furthermore, the SCC strongly depends on the weight attached to the utility of future generations, i.e., on the social discount rate (cf. Nordhaus, 2017). As a result, estimates of the SCC vary widely, not only between the studies applying different methods, but also within the class of IAMs.

Recently, a number of meta-analyses of SCC estimates have been performed that summarise the current state of knowledge (cf. Tol, 2009; Nordhaus, 2013; Newbold and Marten, 2014; Tol, 2014, 2015). However, these meta-analyses are restricted by the small number of available studies. Moreover, the available estimates of the SCC are not independent. Since they come from a limited number of authors using comparable methods, they inevitably suffer from duplication bias (cf. Aldy et al., 2010; Van den Bergh and Botzen, 2015). Ignoring the dependence between different studies gives rise to an exaggerated sense of knowledge about the temperature-damage relationship. Apart from the problems caused by dependence and duplication, the earlier meta-analyses also suffer from heteroscedasticity (because of substantial unobserved heterogeneity in the damage estimates), omitted variable bias (by ignoring methodological differences between studies), publication bias (by relying exclusively on published papers), and from the fact that high-temperature damage estimates have a large effect

on the temperature-damage relationship, despite the overreliance on extrapolation to obtain these estimates.

In their contribution, Howard and Sterner (2017) address these biases by using a larger dataset, dropping duplicate estimates, including unpublished estimates, performing weighted least squares, reporting cluster-robust standard errors at the model level, and including indicator variables of whether the model captures non-market, productivity, and catastrophic climate impacts. The authors start out with a dataset consisting of 49 damage estimates from 41 studies, using 6 estimation strategies. After eliminating duplicates, and dropping estimates judged unreliable for the meta-analysis at hand, 26 non-duplicate estimates from 20 studies remain. Figure 2 shows the 49 initial estimates, of which the 26 remaining ones are shown in black.

Figure 2: Damage estimates



Notes: Non-duplicate observations are shown in black. The observations that are dropped from the meta-analysis by Howard and Sterner (2017) are shown in grey. The dotted grey line represents the outcome of a quadratic OLS regression. *Source:* Howard and Sterner (2017).

Howard and Sterner (2017) perform a weighted least squares regression with weights equal to the inverse of the temperature change, in order to reduce the influence of the more uncertain damage estimates. They present results for specifications including and excluding above-4-degrees temperature increase damage estimates. The authors regress climate damages (as a percentage of GDP) on a quadratic temperature term and include interaction effects with the indicator variables tracking whether the estimate captures non-market, productivity, and catastrophic climate impacts.

The main results of the specification without temperature-increase estimates of more than 4 degrees Celsius are as follows. First, non-catastrophic damages are likely to be 7-8 percent of world GDP for a temperature increase of 3 degrees. Second, when factoring in catastrophic risk, damages are 9-10 percent of world GDP for a similar increase in temperature. Third, there is strong evidence of duplication bias as leaving out duplicates increases standard errors and renders catastrophic impacts statistically insignificant. This emphasises the false precision from duplication. Furthermore, the estimate of non-catastrophic impacts (i.e., the coefficient on temperature squared), almost doubles when leaving out duplicates. Fourth, there is evidence for omitted variable bias, as the previously ignored indicator variables are consistently jointly significant.

In the specification with temperature-increase estimates of more than 4 degrees Celsius, catastrophic impacts remain statistically insignificant after dropping duplicate estimates and the damages at a temperature increase of 3 degrees are estimated to be 4-8 percent excluding and 7-11 percent of world GDP including catastrophic damages. Finally, when feeding the obtained damage function (including both non-catastrophic and catastrophic damages) into the DICE model, the obtained SCC increases four-fold

to five-fold (depending on whether to account for the impact of climate change on productivity).² When including above-4-degrees temperature change damage estimates, this number becomes three-fold to six-fold.

The results of Howard and Sterner (2017) confirm that estimated climate damage functions are sensitive to the high temperature damage estimates. The problem is that they are highly speculative with ‘little or no theoretical or empirical grounding’ (Pindyck, 2016). Because these high-temperature ‘catastrophic’ damages have an important bearing on the SCC, future damage estimates should focus on the above-4-degrees range of temperature change and IAMs should properly account for uncertainty and the probability of catastrophic outcomes (Weitzman, 2012).

6 Looking ahead

The economics of climate change is a thriving field of research which is highly relevant for today’s society. The Special Issue has highlighted that the textbook prescription for dealing with climate policy, i.e., to price carbon at a level equal to the SCC, is unlikely to be adopted by policy makers in the world economy. Much more research is needed into the political distortions that block an ambitious environmental policy. Although the literature so far has suggested the inefficiencies and counter-productivities that arise when only a small number of countries price carbon in the world and when policy makers shift the responsibility of pricing carbon to their successors and prefer subsidies rather than pricing carbon, more investigations are needed to *model* the political economy distortions rather than simply *assume* them. Climate policy should also not be analysed in isolation but within a broader spectrum of tax and spending policies, hence

²The benchmark DICE-2013R estimate used here is 22 US\$ per metric ton of CO₂ (Nordhaus, 2013).

climate economists need to advance their analysis using the most modern methods of public finance and second-best analysis. Finding out how to avoid or delay the onset of non-marginal catastrophic shocks might lead to a narrative that resonates better with policy makers. It has become clear that the damage estimates we use in the climate economics are at best out of date and at worse simply made up. Finally, much more detailed empirical work on the effects of temperature on the economy, both locally and globally, and on the hazard and damages of potential tipping points is needed to improve the credibility of policy recommendations.

References

- ALDY, J. E., A. J. KRUPNICK, R. G. NEWELL, I. W. H. PARRY AND W. A. PIZER, “Designing Climate Mitigation Policy,” *Journal of Economic Literature* 48 (December 2010), 903–934.
- ANDERBERG, D. AND A. BALESTRINO, “Self-enforcing Intergenerational Transfers and the Provision of Education,” *Economica* 70 (February 2003), 55–71.
- BABIKER, M. H., “Climate change policy, market structure, and carbon leakage,” *Journal of International Economics* 65 (March 2005), 421–445.
- BÖHRINGER, C., K. E. ROSENDAHL AND H. B. STORRSTEN, “Robust policies to mitigate carbon leakage,” *Journal of Public Economics* 149 (2017), 35–46.
- BOVENBERG, A. AND B. HEIJDRA, “Environmental Abatement and Intergenerational Distribution,” *Environmental & Resource Economics* 23 (September 2002), 45–84.

- BOVENBERG, A. L. AND B. J. HEIJDR, “Environmental tax policy and intergenerational distribution,” *Journal of Public Economics* 67 (January 1998), 1–24.
- BURKE, M., S. M. HSIANG AND E. MIGUEL, “Global non-linear effect of temperature on economic production,” *Nature* 527 (2015), 235–239.
- BURNIAUX, J.-M. AND J. O. MARTINS, “Carbon leakages: a general equilibrium view,” *Economic Theory* 49 (2012), 473–495.
- CAI, Y., T. M. LENTON AND T. S. LONTZEK, “Risk of multiple interacting tipping points should encourage rapid CO₂ emission reduction,” *Nature Climate Change* 6 (2016), 520 – 525.
- CARATTINI, S., A. BARANZINI, P. THALMANN, F. VARONE AND F. VÖHRINGER, “Green Taxes in a Post-Paris World: Are Millions of Nays Inevitable?,” *Environmental and Resource Economics* (2017).
- CHICHILNISKY, G. AND G. HEAL, “Who should abate carbon emissions?: An international viewpoint,” *Economics Letters* 44 (April 1994), 443–449.
- CIGNO, A., “A constitutional theory of the family,” *Journal of Population Economics* 19 (June 2006), 259–283.
- DAO, N., K. BURGHHAUS AND O. EDENHOFER, “Self-Enforcing Intergenerational Social Contracts for Pareto Improving Pollution Mitigation,” *Environmental and Resource Economics* (2017).
- D’AUTUME, A., K. SCHUBERT AND C. WITHAGEN, “Should the Carbon Price Be the Same in All Countries?,” *Journal of Public Economic Theory* 18 (October 2016), 709–725.

- DELL, M., B. F. JONES AND B. A. OLKEN, "What Do We Learn from the Weather? The New ClimateEconomy Literature," *Journal of Economic Literature* 52 (2014), 740–798.
- EICHNER, T. AND R. PETHIG, "Carbon Leakage, The Green Paradox, And Perfect Future Markets," *International Economic Review* 52 (08 2011), 767–805.
- ELLIOTT, J. AND D. FULLERTON, "Can a unilateral carbon tax reduce emissions elsewhere?," *Resource and Energy Economics* 36 (2014), 6–21.
- FISCHER, C. AND A. K. FOX, "Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates," *Journal of Environmental Economics and Management* 64 (2012), 199–216.
- FISCHER, C., L. PREONAS AND R. NEWELL, "Environmental and Technology Policy Options in the Electricity Sector: Are We Deploying Too Many?," *Journal of the Association fo Environmental and Resource Economists* forthcoming (2017).
- GERLAGH, R., "Too Much Oil," *CESifo Economic Studies* 57 (March 2011), 79–102.
- GOLOSOV, M., J. HASSLER, P. KRUSELL AND A. TSYVINSKI, "Optimal Taxes on Fossil Fuel in General Equilibrium," *Econometrica* 82 (01 2014), 41–88.
- GRAFTON, Q. R., T. KOMPAS AND N. VAN LONG, "Substitution between biofuels and fossil fuels: Is there a green paradox?," *Journal of Environmental Economics and Management* 64 (2012), 328–341.
- GRONWALD, M., N. VAN LONG AND L. ROEPKE, "Simultaneous Supplies of Dirty Energy and Capacity Constrained Clean Energy: Is there a Green Paradox?," *Environmental and Resource Economics* (2017).

- HART, R. AND D. SPIRO, “The elephant in Hotelling’s room,” *Energy Policy* 39 (2011), 7834 – 7838, clean Cooking Fuels and Technologies in Developing Economies.
- HEIJDRA, B. J., J. P. KOOIMAN AND J. E. LIGTHART, “Environmental quality, the macroeconomy, and intergenerational distribution,” *Resource and Energy Economics* 28 (January 2006), 74–104.
- HOEL, M., “Carbon taxes and the Green Paradox,” in *Climate Change and Common Sense: Essays in Honor of Tom Schelling* (Oxford University Press, Oxford, 2012).
- HOWARD, P. AND T. STERNER, “Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates,” *Environmental and Resource Economics* (2017).
- INTERAGENCY WORKING GROUP ON SOCIAL COST OF CARBON, “Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis,” Technical Report, 2010.
- , “Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis,” Technical Report, 2013.
- KVERNDOKK, S., K. E. ROSENDAHL, L. LINDHOLT, F. R. AUNE AND A. C. BØENG, “Fuel Efficiency Improvements - Feedback Mechanisms and Distributional Effects in the Oil Market,” *Environmental and Resource Economics* (2017).
- LEMOINE, D. AND C. P. TRAEGER, “Economics of tipping the climate dominoes,” *Nature Climate Change* 6 (2016), 514 – 519.
- LENTON, T. M. AND J.-C. CISCAR, “Integrating tipping points into climate impact assessments,” *Climatic Change* 117 (2013), 585–597.

- MARTIN, I. W. R. AND R. S. PINDYCK, "Averting Catastrophes: The Strange Economics of Scylla and Charybdis," *American Economic Review* 105 (October 2015), 2947–2985.
- MICHELSEN, T. O., "Brown backstops versus the green paradox," *Journal of Environmental Economics and Management* 68 (2014), 87 – 110.
- MULATU, A., "The Structure of UK Outbound FDI and Environmental Regulation," *Environmental and Resource Economics* (2017).
- NEWBOLD, S. C. AND A. L. MARTEN, "The value of information for integrated assessment models of climate change," *Journal of Environmental Economics and Management* 68 (2014), 111 – 123.
- NORDHAUS, W., *Managing the global commons: the economics of climate change* (MIT Press, Cambridge, 1994).
- , *The climate casino: Risk, uncertainty, and economics for a warming world* (Yale University Press, New Haven, 2013).
- NORDHAUS, W. D., "Revisiting the social cost of carbon," *Proceedings of the National Academy of Sciences* 114 (2017), 1518–1523.
- OATES, W. E. AND P. R. PORTNEY, "The political economy of environmental policy," in K. G. Mler and J. R. Vincent, eds., *Handbook of Environmental Economics* volume 1 of *Handbook of Environmental Economics*, chapter 8 (Elsevier, 2003), 325–354.
- PINDYCK, R. S., "Climate Change Policy: What Do the Models Tell Us?," *Journal of Economic Literature* 51 (September 2013), 860–872.

- , “The Social Cost of Carbon Revisited,” NBER Working Papers 22807, National Bureau of Economic Research, Inc, November 2016.
- PLAMBECK, E. L. AND C. HOPE, “PAGE95,” *Energy Policy* 24 (1996), 783 – 793.
- SINCLAIR, P. J. N., “On the Optimum Trend of Fossil Fuel Taxation,” *Oxford Economic Papers* 46 (Supplemen 1994), 869–877.
- SINN, H.-W., “Public policies against global warming: a supply side approach,” *International Tax and Public Finance* 15 (August 2008), 360–394.
- , *The Green Paradox: A Supply-Side Approach to Global Warming* (MIT Press, Cambridge, 2012).
- TOL, R. S. J., “The damage costs of climate change toward more comprehensive calculations,” *Environmental and Resource Economics* 5 (Jun 1995), 353–374.
- , “The Economic Effects of Climate Change,” *Journal of Economic Perspectives* 23 (Spring 2009), 29–51.
- , “Correction and Update: The Economic Effects of Climate Change,” *Journal of Economic Perspectives* 28 (Spring 2014), 221–226.
- , “Economic impacts of climate change,” Working Paper Series 7515, Department of Economics, University of Sussex, May 2015.
- TSUR, Y. AND A. ZEMEL, “Coping with Multiple Catastrophihic Threats,” *Environmental and Resource Economics* (2017).
- VAN DEN BERGH, J. AND W. BOTZEN, “Monetary valuation of the social cost of CO₂ emissions: A critical survey,” *Ecological Economics* 114 (2015), 33 – 46.

- VAN DER MEIJDEN, G., F. VAN DER PLOEG AND C. WITHAGEN, “International capital markets, oil producers and the Green Paradox,” *European Economic Review* 76 (2015), 275–297.
- VAN DER PLOEG, F., “Abrupt positive feedback and the social cost of carbon,” *European Economic Review* 67 (2014), 28 – 41.
- , “Reacting to multiple tipping points,” *Nature Climate Change* 6 (2016a), 442 – 443.
- , “Second-best carbon taxation in the global economy: The Green Paradox and carbon leakage revisited,” *Journal of Environmental Economics and Management* 78 (2016b), 85 – 105.
- VAN DER PLOEG, F. AND A. DE ZEEUW, “Climate Tipping and Economic Growth: Precautionary Capital and the Price of Carbon,” *Journal of the European Economic Association* (forthcoming 2017).
- VAN DER PLOEG, F. AND C. WITHAGEN, “Is there really a green paradox?,” *Journal of Environmental Economics and Management* 64 (2012a), 342 – 363, 2010 Monte Verita Conference on Sustainable Resource Use and Economic Dynamics(SURED).
- , “Too much coal, too little oil,” *Journal of Public Economics* 96 (2012b), 62 – 77.
- , “Growth, Renewables, And The Optimal Carbon Tax,” *International Economic Review* 55 (02 2014), 283–311.
- , “Global Warming and the Green Paradox: A Review of Adverse Effects of Climate Policies,” *Review of Environmental Economics and Policy* 9 (2015), 285–303.

VON BELOW, D., F. DENNIG AND N. JAAKKOLA, “The climate pension deal: An intergenerational bargain,” Technical Report 039, mimeo, 2016.

WANG, M. AND J. ZHAO, “Monopoly extraction of a nonrenewable resource facing capacity constrained renewable competition,” *Economics Letters* 120 (2013), 503 – 508.

WEITZMAN, M. L., “GHG Targets as Insurance Against Catastrophic Climate Damages,” *Journal of Public Economic Theory* 14 (03 2012), 221–244.