



Essays in Climate and Labour Economics

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Abstract

This thesis consists of four essays.

The first essay, **Optimal carbon taxes with social and private discounting** extends an analytically tractable climate-economy model to allow for a planner that discounts the future differently than private agents. This is relevant to the climate-policy debate: some have argued that climate policy should be designed using a discount rate lower than the rate at which individuals appear to discount their own future utilities. If a social planner discounts the future differently than private agents, laissez-faire and socially optimal rate of fossil-fuel depletion differ substantially. A planner more patient than the market wants to slow down fossil-fuel depletion substantially, which calls for carbon taxes that fall over time, eventually turning into subsidies. Welfare losses in the event that the first-best cannot be implemented are substantially larger when discount rates differ.

The second essay, **Temperature Feedbacks to the Carbon Cycle in Climate–Economy Models** considers the substantial uncertainty about how much of future CO₂ emissions will be absorbed by the biosphere, due in part to uncertainty about climate sensitivity. All else equal, higher temperatures tend to reduce the biosphere’s ability to take up carbon. Well-known climate–economy models do not take this effect into account. We extend the carbon cycle component of DICE to make carbon flows between atmosphere and biosphere temperature dependent. Our results suggest

that, for best-guess values for climate sensitivity, standard carbon-cycle representations may predict atmospheric CO₂ well during the 21st century. For later time periods, where CO₂ concentrations are predicted to fall, we find that atmospheric CO₂ decreases much more slowly. For higher values of climate sensitivity, the standard carbon-cycle representations understate atmospheric CO₂ also during the 21st century, and more so the higher climate sensitivity. How much these changes to the carbon cycle representation translate into optimal climate policy depends on the model’s damage function, as well as on the rate of time preference. For some combinations of plausible parameter values, optimal carbon taxes differ greatly between the baseline DICE–2007 model and the model with our extended carbon cycle component, which we call Bio–DICE.

The third essay, **Uncertainty, Climate Change and the Global Economy** illustrates how one may assess our comprehensive uncertainty about the various relations in the entire chain from human activity to climate change. Using a modified version of the RICE model of the global economy and climate, we perform Monte Carlo simulations, where full sets of parameters in the model’s most important equations are drawn randomly from pre-specified distributions, and present results in the forms of fan charts and histograms. Our results suggest that under a Business-As-Usual scenario, the median increase of global mean temperature in 2105 relative to 1900 will be around 5.0 °C. The 99 percent confidence interval ranges from 3.4 °C to 7.3 °C. Uncertainty about socio-economic drivers of climate change lie behind a non-trivial part of this uncertainty about global warming.

The last essay, **Last In, First Out? Estimating the Effect of Seniority Rules in Sweden**, investigates whether a relaxation in seniority rules (the ‘last-in-first-out’ principle) had any effect

on firms' employment behaviour. Seniority rules exist in several countries, but consequences of seniority rules on firms' employment behaviour have not been examined previously. The 'last-in-first-out' principle in Sweden was reformed in January 2001 such that employers with ten or fewer employees were allowed to exempt two workers from the seniority rule. Using an employer-employee unbalanced panel data for the period 1996–2005, we find that both hires and separations increased in small firms relative to large firms by about 5%. This also implies that there were no effects on firms' net employment. Our results show that firms indeed reacted to changes in the seniority rules, but we argue that the effects are not overwhelmingly large.

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Stockholm, November 2011

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Chapter 1

Introduction

This thesis consists of four essays in climate economics and labour economics.

The first three essays share a common theme—the economics of climate change. What will happen to the global climate in the future, depending on exactly how society and nature develops? What can we, as a society, do to meet the challenge of a changing climate? In particular, can we use economic policy to reduce emissions of greenhouse gases (GHGs) into the atmosphere, and thereby prevent global temperatures from rising too much? How high should the optimal emissions tax be today, if we could implement one globally, and how should it develop over time? Questions such as these are the motivation behind my research within the area of climate economics.

Climate policy aims to find an appropriate way to deal with the problem of a warming climate. Such policy could either be an attempt at slowing down climate change, or indeed to take rising temperatures as given and develop strategies to cope with or adapt to a warming world. It it is the first approach, confusingly referred to as mitigation in the climate-policy debate, that has been the

focus of my attention for the past couple of years.

The problem of global warming has been called the greatest externality ever seen (e.g., Stern, 2006), and the economist's standard approach to dealing with externalities is to impose taxes that, if possible, internalize them. Much of this thesis revolves around the question of what the optimal tax on emissions of greenhouse gases, or analogously, on the burning of fossil fuels should be.

An economist's approach to the climate problem is to think about it in terms of cost-benefit analysis. In order to optimize, we want to weigh the costs of fossil-fuel consumption against the benefits, and strike a balance between the two. The established methodology for examining such issues is to rely on a class of models that I like to refer to as climate-economy models.¹ One family of such models, the DICE and RICE models developed by William Nordhaus (see, e.g, Nordhaus and Boyer, 2000), feature prominently in this thesis.

Several climate-economy models are impressive feats of computer coding, but unfortunately largely inaccessible for the non-initiated. The DICE and RICE models are arguably the easiest to approach, out of the large simulation models available. Documentation is extensive and accessible, and the program code can be downloaded from the web. The analytical model developed by Golosov and coauthors (2011), which I make extensive use of in Chapter 2 of this thesis, is an entirely different kind of climate-economy model. It can in principle be solved using pen and paper, and the important mechanisms are transparent. Although some not entirely innocu-

¹It is also common to refer to them as Integrated Assessment Models, IAMs. However, the term IAM is used for a wide range of models, and can therefore mean very different things to different people. By climate-economy model, I mean a model that describes the world economy as well as the global climatic system, and the links between the two.

ous assumptions are made in order to allow an analytical solution of the model, it is in many ways a substantial improvement for the understanding of climate change among economists.

This thesis would not have existed in its present form without the Mistra-funded *SWEdish research programme on Climate, Impacts and Adaptation* (Mistra–SWECIA). This programme has been ongoing since 2008, and brings together researchers from as diverse fields as meteorology, natural geography, sociology, and economics. During our regular meetings, I have benefited a lot from discussions with knowledgeable colleagues from other disciplines, which has greatly helped my understanding of the Earth system. In addition, Chapter 3 of this thesis is an interdisciplinary research effort that is a direct result of the intellectually stimulating environment within Mistra–SWECIA.

Chapter 2, Optimal carbon taxes with social and private discounting deals with a question that has been one of the major bones of contention in the climate-policy debate: what rate of time preference should be used when designing optimal climate policy? It has been argued, perhaps most famously in the Stern Review (Stern, 2006), that climate policy should be designed using discount rates lower than the rates at which individuals appear to discount their own future utilities. There is far from consensus on this issue, but it is fair to say that the general opinion among economists has tended to gravitate towards Stern’s “ethical” choice of the discount parameter.

Although I agree that ethical considerations must play a role for the appropriate choice of discount rates in climate policy, I do not take a stand on the issue in the study presented here. Rather, I argue that if policymakers want to design climate policy on the basis of a discount rate that is lower than the rate at which market

participants discount even their own future, they may very well do so, but they are still constrained by the fact that market participants behave according to their own preferences. In other words, a social planner may set out to optimize a welfare function that exhibits a large degree of patience, but he cannot simply impose that consumers and firms be patient too. In order to induce market participants to save enough of capital as well as fossil-fuel stocks for the future, optimal taxes will have to be designed with this in mind. To show this formally, I adapt a model developed by Golosov and coauthors (2011), and allow a social planner to discount the future at a different rate than the representative agent.

I show that the optimal rate of depletion of fossil fuel depends on the planner’s time preference, but not on that of the consumer. The optimal sequence of energy taxes needed to implement this optimal allocation is a function of both parameters, however—with a planner that is more patient than the market, optimal energy taxes must fall in a more pronounced way over time, and eventually turn into fossil-fuel subsidies.

The inter-disciplinary project in Chapter 3, **Temperature Feedbacks to the Carbon Cycle in Climate–Economy Models**, is a collaboration with Anders Ahlström. We focus on a specific component in the link from GHG emissions to rising temperatures, namely the carbon cycle. There is great uncertainty about how much of future emissions of carbon dioxide CO₂ will be absorbed by the biosphere, due in part to uncertainty about climate sensitivity. All else equal, higher temperatures tend to reduce the biosphere’s ability to take up carbon. But well-known climate–economy models, such as DICE and RICE, do not take this effect into account.

To remedy this deficiency, we extend the carbon cycle component of DICE to make carbon flows between atmosphere and bio-

sphere temperature dependent. Our results suggest that, for best-guess values for climate sensitivity, standard carbon-cycle representations may predict atmospheric CO₂ well during the 21st century, but for later time periods, where CO₂ concentrations are predicted to fall, we find that atmospheric CO₂ decreases much more slowly. For higher values of climate sensitivity, the standard carbon-cycle representations understate atmospheric CO₂ also during the 21st century, and more so the higher climate sensitivity.

How much these changes to the carbon cycle representation translate into optimal climate policy depends on the model's damage function, as well as on the rate of time preference. For some combinations of plausible parameter values, optimal carbon taxes differ greatly between the baseline DICE–2007 model and the model with our extended carbon cycle component, which we call Bio-DICE.

Chapter 4, Uncertainty, Climate Change and the Global Economy is a joint effort with Torsten Persson. The main question in this study is what will happen to global climate in the absence of any policy to slow climate change. How much fossil fuel will be burnt over the coming century, and how large a rise in the global mean temperature can we expect as a result of that? Given the extensive uncertainty about the multitude of processes involved, natural as well as socio-economic, the answers to these questions should not be thought of as just a single number. Instead, a useful answer to the question of what global temperature increase we might expect over, say, the coming century, would be a probability distribution over a range of values.

The goal in Chapter 4 is precisely to generate such probability distributions, for a number of outcome variables of interest. To this end, we make use of RICE, a climate–economy model with a num-

ber of regions making up the world economy. The original model is deterministic, but we introduce uncertainty by imposing probability distributions over a large number of parameters and variables that are exogenous to the model. We estimate these uncertainties based on available data, in a manner that allows us to stay close to the model formulation. We then perform Monte Carlo simulations, i.e., we make a large number of random draws of the full set of parameters and simulate the entire model for each such draw. Each simulation generates time paths for future output, global temperature, climate damages, etc.

The collection of all such time paths are then used to derive probability distributions at different points in time for the variables of most interest. Climate sensitivity (the effect on equilibrium global mean temperature of a doubled GHG concentration) remains the single most important determinant of uncertainty about global warming, but well-identifiable socioeconomic developments in major regions of the world—such as population growth, and improvements of overall technology and energy efficiency—drive a non-trivial part of that uncertainty. Closing down uncertainty about climate sensitivity altogether, one is left with an uncertainty range of temperature a hundred years from now, which is close to 4 °C.

Finally, Chapter 5 has no relation at all to climate change. Entitled **Last In, First Out? Estimating the Effect of Seniority Rules in Sweden**, this study was carried out together with Peter Skogman Thoursie. We study a reform of a feature of Swedish employment-protection legislation, the so-called last-in-first-out requirement, whereby an employer that chooses to downsize must always first lay off the workers that were employed last. This piece of legislation is a rather controversial subject that is often under scrutiny in the public debate in Sweden.

The ‘last-in-first-out’ principle in Sweden was reformed in January 2001 such that employers with ten or fewer employees were allowed to exempt two workers from the seniority rule. Using an employer-employee unbalanced panel data for the period 1996–2005, we investigate how firms reacted to this change in legislation. Previous work, such as Lindbeck, Palme and Persson (2006), has explored the consequences for employee behaviour of the same reform. We demonstrate that both hires and separations increased in small firms relative to large firms by about 5%, which implies that there were no effects on firms’ net employment. The effects seem to be slightly larger for women and for younger workers, groups which tend to be less established on the labour market. Our results show, therefore, that firms indeed reacted to changes in the seniority rules, but the effects are not particularly large.

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Chapter 2

Optimal carbon taxes with social and private discounting*

2.1 Introduction

Climate change is a long-term phenomenon. The benefits of fossil fuel consumption are enjoyed instantaneously, whereas the costs of the associated emissions of carbon dioxide (CO_2)—often referred to as damages—largely occur in the future. Indeed, parts of our additions of CO_2 to the atmosphere remain there for very long periods of time, if not forever. For this reason, the issue how to weigh future generations against those currently alive has been at the forefront of the climate-policy debate. Much of the discussion has revolved around the appropriate choice of the rate of pure time

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preference in climate-economy models. Weitzman (2007) argues that “it is not an exaggeration to say that the biggest uncertainty of all in the economics of climate change is the uncertainty about which interest rate to use for discounting. In one form or another, this little secret is known to insiders in the economics of climate change, but it needs to be more widely appreciated by economists at large.”

In this paper, I investigate the consequences for optimal carbon taxation of a point made informally by Kaplow et al. (2010). These authors argue that, in principle, two quite different discounting processes are involved, and these should be separated more clearly. Beckerman and Hepburn (2007) stress the distinction between the same individual at different points in time on the one hand, and different generations on the other hand. They write: “Schelling notes that while the Ramsey and Pigou references to ‘impatience’ or ‘myopia’ might accurately describe the virtually universal preference for consumption during one’s lifetime by oneself, it is absurd to apply these adjectives to the consumption of somebody one will never know in 200 years’ time.”

The distinction between private and social discounting may be summarized as follows. On the one hand, individuals discount their own utility at future dates (and that of their offspring, to the extent they value it), using their own preferences for intertemporal consumption smoothing. Let us refer to the time-preference parameter—a discount factor β , say—as a ‘private’ or ‘market’ discounting parameter. This discounting process determines consumers’ savings decisions, which gives rise to capital accumulation, and also the choice of how to optimally deplete an exhaustible resource. Such discounting is not readily affected by policy, and indeed the question at what rate the ‘market’ discounts the future

is an empirical one. On the other hand, when designing optimal climate policy, a policymaker has to aggregate the well-being of different generations into a welfare function. In doing so, she may choose to discount future generations, or indeed not at all. What discounting practices should be employed in this setting is a normative question, and as such an ethical decision rather than an empirical matter. Ramsey (1928), for one, suggests that the only ethically defensible social discount rate is zero.

Climate-economy models such as, for example, DICE (Nordhaus, 2008) or PAGE (Hope, 2006) model consumers as infinitely-lived representative agents, which helps explain why the distinction between the two types of discounting has been blurred in much previous work: individual utility and social welfare coincide, and it is not obvious how to distinguish the two different discounting concepts. In models, such as DICE, where output and consumption are endogenous, this has necessarily led to a ‘descriptive’ stance on discounting: discount parameters do not only determine how to compare climate damages over time, they also govern capital accumulation and fossil fuel depletion. Imposing a low rate of time preference in such a model may lead to, e.g., savings behaviour that does not seem plausible. On the other hand, modellers that see output or consumption streams as exogenous, as in PAGE, can more easily treat discounting as a purely ethical matter.

Stern (2006) advocates a rate of time preference of 0.1% per year, chosen on ethical grounds. Nordhaus (2007) discusses this stance in detail, stressing that such a low time-preference rate, together with an assumption of logarithmic utility, results in an equilibrium interest rate that is much lower than what is observed in reality. He goes on to suggest that a Stern-type time-preference rate can be consistent with ‘reasonable’ interest rates, provided that con-

sumers exhibit strong enough preferences for consumption smoothing. Put differently, if consumers make consumption and savings decisions that give rise to a consumption sequence $\{C_t\}_{t=0,\dots,\infty}$, in order to maximize

$$\sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\eta}}{1-\eta}, \quad (2.1)$$

then observed market interest rates are consistent with a very high degree of patience (a high β) if consumers are also very averse to consumption differences over time (a high η). However, one cannot freely choose any combination of β and η and still get savings behaviour and equilibrium interest rates that match reality.¹

The position implicit in this line of reasoning seems to be as follows. We may study optimal taxes on fossil-fuel consumption using a model with an infinitely-lived representative agent. In that case, we should use preferences for the representative agent that correspond to observed market outcomes², such as interest rates and capital accumulation, and implement climate taxes that maximize

¹A similar argument is used in Manne et al. (1995), in the context of the MERGE model:

Note that a lower or a zero rate of utility time preference would not provide a good description of the collective outcome of individual choices. It would also imply an unrealistically rapid increase in the near-term rate of investment and capital formation [...].

Dasgupta (2007) does not strike a clear balance between private and social discounting, but emphasizes the point that if β is seen as an ethical parameter, then so should η . This is also a central argument in Dasgupta (2008).

²Schneider et al. (2010) show that a representative agent in an infinite-horizon model will appear less patient than a finitely-lived agent in an overlapping-generations model, if both agents exhibit the same preferences for intertemporal consumption smoothing (η). This is due to the fact that in an OLG model, individuals' consumption growth exceeds overall consumption growth, as long as consumers do not fully incorporate the utilities of future generations.

the consumer's lifetime utility, as defined by these preferences. This view is restrictive, for several reasons. Sælen et al. (2008) argue that the preference structure in (2.1), which is standard in climate-economy models, is underspecified. This refers to the fact that the parameter η is forced to simultaneously capture risk aversion, inequality aversion, and individuals' attitudes towards intertemporal consumption smoothing. Requiring η to be such that it ensures that the model produces reasonable interest rates, given a choice of β , makes the model even more underspecified.

In addition, the distinction between the concepts of individual utility and social welfare makes it clear that we may well want to design climate policy in a way that implies a higher weight on future utilities than what is suggested by consumers' investment decisions. It is far from obvious that a social planner, when defining a social welfare function, should weight down the utilities of individuals who are not yet born simply because they will live in the future. Nordhaus's insistence on, e.g., 'reasonable' interest rates precludes such an assessment, however. Climate policy designed using 'market' discount rates forces the social planner to discount the utilities of future generations at the same rate that individuals who are alive today discount their own future utilities.

These arguments seem uncontroversial when applied to the real world, where individuals live finite lives and many who will suffer the most from a changing climate have not yet been born. In climate-economy models, however, the standard approach is to model individuals' preferences with an infinitely-lived representative agent. As alluded to earlier, this makes it unclear how to distinguish between private and social discounting.

An obvious solution to this dilemma would be to instead consider a climate-economy model with finitely-lived agents, possibly

with a structure of overlapping generations (OLG). Schneider et al. develop such a model, and argue that in some respects an OLG model behaves quite differently from a representative-agent model. Howarth (2000), on the other hand, shows that the standard infinitely-lived representative-agent model common in climate economics closely approximates an OLG model, in terms of optimal-policy prescriptions. In an OLG model, the planner's rate of time preference used for aggregating utilities over generations is separate from the individuals' time-preference rate, and can thus in principle be set to a different value.

In Blanchard's (1985) perpetual-youth model, which is somewhat of a hybrid between an infinite-horizon and an OLG model, consumers discount future utilities due to two separate factors. On the one hand, consumers exhibit a pure rate of time preference, θ . They also face a constant (and time-invariant) risk of death, p . Consumers end up discounting future utilities at the rate $\theta + p$. In the paper there is no detailed discussion of what discount rate a policymaker should use in this setting, but the implied default value seems to be θ . In other words, if the planner shares the consumers' pure rate of time preference, she may still discount the future at a lower rate. This is due to the fact that an individual faces a risk of dying, whereas society as a whole does not face a risk of extinction (if nonzero, that risk is much smaller than the individual risk). Indeed, similar arguments were used in the Stern review for why a planner should use a low discount rate.

Still, the standard representative-agent setup has much to recommend it in terms of simplicity, in addition to its widespread use in climate-economy models. In this paper I explore the consequences for climate policy of a difference between social and private discount rates, and I do so within a climate-economy model that is standard

in the sense of considering an infinitely-lived representative agent. More precisely, I make use of the climate-economy model laid out in Golosov et al. (2011), but unlike these authors I allow for ‘social’ and ‘market’ discount factors to differ. I investigate how this affects optimal taxes on emissions of CO₂ (or, equivalently, on the consumption of carbon-based energy), as well as the welfare implications. As we shall see, the optimal rate of depletion of fossil fuels depends on the social planner’s preferences only, and not on the market’s discount rates. By contrast, the sequence of energy taxes required to make market participants deplete fossil-fuel reserves at this optimal rate depend on the difference between social and market discount rates. When the planner is more patient than consumers, a tax sequence that falls more quickly than in the standard case is required, eventually turning into subsidies for fossil-fuel consumption.

The model by Golosov et al. is a simple dynamic model of the global economy and climate, much in the spirit of William Nordhaus’s DICE model (e.g., Nordhaus, 2008). The main difference to DICE is that (carbon-based) energy is explicitly modelled as an input into the production process.³ The authors first present a general model with few assumptions about functional forms.⁴ A num-

³A distinction should be drawn between DICE and the related RICE model in this respect. RICE considers a world economy consisting of several regions, whereas in DICE there is only one globally representative consumer. The version of RICE in Nordhaus and Boyer, (2000) does indeed feature a production technology where energy enters explicitly as an input. In this model, however, exhaustibility of fossil fuels is assumed away.

⁴The general model already embodies assumptions that do not correspond to the most general case. For example, it is assumed that carbon based energy is essential in production, and that—except for the possibility of a so-called backstop that makes carbon-based energy redundant—it will remain essential indefinitely. Dasgupta and Heal (1974) discuss this and many other aspects relevant to optimal fossil-fuel depletion.

ber of simplifying assumptions, some less innocuous than others, are then introduced, which allow the model to be solved analytically. These will be discussed in more detail below.

The paper is organized as follows. Section 2.2 looks at a two-period model, which brings out the main message of the paper in a straightforward manner: when the market discounts the future more heavily than the social planner, the time profile of energy taxes must be adjusted in order to ensure fossil fuels are depleted at an optimal rate. Section 2.3 considers an infinite-horizon model with similar characteristics, which brings out additional insights about the time path of optimal energy taxes. Section 2.4 presents results from a calibrated infinite-horizon model, and discusses welfare considerations. Section 4.5 concludes.

2.2 A Two-Period Model

First, let us consider a simple two-period version of the model laid out in Golosov et al. (2011). Time is denoted by $t \in \{1, 2\}$. Preferences are logarithmic in consumption, and period felicity functions are aggregated into lifetime utility using a discount factor β :

$$U(C_1, C_2) = \ln C_1 + \beta \ln C_2.$$

The central theme of the paper is to explore the implications of market participants using a discount factor different from that of the planner. Throughout, β is used to denote the discount factor of private agents' (consumers'), whereas the discount factor of the planner is referred to as β^* .

Production takes place using a Cobb-Douglas production func-

tion in capital, K_t , labour, N_t , and fossil-fuel based energy, E_t ,

$$Y_t = D_t A_t K_t^\alpha N_t^{1-\alpha-\nu} E_t^\nu.$$

Y_t denotes output, and A_t is a productivity shifter. $D_t \in [0, 1]$ represents the effects of climate change on total production: a fraction $(1 - D_t)$ of total output is destroyed due to the changing climate. D_t depends on the concentration of CO₂ in the atmosphere, S_t . I follow Golosov et al. and use an exponential function $D_t = e^{-\gamma S_t}$, where the parameter γ is a measure of the strength of climate-change impacts. This functional-form assumption implies that the marginal externality damage due to an additional unit of CO₂ is independent of the atmospheric CO₂ stock, S_t . While this assumption is a simplification, Golosov et al. show that the resulting ‘damage function’ D_t approximates the functions used in DICE quite well.

The physical resource constraints are $Y_1 = C_1 + I_1$ and $Y_2 = C_2$ where I_1 denotes first-period investment. Capital has a standard law of motion: $K_2 = (1 - \delta)K_1 + I_1$. In the interest of analytical tractability, capital fully depreciates between time periods, i.e., $\delta = 1$. This is arguably not a very extreme assumption if we consider a time period to be ten years, as is common in climate-economy models.

The natural resource constraint reads $E_1 + E_2 = R$, where R is the available amount of fossil fuel. I will assume that all fossil fuel gets used up, hence the equality.⁵ Atmospheric carbon follows

⁵As will become clear, this is the interesting case in terms of the extension considered in this paper. If it is not optimal to use up all available fossil fuels, then the simple fact that discount factors differ matters very little for optimal policy. In addition, based on the calculations in Golosov et al., it seems likely that at least all globally available oil will be consumed.

a simple decay structure⁶ defined by a decay parameter φ :

$$S_1 = E_1; S_2 = \varphi S_1 + E_2. \quad (2.2)$$

In addition, it is assumed that consumers supply labour inelastically, and there is no population growth. Without loss of generality, labour supply is normalized to unity ($N_t = 1$). The supply of fossil-fuel energy takes place under perfect competition, and there are no extraction costs for oil.

2.2.1 The planner's problem

The planner maximizes the discounted sum of utilities, internalizing the climate externality due to fossil fuel consumption. This is captured by the presence of S_t in the objective function. Here, S_t has been substituted away using the law of motion for the carbon cycle in (2.2). Note that the planner uses the discount factor β^* :

$$\begin{aligned} \max_{K_2, E_1} & [\ln(e^{-\gamma E_1} A_1 K_1^\alpha E_1^\nu - K_2) \\ & + \beta^* \ln(e^{-\gamma(\varphi E_1 + R - E_1)} A_2 K_2^\alpha (R - E_1)^\nu)] \end{aligned}$$

The first-order conditions are

$$K_2 : \frac{1}{C_1} = \beta^* \frac{1}{C_2} \frac{\alpha Y_2}{K_2}, \quad \text{and} \quad (2.3)$$

$$E_1 : \frac{1}{C_1} \frac{\nu Y_1}{E_1} - \frac{1}{C_1} \gamma Y_1 - \beta^* \frac{1}{C_2} \gamma \varphi Y_2 = \beta^* \frac{1}{C_2} \frac{\nu Y_2}{E_2} - \beta^* \frac{1}{C_2} \gamma Y_2. \quad (2.4)$$

⁶The infinite-horizon model discussed in Section 2.3 has a more sophisticated carbon cycle formulation.

Using the physical resource constraints $C_1 + K_2 = Y_1$ and $C_2 = Y_2$, the Euler equation in (2.3) gives standard consumption and investment functions

$$C_1 = \frac{1}{1 + \alpha\beta^*}Y_1 \quad \text{and} \quad K_2 = \frac{\alpha\beta^*}{1 + \alpha\beta^*}Y_1. \quad (2.5)$$

The first-order condition for energy, (2.4), is a Hotelling result (Hotelling, 1931). The first, positive terms on each side of the equality represent the marginal product of energy, valued at the marginal utility of consumption, and discounted. The negative terms capture the externality damage due to fossil fuel consumption. First-period energy use causes negative effects in both time periods, hence the two negative terms on the LHS, whereas period-two energy use only causes damages in the same period, hence the single negative term on the RHS. The equation states that the marginal product of energy net of damages, valued at the marginal utility of consumption and appropriately discounted over time, should be equal across time periods. We can use the expression for C_1 in (2.5), along with the constraint that $C_2 = Y_2$, to arrive at

$$\frac{\nu}{E_1^*} - \gamma \frac{1 + \beta^*(\alpha + \varphi)}{1 + \alpha\beta^*} = \frac{\beta^*}{1 + \alpha\beta^*} \left(\frac{\nu}{E_2^*} - \gamma \right). \quad (2.6)$$

The equation in (2.6), together with the physical resource constraint $E_1 + E_2 = R$, uniquely determines the optimal fossil-fuel consumption over time from the planner's perspective. The notation E_t^* denotes optimal energy consumption. Note that optimal energy consumption is defined by the solution to the planner's problem only, and hence does not involve the market discount rate, β .

2.2.2 The decentralized economy

Consumers

Let consumers discount the future using a discount factor β . The consumer's problem is then

$$\max_{C_1, C_2, K_2, E_1, E_2} \ln C_1 + \beta \ln C_2,$$

subject to budget and resource constraints

$$\begin{aligned} C_1 + K_2 &= (1 - \tau_1^K)r_1 K_1 + w_1 + (p_1 - \tau_1^E)E_1 + T_1, \\ C_2 &= (1 - \tau_2^K)r_2 K_2 + w_2 + (p_2 - \tau_2^E)E_2 + T_2, \quad \text{and} \\ E_1 + E_2 &= R. \end{aligned}$$

Here, two tax instruments are introduced. τ_t^K is a tax on capital returns, and τ_t^E is a tax on energy profits.⁷ It is assumed that the government budget is balanced in each time period: $\tau_t^E E_t + \tau_t^K r_t K_t = T_t$. In other words, any tax revenue is rebated back to consumers in the form of lump-sum transfers. This means that consumers' disposable income is equal to the income generated by total output: $(1 - \tau_t^K)r_t K_t + w_t N_t + (p_t - \tau_t)E_t + T_t = Y_t$. The

⁷The former is formulated as a standard *ad valorem* tax. As we will see, a constant *ad valorem* capital tax (subsidy) will be required to decentralize the optimal allocation; hence this formulation is more straightforward. A per-unit capital tax (subsidy) could be used instead, with the same results. The energy tax is expressed as a per-unit tax, as in Golosov et al. The advantage of such a formulation is that optimal taxes are expressed in terms of, say, dollars per tonne of carbon, which is the standard measure for carbon taxes in the climate-policy debate (as opposed to what percentage of the gross oil price that is accounted for by taxes, which would be the interpretation of an ad-valorem tax).

first-order conditions of the consumer's problem are

$$K_2 : \frac{1}{C_1} = \beta \frac{1}{C_2} r_2 (1 - \tau_2^K), \quad \text{and} \quad (2.7)$$

$$E_1 : \frac{1}{C_1} (p_1 - \tau_1^E) = \beta \frac{1}{C_2} (p_2 - \tau_2^E) \quad (2.8)$$

$$\Leftrightarrow \frac{(p_2 - \tau_2^E)}{(p_1 - \tau_1^E)} = r_2 (1 - \tau_2^K). \quad (2.9)$$

The Euler equation in (2.7) states a standard result, and the Hotelling equation in (2.9) is also familiar. In equilibrium, the after-tax price on the exhaustible resource must rise at a rate which corresponds to the return on other assets. The relevant rate of return is the effective interest rate on capital, also inclusive of the (capital) tax.

Firms

Firms maximize profits, taking factor prices as given:

$$\max_{K_t, N_t, E_t} D_t A_t K_t^\alpha N_t^{1-\alpha-\nu} E_t^\nu - r_t K_t - w_t N_t - p_t E_t.$$

Equilibrium factor prices are determined by the first-order conditions (FOCs) for firms,

$$K_t : r_t = \alpha \frac{Y_t}{K_t},$$

$$N_t : w_t = (1 - \alpha - \nu) \frac{Y_t}{N_t}, \quad \text{and}$$

$$E_t : p_t = \nu \frac{Y_t}{E_t}.$$

Market equilibrium

Using the Euler equation in (2.7), the firm's FOC for K_t , and the budget constraints, we find

$$K_2 = \frac{\alpha\beta(1 - \tau_2^K)}{1 + \alpha\beta(1 - \tau_2^K)} Y_1 \quad \text{and} \quad C_1 = \frac{1}{1 + \alpha\beta(1 - \tau_2^K)} Y_1.$$

Substitute the Euler equation and the expressions for r_2 and p_t from the firms' first-order conditions into the Hotelling equation, and rewrite it as

$$\frac{\left(\frac{\nu}{E_2}Y_2 - \tau_2^E\right)}{\left(\frac{\nu}{E_1}Y_1 - \tau_1^E\right)} = \alpha \frac{Y_2}{K_2}(1 - \tau_2^K).$$

Divide through by $\frac{Y_2}{Y_1}$, and, as in Golosov et al. define $\hat{\tau}_t^E$ energy taxes as a proportion of output, $\hat{\tau}_t^E \equiv \tau_t^E/Y_t$ ⁸. Simplify using the physical resource constraints, and arrive at the following equation, which pins down E_1 and $E_2 = R - E_1$, for a given set of taxes $\hat{\tau}_1$ and $\hat{\tau}_2$:

$$\left(\frac{\nu}{E_1} - \hat{\tau}_1^E\right) = \frac{\beta}{1 + \alpha\beta(1 - \tau_2^K)} \left(\frac{\nu}{E_2} - \hat{\tau}_2^E\right). \quad (2.10)$$

2.2.3 Implementing the optimal allocation

Assume there exists a set of tax parameters $\{\tau_2^K, \tau_1^E, \tau_2^E\}$ that allows the planner to implement the optimal allocation.⁹ Output, consumption, capital stocks and energy consumption in the decentralized equilibrium will then be identical to the planner's solution.

⁸Although $\hat{\tau}_t^E$ should properly be considered as 'per-unit energy taxes as a proportion of output', I will refer to τ_t^E and $\hat{\tau}_t^E$ interchangeably as energy taxes. The usefulness of defining the object $\hat{\tau}_t^E$ will become clear in the infinite-horizon model discussed below.

⁹Unsurprisingly, the first-period capital tax τ_1^K is redundant.

In such a solution, both Euler equations (2.3) and (2.7) must hold, with identical consumption levels. In other words,

$$\begin{aligned} \beta^* \frac{\alpha Y_2}{K_2} &= \beta r_2 (1 - \tau_2^K) \\ &= \beta \frac{\alpha Y_2}{K_2} (1 - \tau_2^K) \\ \Rightarrow \quad \tau_2^K &= -\frac{(\beta^* - \beta)}{\beta}. \end{aligned}$$

To implement the optimal allocation, the capital tax must be a subsidy when $\beta^* > \beta$: a government should subsidize the return to capital such that the effective return at the desired savings rate is consistent with the consumer's private discount rate β . The decentralized Hotelling equation in (2.9) can then be written as

$$\frac{\nu}{E_1} - \hat{\tau}_1^E = \frac{\beta}{1 + \alpha \beta^*} \left(\frac{\nu}{E_2} - \hat{\tau}_2^E \right). \quad (2.11)$$

The condition in (2.11) pins down energy consumption $\{E_1, E_2\}$, assuming that all fossil fuel gets used ($E_1 + E_2 = R$), for a given set of energy taxes $\{\hat{\tau}_1^E, \hat{\tau}_2^E\}$. From the planner's point of view, optimal oil consumption is defined by (2.6):

$$\frac{\nu}{E_1} - \gamma \frac{1 + \beta^*(\alpha + \varphi)}{1 + \alpha \beta^*} = \frac{\beta^*}{1 + \alpha \beta^*} \left(\frac{\nu}{E_2} - \gamma \right)$$

Comparing (2.6) and (2.11), we notice a number of things. First, consider a situation where the optimal sequence for fossil-fuel consumption does not deplete the total available stock, R . This happens when (2.6) holds, with $E_1^* + E_2^E < R$, i.e., it is not optimal to

increase either E_1^* or E_2^* . This means that

$$\frac{\nu}{E_1^*} = \gamma \frac{1 + \beta(\alpha + \varphi)}{1 + \alpha\beta} \quad \text{and} \quad \frac{\nu}{E_2^*} = \gamma.$$

Increasing fossil-fuel consumption in either period would then push down the marginal product of energy, making it fall short of the marginal externality damage. In other words, both sides of (2.6) will equal 0. From (2.11), we see that this must imply

$$\hat{\tau}_1^E = \gamma \frac{1 + \beta(\alpha + \varphi)}{1 + \alpha\beta} \quad \text{and} \quad \hat{\tau}_2^E = \gamma.$$

Now, the difference in discount factors plays no role: optimal energy taxes, as a proportion of output, depend on the planner's discount factor, β^* , but not on the consumers' discount factor, β . This highlights why the interesting case, for the purposes of this paper, is the one with scarcity of fossil fuels.

Let us thus consider the case with scarcity, i.e., all fossil fuel gets used up.¹⁰ First, notice that if $\beta = \beta^*$, it is easy to see that

$$\hat{\tau}_1^E = \gamma \frac{1 + \beta(\alpha + \varphi)}{1 + \alpha\beta} \quad \text{and} \quad \hat{\tau}_2^E = \gamma$$

will still implement the optimal allocation, together with $\tau_2^K = 0$. These are Pigouvian taxes: simply set the tax equal to the marginal climate damage caused by the optimal energy consumption, discounted appropriately. This is not the only set of taxes that works, however—an infinite number of combinations of taxes $\{\hat{\tau}_1^E, \hat{\tau}_2^E\}$ will do. Any $\{\hat{\tau}_1^E, \hat{\tau}_2^E\}$ that satisfies (2.11), where $\{E_1, E_2\}$ is defined by (2.6), will implement the optimal energy consumption, as long

¹⁰Technically, there is also a boundary case where the optimal total fossil fuel consumption $E_1 + E_2$ is exactly R . In such a situation, all oil gets used up, but there is still no scarcity.

as $\frac{\nu}{E_t} \geq \hat{\tau}_t^E \ \forall t$.¹¹

To see how optimal $\hat{\tau}_1^E$ and $\hat{\tau}_2^E$ relate to each other when private and social discount rates differ, fix $\hat{\tau}_2^E = \gamma$ and substitute this into (2.11), which gives

$$\hat{\tau}_1^E = \frac{\nu}{E_1} - \frac{\beta}{1 + \alpha\beta^*} \left(\frac{\nu}{E_2} - \gamma \right).$$

Combine this expression with (2.6) to find

$$\begin{aligned} \frac{\nu}{E_1} &= \gamma \frac{1 + \beta^*(\alpha + \varphi)}{1 + \alpha\beta^*} + \frac{\beta^*}{1 + \alpha\beta^*} \left(\frac{\nu}{E_2} - \gamma \right) \\ \Rightarrow \hat{\tau}_1^E &= \gamma \frac{1 + \beta^*(\alpha + \varphi)}{1 + \alpha\beta^*} + \frac{(\beta^* - \beta)}{1 + \alpha\beta^*} \left(\frac{\nu}{E_2} - \gamma \right). \end{aligned} \quad (2.12)$$

If $\hat{\tau}_2^E$ is set to γ , the first-period energy tax must be set at a higher level; this is necessary in order to induce an optimal postponement of fossil-fuel consumption. Part of this is captured by the first term on the RHS of (2.12) (which is greater than γ , as $\varphi > 0$). The second term on the right-hand side is only relevant when social and private discount factors differ. The term is positive when $\beta^* > \beta$ ($\frac{\nu}{E_2} > \gamma$, by assumption), which can be interpreted as follows: When the planner is more patient than private agents, the tax differential between periods 1 and 2 must be even greater in order to induce an optimal postponement of fossil-fuel depletion. Note that this second term is directly proportional to the difference in discount factors, $(\beta^* - \beta)$.

¹¹If this latter condition were not met, the marginal units of energy used would incur taxes that exceed their product, in which case firms and consumers would be better off leaving some of the oil in the ground—which is not optimal, by assumption.

2.3 An Infinite-Horizon Model

Let us turn to a full infinite-horizon model as in Golosov et al. Most properties of the infinite-horizon model are directly analogous to the two-period model. The main difference is the carbon cycle, which is based on Archer (2005). This study shows that large proportions of greenhouse gas (GHG) emissions will remain in the atmosphere indefinitely, a fact that is not captured by the carbon-cycle formulations in existing climate-economy models, such as DICE. This turns out to matter a great deal for how society should value the dynamic externality due to GHG emissions.

Here, it is assumed that a proportion φ_L of emissions remains in the atmosphere forever. Out of the proportion $(1 - \varphi_L)$ that does not remain forever, $(1 - \varphi_0)$ disappears from the atmosphere immediately (within a decade). The remaining proportion, $\varphi_0(1 - \varphi_L)$, disappears slowly from the atmosphere, at the rate φ per decade. This carbon cycle setup is summarized in equation (2.14) below. R_0 denotes the initial stock of fossil fuels, and the natural-resource constraint is then that the sum of all energy consumption equals this resource stock R_0 , as given by equation (2.15).

The setup here differs somewhat from that of the original paper, the most important difference being the separation between the planner's and the consumers' discount factors. In addition, Golosov et al. consider uncertainty about the damage parameter γ ; I abstract from that here. Finally, the original paper considers two types of fossil fuel, oil and coal, with substantially different extraction technologies. I abstract from the coal type in their paper, and treat all fossil fuel as if it were oil (i.e., all the available fossil-fuel resource stock can be extracted at zero cost).

2.3.1 Infinite-horizon: Planner's problem

The planner's optimization problem is

$$\max_{C_t, K_{t+1}, S_t, E_t} \sum_{t=0}^{\infty} \beta^{*t} \ln(C_t),$$

subject to physical and natural resource constraints, and the dynamics of the carbon cycle:

$$C_t = e^{-\gamma S_t} A_t K_t^\alpha N_t^{1-\alpha-\nu} E_t^\nu - K_{t+1}, \quad (2.13)$$

$$S_t = \sum_{s=0}^t (\varphi_L + (1 - \varphi_L) \varphi_0 (1 - \varphi)^s) E_{t-s}, \quad \text{and} \quad (2.14)$$

$$\sum_{t=0}^{\infty} E_t = R_0. \quad (2.15)$$

The first-order conditions from this optimization problem are similar to the ones found in the two-period model. Combining the FOCs for C_t and K_{t+1} gives us the Euler equation

$$\frac{C_{t+1}}{C_t} = \alpha \beta^* \frac{Y_{t+1}}{K_{t+1}}. \quad (2.16)$$

As expected, given the assumption of full depreciation, this gives a constant savings rate $\alpha \beta^*$. In other words,

$$C_t = (1 - \alpha \beta^*) Y_t \quad \text{and} \quad K_{t+1} = \alpha \beta^* Y_t \quad (2.17)$$

satisfy the Euler equation. The FOC for S_t can be simplified to give

$$\psi_t = \gamma \frac{1}{1 - \alpha \beta^*},$$

Where ψ_t is the multiplier on the carbon-cycle constraint (2.14) in period t (this result stems from the assumption of a constant γ , i.e., a marginal externality damage due to GHG emissions that is independent of S_t). Combine this with the FOC for E_t to find

$$\begin{aligned} \beta^{*t} \left(\frac{Y_t}{C_t} \frac{\nu}{E_t} - \gamma \frac{1}{1 - \alpha\beta^*} \left[\frac{\varphi_L}{1 - \beta^*} + \frac{(1 - \varphi_L)\varphi_0}{1 - \beta^*(1 - \varphi)} \right] \right) - \mu = 0 \\ \Rightarrow \beta^{*t} \left(\frac{\nu}{E_t} - \Gamma(\beta^*) \right) - \mu(1 - \alpha\beta^*) = 0, \end{aligned} \quad (2.18)$$

where μ is the (time-invariant) multiplier on the natural-resource constraint (2.15), and $\Gamma(\beta^*)$ is defined as

$$\Gamma(\beta^*) \equiv \gamma \left[\frac{\varphi_L}{1 - \beta^*} + \frac{(1 - \varphi_L)\varphi_0}{1 - \beta^*(1 - \varphi)} \right],$$

for notational convenience. $\Gamma(\beta^*)$ is expressed as a function of the social discount rate β^* to emphasize that society's valuation of the dynamic climate externality due to GHG emissions necessarily depends on the rate at which the future is discounted. $\Gamma(\beta^*)$ measures the externality damage associated with a unit of carbon emitted into the atmosphere, incorporating the immediate externality γ as well as the discounted stream of damages incurred throughout the infinite future. Using (2.18) in periods t and $t + 1$ to eliminate the term in μ , we arrive at

$$\frac{\nu}{E_t^*} - \Gamma(\beta^*) = \beta^* \left[\frac{\nu}{E_{t+1}^*} - \Gamma(\beta^*) \right]. \quad (2.19)$$

As in the two-period model, E_t^* is used to denote optimal energy consumption. Together with the physical resource constraint (2.15), (2.19) defines the optimal path for fossil fuel consumption, $\{E_t^*\}_t$. As in the two-period model, optimal depletion of the exhaustible

fossil-fuel resource only depends on β^* , γ and the parameters of the carbon cycle. The market discount factor, β , does not play any role.

2.3.2 Infinite-horizon: Decentralized equilibrium Consumers

Consumers optimize using a discount factor β , according to

$$\max_{C_t, K_{t+1}, E_t} \sum_{t=0}^{\infty} \beta^t \ln(C_t)$$

subject to physical and natural resource constraints:

$$C_t = r_t(1 - \tau_t^K)K_t + w_t N_t + (p_t - \tau_t^E)E_t + T_t - K_{t+1}, \quad \text{and} \tag{2.20}$$

$$\sum_{t=0}^{\infty} E_t = R_0. \tag{2.21}$$

Once more, it is assumed that the government budget is balanced in each time period,

$$\tau_t^E E_t + \tau_t^K r_t K_t = T_t,$$

which means that disposable income equals total output in each time period. Combining the first-order conditions with respect to C_t and K_{t+1} gives the Euler equation

$$\frac{C_{t+1}}{C_t} = \beta r_{t+1}(1 - \tau_{t+1}^K). \tag{2.22}$$

To arrive at the Hotelling equation, note that the FOC for E_t in the consumer's problem can be written as

$$\beta^t \theta_t (p_t - \tau_t^E) - \xi = 0, \quad (2.23)$$

where θ_t is the multiplier on the physical-resource constraint (2.20) at t , and ξ is the multiplier on the natural-resource constraint (2.21). Combine (2.23) in periods t and $t + 1$ to eliminate ξ :

$$\begin{aligned} \beta^t \theta_t (p_t - \tau_t^E) &= \beta^{t+1} \theta_{t+1} (p_{t+1} - \tau_{t+1}^E) \\ \Rightarrow r_{t+1} (1 - \tau_{t+1}^K) &= \frac{(p_{t+1} - \tau_{t+1}^E)}{(p_t - \tau_t^E)}. \end{aligned} \quad (2.24)$$

This Hotelling equation is directly analogous to the two-period version in (2.9).

Firms

The firms' optimization problem in the infinite-horizon case is identical to the two-period setting. The firms' objective function is

$$\max_{K_t, N_t, E_t} D_t A_t K_t^\alpha N_t^{1-\alpha-\nu} E_t^\nu - r_t K_t - w_t N_t - p_t E_t, \quad (2.25)$$

and the first-order conditions are $r_t = \alpha \frac{Y_t}{K_t}$, $w_t = (1 - \alpha - \nu) \frac{Y_t}{N_t}$, and $p_t = \nu \frac{Y_t}{E_t}$, as previously.

2.3.3 Infinite-horizon: Implementing the optimal allocation

The Euler equation in (2.22), together with the firm's FOC for K_t and the budget constraints, leads to consumption and savings

functions

$$C_t = (1 - \alpha\beta(1 - \tau_2^K))Y_t \quad \text{and} \quad K_{t+1} = \alpha\beta(1 - \tau_2^K)Y_t.$$

Once more, assume there to be a set of taxes $\{\tau_{t+1}^K, \tau_t^E\}_t$ that implements the optimal allocation. Both (2.16) and (2.22) must then hold, with identical values for consumption, output and capital, which means that

$$\alpha\beta^* \frac{Y_{t+1}}{K_{t+1}} = \alpha\beta(1 - \tau_{t+1}^K) \frac{Y_{t+1}}{K_{t+1}}$$

must hold. In other words,

$$\begin{aligned} \beta^* &= \beta(1 - \tau_{t+1}^K) \\ \Rightarrow (1 - \tau_{t+1}^K) &= \frac{\beta^*}{\beta} \Leftrightarrow \tau_{t+1}^K = -\frac{(\beta^* - \beta)}{\beta}, \end{aligned}$$

i.e., a constant capital tax implements the optimal savings rate (indeed, the same tax as in the two-period case). In the case where the planner is more patient than private agents, the capital tax is negative, i.e., a subsidy to capital returns is required to induce high enough savings.

Now we can rewrite the Hotelling equation in (2.24), using the expressions for r_{t+1} and p_t from the firm's first-order conditions, together with the result that $(1 - \tau_{t+1}^K) = \frac{\beta^*}{\beta}$ must hold, as

$$\alpha \frac{Y_{t+1}}{K_{t+1}} \left(\frac{\beta^*}{\beta} \right) = \frac{\left(\frac{\nu}{E_{t+1}} Y_{t+1} - \tau_{t+1}^E \right)}{\left(\frac{\nu}{E_t} Y_t - \tau_t^E \right)}.$$

Divide through by $\frac{Y_{t+1}}{Y_t}$, and again define $\hat{\tau}_t \equiv \frac{\tau_t}{Y_t}$. Using this and

the savings function for K_{t+1} , we arrive at

$$\alpha \frac{Y_t}{\alpha \beta^* Y_t} \left(\frac{\beta^*}{\beta} \right) = \frac{1}{\beta} = \frac{\left(\frac{\nu}{E_{t+1}} - \hat{\tau}_{t+1}^E \right)}{\left(\frac{\nu}{E_t} - \hat{\tau}_t^E \right)} \quad (2.26)$$

$$\Rightarrow \left(\frac{\nu}{E_t} - \hat{\tau}_t^E \right) = \beta \left(\frac{\nu}{E_{t+1}} - \hat{\tau}_{t+1}^E \right). \quad (2.27)$$

The condition in (2.27) defines how the market will choose to consume energy over time, given a sequence of energy taxes $\{\hat{\tau}_t^E\}_t$, whereas (2.19) defines the optimal sequence for energy consumption, given parameter values ν, β^* , and the various carbon cycle parameters. If social and market discount factors coincide ($\beta^* = \beta$), one set of taxes that implements the optimal allocation is to simply set energy taxes equal to $\Gamma(\beta^*)$ in each time period. This is the central insight in Golosov et al.—optimal taxes on fossil fuel can be set to a constant proportion of output.¹² However, with different discount factors, this elegant solution is no longer available. To explore the general case, consider the difference equation in (2.28) below. This equation gives a relationship between $\hat{\tau}_t^E$ and $\hat{\tau}_{t+1}^E$, for any set of energy taxes $\{\hat{\tau}_t^E\}_t$ that implements the optimal allocation (the derivation of this equation is given in Appendix A2.1 below)

$$\hat{\tau}_{t+1}^E = \frac{1}{\beta} \hat{\tau}_t^E - \frac{(\beta^* - \beta)}{\beta^* \beta} \frac{\nu}{E_t^*} - \frac{(1 - \beta^*)}{\beta^*} \Gamma(\beta^*). \quad (2.28)$$

Let us first consider the case when $\beta^* = \beta$. The difference equation

¹²At this point, the usefulness of considering carbon taxes as a proportion of output, $\hat{\tau}_t^E$, becomes evident.

in (2.28) then reduces to

$$\hat{\tau}_{t+1}^E = \frac{1}{\beta} \hat{\tau}_t^E - \frac{(1-\beta)}{\beta} \Gamma(\beta^*),$$

which is straightforward to interpret. First, note that there is a stationary point at $\Gamma(\beta^*)$, i.e., $\hat{\tau}_t^E = \Gamma(\beta^*) \ \forall t$ is a solution. Moreover, this is an unstable equilibrium: for an initial $\hat{\tau}_0^E$ that exceeds $\Gamma(\beta^*)$, $\hat{\tau}_t^E$ must increase indefinitely. For a $\hat{\tau}_0^E$ that is lower than $\Gamma(\beta^*)$, the opposite holds, i.e., taxes decrease and eventually turn into subsidies. The highest possible initial-period tax that would implement the optimal sequence for fossil-fuel consumption is $\hat{\tau}_0^E = \frac{\nu}{E_0^*}$, which constitutes a full appropriation of all surplus due to energy (see Appendix A2.2 below).

When social and market discount factors differ, we must consider the more general difference equation in (2.28). The presence of a term involving E_t^* indicates that it is not possible to find a constant value for $\hat{\tau}_t^E$ that solves the equation. By contrast, the only tax sequences that will implement the optimal allocation are either a complete expropriation of fossil-fuel reserves, or a sequence of taxes that may increase initially, but will eventually have to start decreasing and finally turn into a subsidy. To see this, first note that the full-expropriation tax schedule is still available, as shown in Appendix A2.2. This is indeed a sequence of ever increasing taxes $\hat{\tau}_t^E$, starting out in period 0 with $\hat{\tau}_0^E = \frac{\nu}{E_0^*}$. Starting above this level is not feasible, in the sense that such a tax sequence will not implement the optimal allocation. Finally, a tax schedule that starts out at less than full expropriation, $\hat{\tau}_0^E < \frac{\nu}{E_0^*}$, is feasible if it obeys (2.28). Appendix A2.3 shows that any such tax sequence is such that $\hat{\tau}_t^E$ must eventually turn negative, i.e., taxes must turn into subsidies over time.

2.4 A Calibrated Example

This section presents results from a calibrated version of the model discussed in Section 2.3. Most parameter values are taken from Golosov et al. The factor shares are set to $\alpha = 0.3$ and $\nu = 0.03$. The carbon-cycle parameters are chosen such that 20% of CO₂ emissions remain in the atmosphere forever ($\varphi_L = 0.2$), half of the remaining 80% has decayed after 300 years ($\varphi = 0.0228$), and half of the total emissions has decayed after 20 years ($\varphi_0 = 0.393$). The damage parameter, which is calibrated using the damage function from DICE, is set to $\gamma = 2.379 \times 10^{-5}$ (see Golosov et al. for details). The initial capital stock K_0 is arbitrarily set to a fraction $\alpha\beta$ of first-period output, and the initial TFP level A_0 is chosen to match global output in 2010, 63 trillion 2010 US dollars (World Bank). A TFP growth of 0.5% per year is assumed. This does not matter for the optimal sequence of taxes per unit of output, $\hat{\tau}_t^E$, but productivity growth of course leads to output growth and hence plays a role for τ_t^E , i.e., taxes measured as dollars per tonne of carbon. Finally, a fossil-fuel supply $R_0 = 400$ GtC is used. This corresponds to the available reserves of oil assumed in Golosov et al.

Two discount factors, a higher β^* and a lower β , are defined. In most of what follows, the social planner is assumed to discount the future using a pure rate of time preference of 0.1% per year, based on Stern (2006). Refer to this time-preference rate as $\rho^* = 0.001$, and then define the corresponding discount factor

$$\beta^* = \left(\frac{1}{1 + \rho^*} \right)^{10}.$$

Note that β^* refers to the discount factor in a setting where the

time step is ten years. The higher time-preference rate, ρ , is chosen to be 1.5% per year ($\rho = 0.015$), based on Nordhaus (2008), and the discount factor β is defined in a manner analogous to β^* .

2.4.1 Optimal energy taxes

First, let us consider the standard case, where the planner discounts the future at the same rate as consumers. Optimal and laissez-faire fossil-fuel consumption is illustrated in Figure 2.1 below. Panel A illustrates the case when both the planner and consumers use a discount factor β , and in Panel B both use a discount factor β^* . In both panels, optimal climate policy is used in order to postpone the consumption of fossil fuel from the laissez-faire sequence (represented by the dashed line) to the optimal sequence (given by the solid line). In Panel B, the high β^* used by the social planner implies a fossil-fuel depletion schedule that is much flatter than that in Panel A. However, this optimal schedule is not too far from the laissez-faire schedule in Panel B, given the assumption that consumers discount also using β^* .

Consider now a situation where consumers discount using β , but the planner discounts using β^* . Optimal climate policy then amounts to shifting the extraction path for fossil fuel from the dashed line in Panel A to the solid line in Panel B. This is a graphical illustration of the need for a substantially more pronounced tax differential between time periods, in order to induce the optimal postponement of fossil-fuel depletion.

Figure 2.2 is an attempt at comparing optimal energy taxes in the standard model, where the planner as well as consumers discount in the same way, with the extended model presented here, where consumers discount using β and the planner uses β^* . Panel A

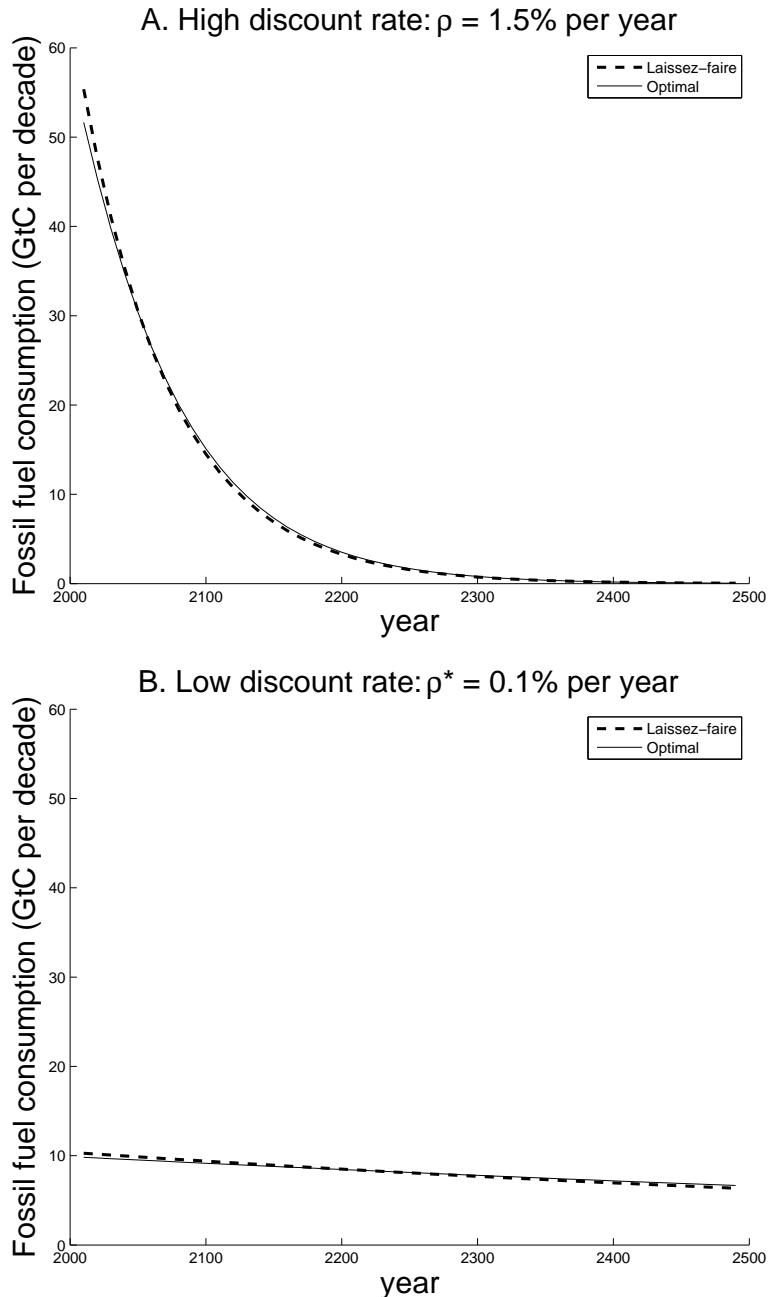


Figure 2.1: Fossil-fuel consumption

plots energy taxes as a proportion of output, $\hat{\tau}_t^E$, over time, whereas Panel B plots taxes measured as dollars per tonne of carbon, τ_t^E , for three model setups. For the standard model, the constant- $\hat{\tau}_t^E$ solution is shown, for the case when both the planner and the markets discount the future heavily (shown by the grey line), and for the situation where both the planner and the markets are more patient (the black line). The dashed line shows a tax schedule that implements the optimal allocation (together with an interest rate subsidy, as discussed above), when the planner is more patient than the market. This tax schedule is one of an infinite number of tax schedules that will implement the optimal allocation, and it is chosen such that the discounted stream of tax revenue from energy taxes is the same as in the case when both the planner and the market use $\rho^* = 0.1\%$ per year (the black solid line).

With different social and market discount rates, carbon taxes rise initially, but must eventually turn into substantial subsidies.

2.4.2 Welfare considerations

Let us now turn to the welfare effects of climate policy, first looking at the standard model, where both the planner and the market discount by β^* . In the standard model, the optimal allocation can be implemented using only one tax instrument, the sequence $\{\hat{\tau}_t^E\}_t$. The relevant welfare comparison in this setting is between the optimal allocation, or first best, and the laissez-faire solution. For each consumption stream $\{C_t\}_t$, define a constant consumption level \bar{C} , such that

$$\sum_{t=0}^{\infty} \beta^{*t} \ln(\bar{C}) = \sum_{t=0}^{\infty} \beta^{*t} \ln(C_t).$$

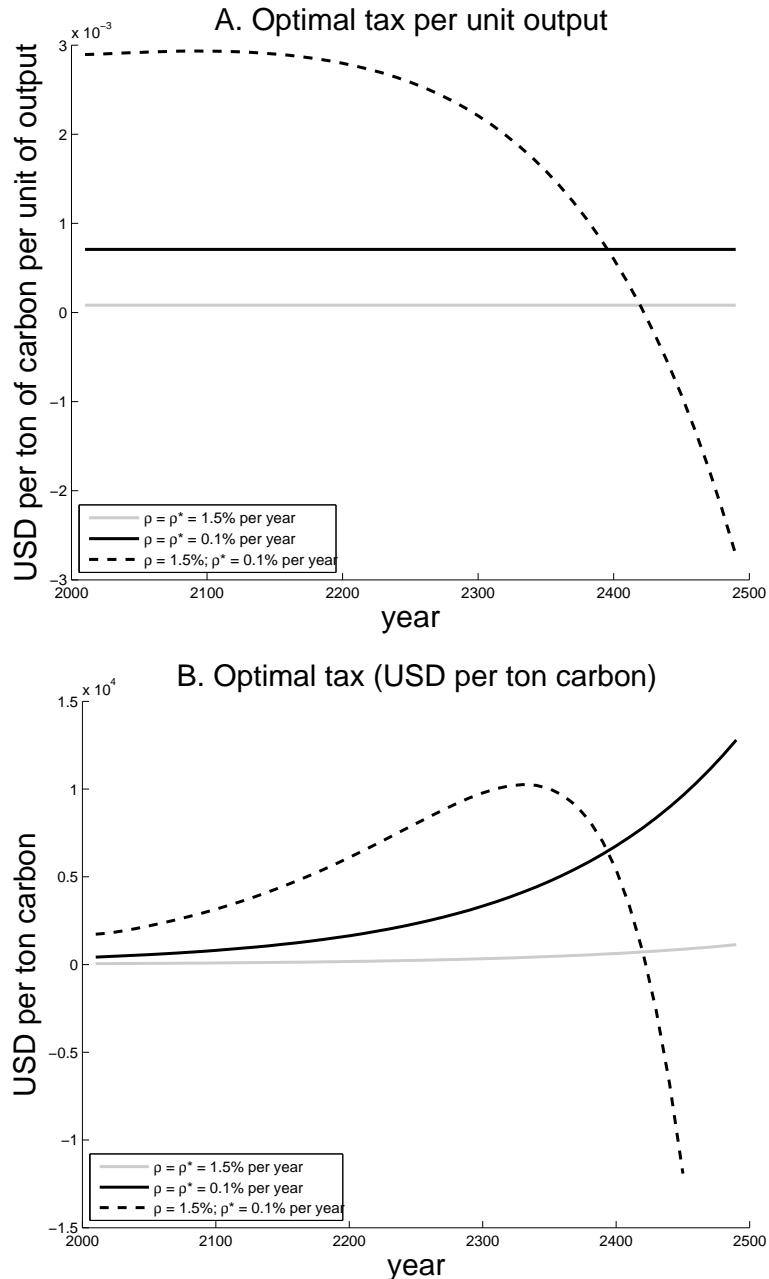


Figure 2.2: Optimal energy taxes

The difference in \bar{C} between the laissez-faire outcome and the first-best outcome is a mere 0.0013%. This corresponds to the first row in Table 2.1 below, which summarizes the welfare comparisons discussed in this section. With a discount rate of 1.5% per year, common to both planner and market, the welfare loss in the laissez-faire outcome is even more negligible (second row in Table 2.1). In the extended model however, with the planner discounting with β^* and the market with β , the welfare loss in terms of \bar{C} is now a substantial 6.10% (row 3 in the table).

In the extended model, two types of tax are needed in order to implement the first-best allocation. One could therefore imagine more outcomes than only the first-best and the laissez-faire solutions. For example, although a globally implemented tax on fossil-fuel consumption seems far-fetched politically, it may well be easier to implement a global energy tax only, compared to a global energy tax *and* a global subsidy to capital returns. Therefore, it is interesting to consider a second-best policy of optimal energy taxes without the capital subsidy (row 4 in Table 2.1).¹³ Such a policy would amount to a drop in \bar{C} of 0.40% only, around 7% of the consumption drop in the laissez-faire solution.

We can consider two more thought experiments. First, suppose that a planner uses a discount factor β^* , and thinks that this is also the case for the market, while consumers actually discount using β .

¹³Note that optimal energy taxes $\{\hat{\tau}_t^E\}_t$ are the same, even if the capital subsidy is not available. To see this, notice that the optimal sequence for fossil-fuel consumption, defined by (2.19), only depends on parameters ν, β^* , and the carbon-cycle parameters. Therefore, optimal fossil-fuel consumption, $\{E_t^*\}_t$, is unchanged. Moreover, the market's choice of fossil-fuel consumption, in the presence of taxes, is still defined by (2.27), which is also independent of capital stocks and output levels. Hence, any sequence of energy taxes that implements the first-best allocation will still implement the optimal sequence for fossil-fuel consumption if capital subsidies are not available.

The planner would then choose a tax sequence $\hat{\tau}_t^E = \Gamma(\beta^*) \forall t$, hoping to implement the optimal depletion of fossil fuels. However, the sequence for fossil-fuel consumption actually implemented with this tax policy would not be the optimal one, defined by (2.19). Instead, it will be the sequence that satisfies (2.27), given the chosen tax policy $\hat{\tau}_t^E = \Gamma(\beta^*) \forall t$. This energy consumption profile lies in between the laissez-faire outcome (the dashed curve in Figure 2.1A) and the optimal outcome (the solid curve in Figure 2.1B). The welfare loss in such a scenario would amount to 3.29%, as measured by a drop in \bar{C} (row 5 in Table 2.1). This situation could be thought of as ‘Stern’s mistake’: the planner sets energy taxes based on her rate of time preference, but ignores the fact that consumers discount the future at a different rate. Climate damages are valued correctly over time, but energy taxes do not induce consumers to leave behind enough of the fossil-fuel stocks to future generations.

Finally, consider what may be referred to as ‘Nordhaus’s mistake’. The planner still discounts the future at a low rate, 0.1% per year, but is persuaded by the argument that carbon taxes should be set with a market discount rate in mind. Such a planner would implement a lower constant tax per unit of output $\hat{\tau}_t^E = \Gamma(\beta)$. According to row 6 in the table, such a policy leads to a welfare loss that is near the laissez-faire outcome in row 3, when the resulting consumption streams are valued using the planner’s true discount rate of 0.1% per year.

2.5 Conclusions

It has been argued, most famously in the Stern Review (Stern, 2006), that climate policy should be designed with a high weight on future generations, higher indeed than the weight individuals

Table 2.1: Welfare comparisons

| | Consumers' discount rate | Planner's discount rate | Policy instruments | Welfare loss |
|---|-----------------------------|----------------------------|--|-------------------------|
| 1 | 0.1% | 0.1% | none | 0.0013% |
| 2 | 1.5% | 1.5% | none | $6.71 \times 10^{-6}\%$ |
| 3 | 1.5% | 0.1% | none | 6.10% |
| 4 | 1.5% | 0.1% | optimal $\{\hat{\tau}_t^E\}_t$ | 0.40% |
| 5 | 1.5% | 0.1% | $\hat{\tau}_t^E = \Gamma(\beta^*) \forall t$ | 3.29% |
| 6 | 1.5% | 1.5% | $\hat{\tau}_t^E = \Gamma(\beta) \forall t$ | 5.88% |

currently alive seem to place on their own future selves. This may well be a very reasonable approach to the issue of climate-change externalities, but policy-makers must consider the fact that individual consumers still behave according to their own preferences, which involves discounting the future (including their own future selves) more heavily. This has some implications for optimal taxation of fossil-fuel consumption.

A policy-maker that cares for future generations must therefore not only pay attention to impacts due to climate change arising in the future, but should also induce generations currently alive to save more for the future, and leave more of the available stock of fossil fuels in the ground for future generations to enjoy. Such considerations lie behind the main result in this paper: optimal carbon taxes must in general decrease over time, and finally become subsidies, in order to induce a consumption path for fossil fuels that is optimal from the social planner's perspective.

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A2 Appendix

A2.1 Difference equation for optimal energy taxes

Optimal depletion of fossil fuels is given by (2.19), as

$$\left[\frac{\nu}{E_t^*} - \Gamma(\beta^*) \right] = \beta^* \left[\frac{\nu}{E_{t+1}^*} - \Gamma(\beta^*) \right].$$

Rearrange this to find $\frac{\nu}{E_{t+1}^*}$ as a function of $\frac{\nu}{E_t^*}$,

$$\frac{\nu}{E_{t+1}^*} = \frac{1}{\beta^*} \frac{\nu}{E_t^*} - \left(\frac{1 - \beta^*}{\beta^*} \right) \Gamma(\beta^*). \quad (2.29)$$

Now use (2.27), which defines how the market will consume energy in the presence of taxes, substituting out $\frac{\nu}{E_{t+1}^*}$ using (2.29):

$$\begin{aligned} \left(\frac{\nu}{E_t^*} - \hat{\tau}_t^E \right) &= \beta \left(\frac{\nu}{E_{t+1}^*} - \hat{\tau}_{t+1}^E \right) \\ \Rightarrow \beta \hat{\tau}_{t+1}^E &= \hat{\tau}_t^E + \frac{\beta}{\beta^*} \frac{\nu}{E_t^*} - \frac{\nu}{E_t^*} - \frac{\beta(1 - \beta^*)}{\beta^*} \Gamma(\beta^*) \\ \Rightarrow \hat{\tau}_{t+1}^E &= \frac{1}{\beta} \hat{\tau}_t^E - \frac{(\beta^* - \beta)}{\beta^* \beta} \frac{\nu}{E_t^*} - \frac{(1 - \beta^*)}{\beta^*} \Gamma(\beta^*) \end{aligned}$$

A2.2 Full expropriation of fossil-fuel reserves

The marginal net private benefit to using energy in production in period t is given by $(\frac{\nu Y_t}{E_t} - \tau_t^E)$. This expression will never be negative—if it were, energy use would fall, pushing up the marginal product until it reaches the level of the tax. Any sequence of taxes that implements the optimal allocation $\{E_t^*\}_t$ must therefore be such that

$$\tau_t^E \leq \frac{\nu Y_t}{E_t} \Leftrightarrow \hat{\tau}_t^E \leq \frac{\nu}{E_t}.$$

Setting $\hat{\tau}_t^E = \frac{\nu}{E_t}$ in each period taxes away all profits in the energy market. To see that this set of taxes is a solution to (2.28), consider a period- t tax $\hat{\tau}_t^E - \frac{\nu}{E_t^*}$. By (2.28), next period's tax is then

$$\begin{aligned}\hat{\tau}_{t+1}^E &= \frac{1}{\beta} \frac{\nu}{E_t^*} - \frac{(\beta^* - \beta)}{\beta^* \beta} \frac{\nu}{E_t^*} - \frac{(1 - \beta^*)}{\beta^*} \Gamma(\beta^*) \\ &= \frac{1}{\beta^*} \frac{\nu}{E_t^*} - \frac{(1 - \beta^*)}{\beta^*} \Gamma(\beta^*).\end{aligned}$$

From (2.19), we see that $\frac{\nu}{E_t^*} = \beta^* \frac{\nu}{E_{t+1}^*} + (1 - \beta^*) \Gamma(\beta^*)$. Hence,

$$\begin{aligned}\hat{\tau}_{t+1}^E &= \frac{1}{\beta^*} \left(\beta^* \frac{\nu}{E_{t+1}^*} + (1 - \beta^*) \Gamma(\beta^*) \right) - \frac{(1 - \beta^*)}{\beta^*} \Gamma(\beta^*) \\ &= \frac{\nu}{E_{t+1}^*}.\end{aligned}$$

In other words, setting $\hat{\tau}_t^E = \frac{\nu}{E_t^*}$ for all t implements the optimal consumption path for fossil fuels, and taxes away all the surplus. Indeed, this may be considered an expropriation of all existing fossil fuel reserves.

A2.3 Energy taxes must turn into subsidies

Suppose we start out with a first-period tax $\hat{\tau}_0^E = \frac{\nu}{E_0^*} - \varepsilon$, and let future tax levels be defined by (2.28), so as to implement the optimal sequence for energy consumption, $\{E_t^*\}_t$. Energy taxes will then eventually have to turn into subsidies, for any $\varepsilon > 0$. To see this, start with $\hat{\tau}_0^E$ and iterate forward using (2.28), making use of (2.29) when necessary:

$$\begin{aligned}\hat{\tau}_0^E &= \frac{\nu}{E_0^*} - \varepsilon \\ \Rightarrow \hat{\tau}_1^E &= \frac{1}{\beta} \left(\frac{\nu}{E_0^*} - \varepsilon \right) - \frac{\beta^* - \beta}{\beta^* \beta} \frac{\nu}{E_0^*} - \frac{1 - \beta^*}{\beta^*} \Gamma(\beta^*) \\ &= \frac{1}{\beta^*} \frac{\nu}{E_0^*} - \frac{1 - \beta^*}{\beta^*} \Gamma(\beta^*) - \frac{1}{\beta} \varepsilon \\ \Rightarrow \hat{\tau}_2^E &= \frac{1}{\beta} \left(\frac{1}{\beta^*} \frac{\nu}{E_0^*} - \frac{1 - \beta^*}{\beta^*} \Gamma(\beta^*) - \frac{1}{\beta} \varepsilon \right) \\ &\quad - \frac{\beta^* - \beta}{\beta^* \beta} \left(\frac{1}{\beta^*} \frac{\nu}{E_0^*} - \frac{1 - \beta^*}{\beta^*} \Gamma(\beta^*) \right) - \frac{1 - \beta^*}{\beta^*} \Gamma(\beta^*) \\ &= \left(\frac{1}{\beta^*} \right)^2 \frac{\nu}{E_0^*} - \left(\frac{1 - \beta^*}{\beta^*} \right)^2 \Gamma(\beta^*) - \left(\frac{1}{\beta} \right)^2 \varepsilon \\ \Rightarrow \hat{\tau}_t^E &= \left(\frac{1}{\beta^*} \right)^t \frac{\nu}{E_0^*} - \left(\frac{1 - \beta^*}{\beta^*} \right)^t \Gamma(\beta^*) - \left(\frac{1}{\beta} \right)^t \varepsilon\end{aligned}$$

The middle term in the above expression converges to 0 as t grows, whereas the other terms grow exponentially. When $\beta^* > \beta$, the latter term grows faster than the first term. Hence, for any $\varepsilon > 0$, $\hat{\tau}_t^E$ must eventually turn negative. In other words, for any set of taxes $\{\hat{\tau}_t^E\}_t$ that implements the optimal allocation, and that does not constitute a full expropriation of fossil fuel reserves, energy taxes must eventually turn into a subsidy.

Chapter 3

Temperature Feedbacks to the Carbon Cycle in Climate–Economy Models*

3.1 Introduction

The carbon cycle plays an important role for climate change. Since the industrial revolution, burning of fossil fuels and deforestation has caused substantial emissions of carbon dioxide (CO_2 ; the most important greenhouse gas) into the atmosphere. But less than 50%

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of the emitted amounts remain today—the remainder has been taken up by oceans and by the biosphere, i.e., vegetation and soils (Denman et al., 2007; Figure 7.3. provides a schematic overview of stocks and flows of carbon in the global carbon cycle.).

Future increases in atmospheric temperature will depend on how much of future CO₂ emissions stay in the atmosphere. Oceans and forests will likely absorb a large proportion of additions to the atmospheric carbon stock, but great uncertainty remains about how large this proportion will be (e.g., Friedlingstein et al., 2006). One reason for this are the feedbacks from climate change to the carbon cycle: the ability of the Earth system to absorb additional CO₂ will be negatively affected by changes in the climate, in particular by rising temperatures. This is because important processes governing the exchange of carbon between the atmosphere and the biosphere are affected by temperature changes. On the one hand, higher temperatures are not conducive to biomass production (photosynthesis), at a global level. Wherever water is in short supply, plants are less prone to growing as temperatures rise.¹ Another temperature effect is that respiration, i.e., the process whereby decomposing plant matter on the ground and in soils is broken down, is sped up with higher temperatures. This causes a faster release of CO₂ back into the atmosphere than with a colder climate.

Uncertainty about the future path of atmospheric CO₂ concentrations is substantial, for a number of reasons. Socio-economic processes give rise to burning of fossil fuels and deforestation, which causes emissions of CO₂ into the atmosphere. The magnitude of

¹It should be noted that rising global temperatures will also lead to extended growing seasons in cooler parts of the world, which boosts biomass production and hence carbon uptake by the biosphere. However, it seems that the global net effect of rising temperatures is negative, i.e., in a warmer world, the biosphere will take up less carbon, all other things equal.

these emissions depends on the availability of alternative (non-fossil-fuel) technologies, economic development, climate policy, and a number of other factors. Uncertainty about the natural system accounts for the uncertainty about how much CO₂ will stay in the atmosphere, for a given sequence of emissions. This uncertainty can, in turn, be attributed to two sources. On the one hand, uncertainty about climate sensitivity (how much global temperatures will increase for a doubling of atmospheric CO₂) captures the uncertainty about the temperature feedbacks discussed above. On the other hand, our understanding of the carbon cycle itself is still limited: even if future CO₂ emissions as well as the climate sensitivity were known, carbon uptake by the biosphere and the oceans would still be uncertain. Huntingford et al. (2009) suggest that both sources of uncertainty are important.

In this paper, we focus on the temperature feedbacks to the terrestrial carbon cycle (flows of carbon between the atmosphere and land vegetation), and how they interact with uncertainty about climate sensitivity. Other potential temperature feedbacks to the carbon cycle are not considered here. For example, it seems likely that oceans too will absorb less carbon as they warm up (Archer, 2005). There is also some concern that Methane (CH₄, another greenhouse gas), currently trapped under permanently frozen ground in the northern hemisphere, may be released as the climate warms and the permafrost starts thawing (Tarnocai et al., 2009).

The paper is organized as follows. The next section discusses how the carbon cycle is modelled in existing climate–economy models. In Section 3 we describe Bio–DICE, our extension of DICE, a well-known climate–economy model, to include temperature feedbacks to the carbon cycle. Section 4 presents results from running Bio–DICE, including some sensitivity analysis over important

model parameters. Finally, Section 5 concludes.

3.2 The carbon cycle in climate–economy models

Climate–economy models² are models of the global economic system and the climate, designed for comparing the costs and benefits of burning fossil fuels. This cost-benefit analysis can then be used to draw conclusions about how much of available fossil fuels should be used up, in order to maximize the welfare of humanity, taking into account the interests of people alive today as well as all future generations, on a global scale. Such models represent the economic system and the climate system, along with the interactions between the two, in a stylized fashion: economic activity involves burning of fossil fuels, which causes emissions of CO₂ into the atmosphere. The carbon cycle determines how much CO₂ remains in the atmosphere, which in turn raises temperatures. Higher temperatures affect human societies negatively, through various channels. Climate–economy models are often used to draw conclusions about what would be the optimal tax on emissions of CO₂, assuming that we could implement such a tax globally.

We make use of DICE–2007 (a Dynamic Integrated model of Climate and the Economy; Nordhaus, 2008), one of the most well-known climate–economy models. The carbon cycle in DICE is not temperature dependent, i.e., temperatures realized within the model do not affect the ability of the carbon sinks (the oceans and the biosphere) to absorb carbon. The system of difference equations in (3.1) represents the carbon cycle in DICE. Carbon flows between

²Sometimes referred to as Integrated Assessment Models.

three reservoirs, or boxes: the atmosphere (A), the upper layer of the oceans together with the terrestrial biosphere (C), and the deep oceans (D). Emissions of CO_2 , which originate in economic activity, are represented by E . Emissions appear in the atmosphere, and over time excess carbon is transported first into the upper oceans, and then slowly into the deep oceans. The constant parameters ϕ_{ij} , $i, j \in \{A, C, D\}$ determine what proportion of carbon in box i is transported to box j in each time period (time is indexed by t , and each time period corresponds to a decade).

$$\begin{bmatrix} A_{t+1} \\ C_{t+1} \\ D_{t+1} \end{bmatrix} = \begin{bmatrix} \phi_{AA} & \phi_{CA} & 0 \\ \phi_{AC} & \phi_{CC} & \phi_{DC} \\ 0 & \phi_{CD} & \phi_{DD} \end{bmatrix} \begin{bmatrix} A_t \\ C_t \\ D_t \end{bmatrix} + \begin{bmatrix} E_t \\ 0 \\ 0 \end{bmatrix} \quad (3.1)$$

The carbon cycle plays an important role in determining the size of the dynamic climate externality due to fossil-fuel consumption. A carbon cycle that leaves more CO_2 in the atmosphere for a longer time implies more long-lived climate damages. The importance of the carbon cycle for calculating optimal carbon taxes is highlighted in Golosov et al. (2011), where the parameters governing the decay structure of carbon in the atmosphere, together with a discount factor and a damage parameter, define the optimal tax level.³

³The carbon cycle used by these authors is given by

$$S_t = \sum_{s=0}^t (\varphi_L + (1 - \varphi_L)\varphi_0(1 - \varphi)^s) E_{t-s},$$

where S_t denotes atmospheric CO_2 in period t , and E_t represents emissions of CO_2 . The parameters are chosen such that φ_L represents the amount of CO_2 emissions that stays in the atmosphere forever, a proportion $(1 - \varphi_0)(1 - \varphi_L)$ disappears from the atmosphere instantaneously (within a decade), and the fraction $(1 - \varphi_L)\varphi_0$ decays slowly, at a rate φ per decade. The fact that a proportion φ_L remains in the atmosphere forever matters a great deal for the externality impact due to climate change. The authors assume that 20% of

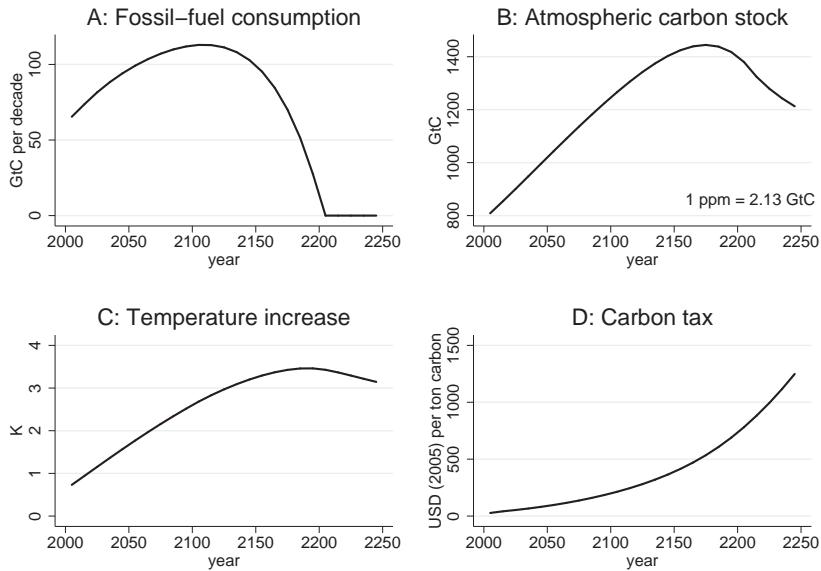


Figure 3.1: Optimal-policy output from DICE–2007

Figure 3.1 shows optimal trajectories for some key output variables in DICE. Fossil fuel consumption exhibits peak oil (Panel A), and falls to zero around the year 2200, after which only alternative energy technologies are used. Atmospheric CO₂ peaks later than emissions (Panel B), due to lags in the system, and atmospheric temperature increase peaks even later (Panel C). Optimal carbon taxes start out at around USD 27 per ton of carbon in 2005, and increase over time (Panel D).

carbon emissions will remain in the atmosphere indefinitely ($\varphi_L = 0.2$), based on Archer (2005). This leads to a dynamic externality due to an additional tonne of carbon that is nearly twice as large as if $\varphi_L = 0$ were used, with φ_0 recalibrated to reflect short-term carbon decay properties. These results show that optimal CO₂ taxes are highly sensitive to the amount of carbon that remains in the atmosphere for a long time—using a carbon cycle that allows atmospheric CO₂ to return to pre-industrial levels relatively quickly may therefore significantly underestimate optimal carbon taxes.

We extend the carbon cycle in DICE, allowing the flows of carbon between boxes to depend on temperature, as described in the next section. We present our results in terms of the DICE model, but one might expect similar results if one were to perform the same exercise with other climate–economy models. RICE, a version of DICE with multiple regions, has the same carbon cycle formulation (Nordhaus and Boyer, 2000). PAGE (Hope, 2006) and MERGE (Manne, Mendelsohn and Richels, 1995), two other well-established models, share this feature of a carbon cycle formulation which is not temperature dependent.⁴

3.3 Methodology

We augment the carbon-cycle component of DICE–2007 with an explicit biosphere, as in the equation system in (3.2). Entries in **bold** represent our additions to the baseline model. We introduce an explicit biosphere, the carbon content of which we denote by B . We keep the same structure for the flows of carbon between the atmosphere and the oceans, adjusting the parameters ϕ_{ij} such that they are consistent with box C now representing only the upper

⁴PAGE2002 does allow for some uncertainty in the strength of the carbon sinks, but does not link this to temperature or climate sensitivity.

layer of the oceans.⁵

$$\begin{bmatrix} A_{t+1} \\ \mathbf{B}_{t+1} \\ C_{t+1} \\ D_{t+1} \end{bmatrix} = \begin{bmatrix} \phi_{AA} & \mathbf{0} & \phi_{CA} & 0 \\ \mathbf{0} & 1 & \mathbf{0} & \mathbf{0} \\ \phi_{AC} & \mathbf{0} & \phi_{CC} & \phi_{DC} \\ 0 & \mathbf{0} & \phi_{CD} & \phi_{DD} \end{bmatrix} \begin{bmatrix} A_t \\ \mathbf{B}_t \\ C_t \\ D_t \end{bmatrix} + \begin{bmatrix} E_t - V(A_t, \mathbf{B}_t, T_t) + U(\mathbf{B}_t, T_t) \\ V(A_t, \mathbf{B}_t, T_t) - U(\mathbf{B}_t, T_t) \\ 0 \\ 0 \end{bmatrix} \quad (3.2)$$

Flows of carbon between atmosphere (A) and biosphere (B) are modelled not as proportions of carbon stocks, but as absolute amounts of carbon, represented by the functions $V(\cdot)$ and $U(\cdot)$. The exact flow functions are the following:

$$V(A_t, B_t, T_t) = v_0 + v_1 A_t + v_2 A_t^2 + v_3 B_t + v_4 T_t \quad (3.3)$$

$$U(B_t, T_t) = u_0 + u_1 B_t + u_2 T_t \quad (3.4)$$

Carbon uptake by the biosphere, $V(\cdot)$, depends on the amount of carbon in the atmosphere, A : a higher concentration of CO₂ facilitates carbon uptake by plants—this is the so-called CO₂ fertilization effect. The quadratic term on A allows for non-linearities in this effect. The size of the biosphere, B , also matters for carbon uptake: with a larger biosphere, more biomass can grow by taking up carbon from the atmosphere through photosynthesis. In other

⁵We calibrate the ϕ_{ij} to match the time path of atmospheric carbon, following a doubling of CO₂ from pre-industrial levels, using the pulse-response version of HILDA, the oceanic component of the Bern model (Joos et al., 1999). In particular, we choose the parameter values that minimize the sum of squared deviations from HILDA output during 200 years after CO₂ doubling, in 10-year time steps.

words, the parameter v_3 is expected to be positive. The final term captures the temperature effect on carbon uptake, as discussed in the introduction. T represents annual global mean atmospheric temperature (over land). Parameter v_4 is expected to be negative, capturing how a higher temperature hampers biomass production.

Carbon is released from the biosphere to the atmosphere through the process of respiration, represented by $U(\cdot)$. The amount of carbon released through respiration depends on the size of the biosphere: the larger is B , the greater the amount of decaying organic matter. The temperature term captures the fact that organic matter breaks down faster, releasing CO₂ back into the atmosphere, in a warmer climate.

We estimate the parameters of our augmented carbon-cycle component using model output from LPJ–GUESS, a detailed individual-based process model of vegetation dynamics and biogeochemistry, combining features from the Lund-Potsdam-Jena (LPJ) DGVM (Gerten et al., 2004; Sitch et al., 2003) with a detailed treatment of demography and plant competition for resources (Smith et al., 2001). We forced LPJ–GUESS with monthly data on precipitation, temperature, cloudiness, and number of rainy days per month (precipitation exceeding 1mm), on a 0.5×0.5 degree regular grid, and annual global atmospheric CO₂ concentrations. The simulations were initially forced by a 30-year (1901–1930) period of detrended climate data from the CRU ts2.1 dataset (Mitchell and Jones, 2005), repeated every 30 years, and a constant 1901 CO₂ concentration, until reaching equilibrium after 500 years (a so-called spin up). After this initialization, we switched to varying CRU ts2.1 climate data and historical CO₂ concentrations. At 2001 we superimposed future scenario anomalies (relative to the 1960–1990 climatology in the respective General Circulation Model (GCM)

simulation) on the CRU ts2.1 1960–1990 climatology, and switched to the respective SRES emission scenario (Nakićenović et al., 2000) CO₂ concentrations. The GCM climate data were attained from the CMIP3 data archive (Meehl et al., 2007).

The table below lists our three simulations, labelled 1, 2 and 3.

| run | colour | CO ₂ scenario | climate model |
|-----|--------|--------------------------|-----------------------------|
| 1 | blue | B1 | HadCM3 (UK Hadley Centre) |
| 2 | red | A2 | HadCM3 |
| 3 | black | A2 | PCM1 (US NCAR <i>etc.</i>) |

The two emissions scenarios used are the B1 and A2 SRES scenarios (Nakićenović et al., 2000). These are scenarios for how atmospheric CO₂ will increase in the future, based on different assumptions about various socio-economic processes. A2 is supposed to be a high-emissions scenario, characterized by high population growth, little convergence in living standards across world regions, and technological progress that is less geared towards resource saving and environmental improvements. B2 is supposed to be based on more environmentally optimistic assumptions, such as a stabilization and later decrease of world population, as well as cleaner technology.

The climatic data used are output data from two GCMs, the HadCM3 and the PCM1, which have been run with the corresponding emissions scenarios as inputs. Figure 3.2 summarizes the CO₂ (Panel A) and temperature data (Panel B) used as inputs in our LPJ-GUESS simulations. Note that the CO₂ concentration is necessarily a global variable in these simulations, measured at annual intervals. Temperature data, however, is available at daily intervals, a high geographical resolution. Here we show only annual global mean temperatures over land, which is the information used to estimate the parameters of our carbon cycle extension.

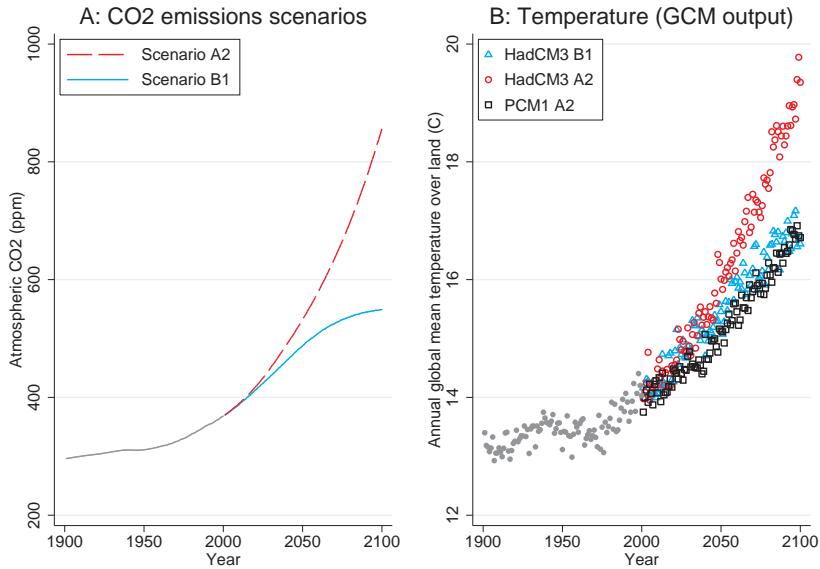


Figure 3.2: CO₂ and temperature data, used as inputs in LPJ-GUESS runs

Panel B of Figure 3.2 shows how global mean temperature develops under different emissions scenarios as well as different climate models. The HadCM3 model gives a lower temperature increase when run with a low-emissions scenario (blue data points), relative to the high-emissions scenario (red data points). A different climate model, the PCM1, gives the lowest temperature increase even when run with the high-emissions scenario (black data points). This is because the PCM1 has a lower internal climate sensitivity than the HadCM3.

Output data from our vegetation model simulations are summarized in Figure 3.3. Panel A shows yearly data for carbon uptake by the biosphere, referred to as Net Primary Production (NPP), and Panel B shows carbon released from the biosphere, respiration.

In Panel A, carbon uptake by the biosphere is lowest for HadCM3–B1; this is mainly due to there being less CO₂ in the atmosphere under this scenario (the CO₂ fertilization effect). Carbon uptake is greater for PCM1–A2 than for HadCM3–A2; this is partly due to lower temperatures under PCM1–A2, as illustrated in Figure 3.2. Similarly, the patterns in Panel B correspond to how B_t and T_t influence respiration.

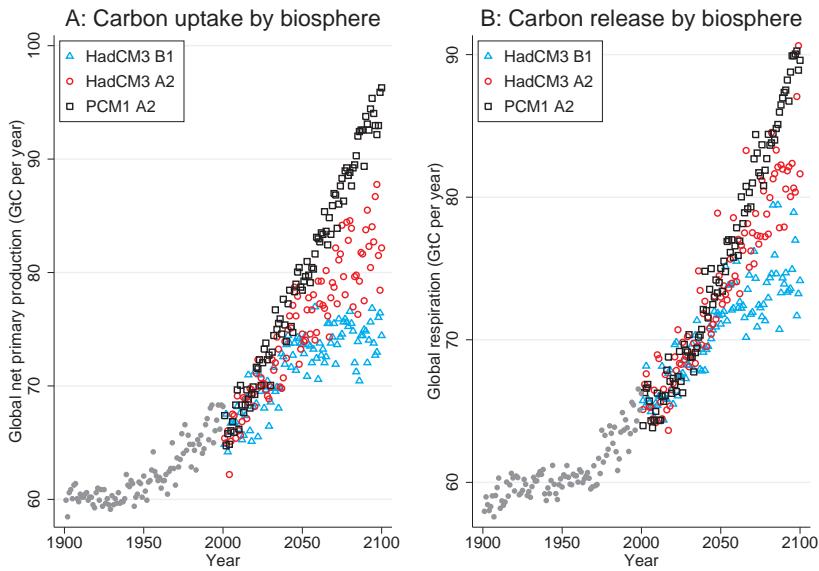


Figure 3.3: Carbon flows between atmosphere and biosphere; LPJ–GUESS output

The net of these two effects, i.e., the difference between carbon uptake and carbon release by the biosphere, determines how the biosphere grows over time. Formally, let NPP_t denote the New Primary Production in period t , and R_t denote respiration in period t . We then make use of the concept of Net Ecosystem Exchange,

NEE_t , defined as

$$NEE_t = NPP_t - R_t.$$

NEE_t is a measure of the net carbon uptake by the biosphere in period t . Figure 3.4 plots cumulative NEE_t over time for our three simulations (the thin lines; we will get back to the thick lines shortly). The biosphere takes up much more carbon with climate realizations like in PCM1, the climate model with lower climate sensitivity, compared to the warmer scenarios. The difference is striking: in 2100, biospheric carbon under PCM1–A2 has grown by over 200 GtC more than under HadCM3–A2, which is based on the same emissions scenario.

Using the data produced by the three runs with LPJ–GUESS, we estimate regression models for NPP and respiration, corresponding to equations (3.3) and (3.4), as follows:

$$NPP_t = v_0 + v_1 A_t + v_2 A_t^2 + v_3 B_t + v_4 T_t + \varepsilon_t \quad (3.5)$$

$$R_t = u_0 + u_1 B_t + u_2 T_t + \nu_t \quad (3.6)$$

The terms ε_t and ν_t are random errors. We estimate each equation by Ordinary Least Squares (OLS), pooling all the data presented in Figures 3.3A and 3.3B respectively. Results are reported below. The carbon fertilization effect is decreasing with higher atmospheric concentrations, as suggested by the negative coefficient on A_t^2 . A larger biosphere increases both NPP and respiration, as expected (positive coefficients on B_t in both equations). Higher temperature reduces NPP, but increases respiration.

| | NPP_t | R_t |
|---------|-------------------------|------------------|
| A_t | .0666 (.004) | — |
| A_t^2 | -.0000137 (1.08e-06) | — |
| B_t | .0142 (.002) | .0389 (.0007) |
| T_t | -3.213 (.261) | 2.431 (.063) |
| n | 400 | 400 |
| R^2 | .975 | .972 |

The R^2 is high in the regressions presented above, which suggests that we do capture most of the year-to-year variation in NPP and respiration with the variables included in the regressions. However, to conclude that this is a good specification it should also be able to match the cumulative build-up of carbon in the biosphere, i.e., the patterns presented in Figure 3.4.

The thin lines are simulated data, i.e., the output from the three runs with LPJ–GUESS. The thick lines are the “fitted values” for cumulative NEE, using the regression models in (3.5) and (3.6) to predict NPP and respiration, and then calculating the cumulative net flows. The predicted cumulative NEE follows the data reasonably well.⁶

A number of caveats are in order. Firstly, we apply the Bio-DICE carbon cycle for values of CO_2 and global mean temperatures that are outside the range of the data on which that cycle

⁶We have tried a number of alternatives to equations (3.5) and (3.6), including varying the functional form for the carbon flow functions $V(\cdot)$ and $U(\cdot)$, as well as using an altogether different specification where some of the carbon flow parameters ϕ_{ij} are made temperature dependent, as in (3.7) below, instead of the specification in (3.2).

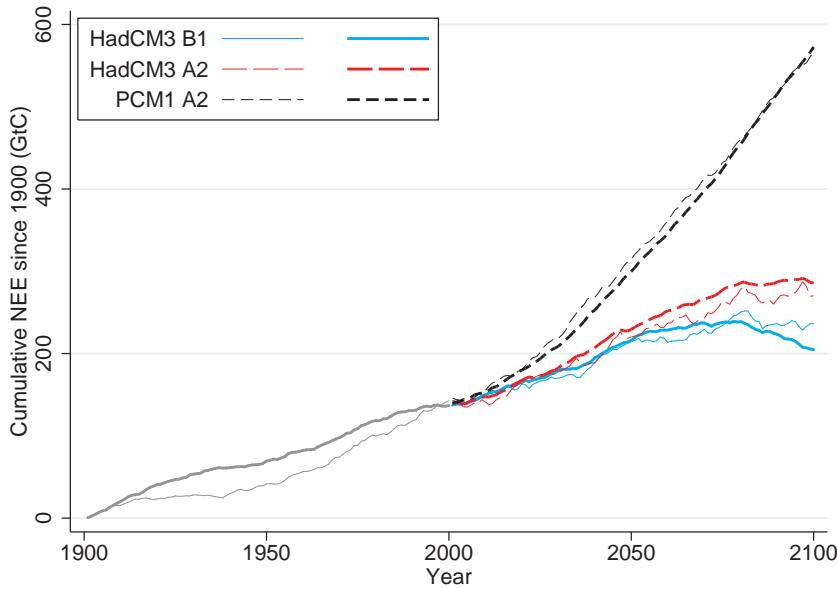


Figure 3.4: Cumulative net carbon flow: model output and statistical fit

has been estimated. More importantly, equations (3.5) and (3.6) have been estimated based on CO₂ concentration paths that increase throughout their domain. It is not clear that carbon fluxes between the atmosphere and the biosphere will behave the same way when atmospheric CO₂ is falling, due to little or no fossil-

$$\begin{bmatrix} A_{t+1} \\ B_{t+1} \\ C_{t+1} \\ D_{t+1} \end{bmatrix} = \begin{bmatrix} \phi_{AA}(\cdot) & \phi_{BA}(\cdot) & \phi_{CA} & 0 \\ \phi_{AB}(\cdot) & \phi_{BB}(\cdot) & 0 & 0 \\ \phi_{AC} & 0 & \phi_{CC} & \phi_{DC} \\ 0 & 0 & \phi_{CD} & \phi_{DD} \end{bmatrix} \begin{bmatrix} A_t \\ B_t \\ C_t \\ D_t \end{bmatrix} + \begin{bmatrix} E_t \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (3.7)$$

The specification in (3.5) and (3.6) is the one that fits the data best, defined as the equivalent of an R² for cumulative NEE. It is also a parsimonious specification, where the estimated effects correspond with our knowledge of how the carbon flows should interact with the variables in question. All other specifications gave results qualitatively similar to the ones presented here.

fuel burning. All the GCM simulations currently accessible in the CMIP3 data archive are forced by either increasing or time invariant CO₂ concentrations, which limits our possibilities to test and parameterize the Bio-DICE carbon cycle model under decreasing atmospheric CO₂ concentrations. We hope that we can utilize the coupled simulations of the next round of the Coupled Model Intercomparison Project, CMIP5, to better constrain a temperature dependent carbon-cycle model to climate and CO₂ concentrations after a concentration peak.⁷

We will refer to (3.2) as the Bio-DICE carbon cycle, and by Bio-DICE we will mean DICE-2007 but with (3.2) instead of (3.1). This stresses the role of the biosphere in our extension to the carbon cycle.

3.4 Results

3.4.1 Properties of the Bio-DICE carbon cycle

Figure 3.5 illustrates the properties of the Bio-DICE carbon cycle introduced here. Panel A shows atmospheric CO₂, for the default value of climate sensitivity (CS) of 3, comparing the carbon cycles in (3.1) and (3.2). The solid black curve shows CO₂ with the carbon cycle in the baseline DICE-2007 model. The dashed black

⁷As mentioned above, we have explored a number of different alternatives to equations (3.5) and (3.6). Throughout the period when atmospheric CO₂ increases, these specifications behave almost identically. After atmospheric CO₂ has peaked, the CO₂ trajectories diverge somewhat across specifications. This reinforces the notion that there is genuine uncertainty about how the carbon cycle will behave once fossil fuels have been phased out. It should be noted, however, that with all specifications atmospheric CO₂ peaks at a higher level and falls more slowly, compared with the carbon cycle in DICE. The chosen specification does not exhibit more extreme CO₂ trajectories than some other specifications considered.

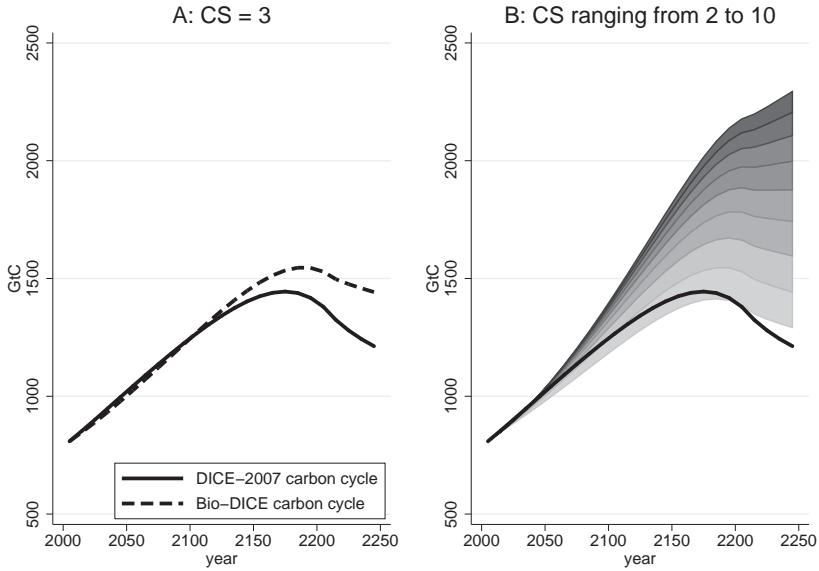


Figure 3.5: Properties of the temperature-dependent carbon cycle, relative to DICE-2007

curve gives CO₂ using Bio-DICE, i.e., the equation system in (3.2). Note that for both curves, the underlying emissions profile is kept constant at what is optimal in DICE-2007, i.e., fossil fuel consumption, and hence emissions, are fixed at the profile in Figure 3.1A. In other words, the difference in atmospheric CO₂ shown here is not due to how the different carbon cycle formulations affect optimal fossil fuel use within the model; instead the difference is only due to the change in the properties of the carbon cycle itself. A fuller analysis would let the new carbon cycle influence optimal policy; this is done in the next subsection.

During the 21st century, the two formulations produce nearly identical trajectories for atmospheric CO₂. Around the year 2100, they start to diverge, however. CO₂ peaks at a level 100 GtC

higher, and at a later time, with Bio-DICE. Moreover, the speed at which CO_2 falls back towards pre-industrial levels, once fossil fuels have been phased out, is slower with Bio-DICE. In the standard version, carbon sinks keep absorbing constant proportions of excess carbon, regardless of atmospheric temperatures. This allows carbon to disappear from the atmosphere relatively quickly, once the economy manages to switch to alternative energy sources. Allowing a temperature dependence in the carbon cycle captures the fact that biomass production is impeded by higher temperatures, causing a much slower return towards pre-industrial concentrations.

Panel B of Figure 3.5 shows the same information, but for a range of climate sensitivities. The black curve is the same as in Panel A, showing atmospheric CO_2 with the baseline carbon cycle. Note that this trajectory is independent of realised temperatures, and hence of the climate sensitivity. The shaded fan shows atmospheric CO_2 with Bio-DICE, for values of CS ranging from 2 to 10: each colour shift corresponds to an increase in the value of climate sensitivity by one unit. (CO_2 emissions are still kept fixed at the path given in Figure 3.1A.) For low values of climate sensitivity, corresponding to the light areas at the bottom of the fan, atmospheric temperatures go up relatively little, and the biosphere remains a good carbon sink. If climate sensitivity turns out to be high, the darker fields illustrate what happens to atmospheric carbon—the earth warms more, and the biosphere is less prone to taking up carbon, leaving more of it in the atmosphere. The slow return to pre-industrial concentrations mentioned above applies for all values of CS.

Figure 3.6 further illustrates the difference between the two carbon cycle formulations, now looking at atmospheric temperature increase. Again, the underlying CO_2 emissions are taken to be the

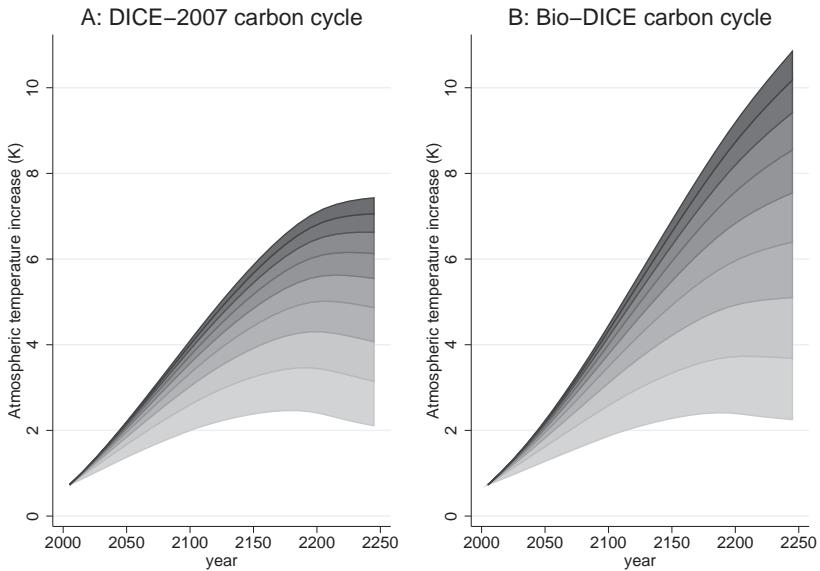


Figure 3.6: Temperature increase: comparing two carbon cycle formulations

trajectory in Figure 3.1A, in both panels and for all values of CS. Panel A plots temperature increase for values of CS ranging from 2 to 10, with the DICE–2007 carbon cycle, whereas Panel B shows the same thing using the Bio–DICE carbon cycle. In other words, Panel A shows how the black curve in Figure 3.5 maps to temperatures, and Panel B shows how the shaded fan in Panel B of Figure 3.5 maps to temperatures. For low values of CS, corresponding to the light fields at the bottom of the fans, as well as during the first 100 years for all values of CS, differences are minor. However, even for a CS as low as 4, the temperature difference between the models is around 1 °C in 2250. Note also that in Panel A, temperatures seem to have peaked by 2250, for all values of CS. This is not the case in Panel B, however.

3.4.2 Optimal policy in Bio-DICE

We now turn to the results obtained when running Bio-DICE, and how they differ from the conclusions in the original DICE-2007 model. We will focus on two policy variables: optimal CO₂ taxes, and optimal fossil fuel consumption. For fossil fuel consumption, it is particularly interesting to see how much fossil fuels society should optimally consume before we switch to only using alternative technologies. For this reason, fossil fuel consumption results will be presented in terms of cumulative consumption.

Apart from varying the climate sensitivity parameter, we also vary two other important parameters in the model. The main difference between Bio-DICE and DICE-2007 is that, for the same emissions, the former results in more warming, but mainly in the distant future. Whether this will result in large effects on optimal policy depends on how we value this additional warming, which will be noticeable only in the next century and later. The choice of how we discount the future therefore plays a central role when comparing the models. We present results with a time-preference rate of 1.5% per year, which is the default in DICE-2007, as well as a time-preference rate of 0.1% per year, which is the approach taken in Stern (2006). We will also use two different ways of valuing climate impacts due to rising temperature, i.e., we present results with two different damage functions. There is ongoing debate, and genuine uncertainty, about how large the impacts on human societies will be, for a given temperature increase. If higher temperatures turn out to be very damaging, the strengthened warming we find with Bio-DICE is more of a problem than if damages are actually fairly low. We use the default damage function from DICE-2007 as the low-damage alternative, and the damage function specified

by Joos et al. (1999) as the high-damage alternative. In the latter, the marginal damage due to an additional ton of CO₂ rises very sharply with CO₂ concentrations.

Performing this sensitivity analysis is important. Even though DICE is designed as a deterministic model, there is substantial and genuine uncertainty about what are appropriate values for some of the parameters, in particular the ones just mentioned. Climate sensitivity is thought to be around 3, but this value is highly uncertain (Roe and Baker, 2007), and although values as high as 10 seem unlikely, they cannot be ruled out. How to appropriately discount the future is rather a policy matter, with important consequences for optimal climate policy, but so far there is no clear consensus on how to correctly discount the future. Furthermore, the damage functions used in climate-economy models are arguably their least well-understood building blocks. We are therefore interested not only in how Bio-DICE differs from DICE-2007 under the latter's default parameter values, but also how they compare under other plausible values of these important parameters.

Furthermore, it is becoming increasingly common in climate-economics research to examine existing climate-economy models by varying combinations of parameters to see how results change. For example, a recent paper by Ackerman et al. (2009) varies climate sensitivity and the damage function in DICE, in order to explore how policy conclusions change if both happen to take on unfavourable values. When performing such exercises, one would like to be sure that other parts of the models, such as the carbon cycle, perform well despite varying parameter values.

When varying the climate sensitivity, we also vary the speed of adjustment of the thermodynamic system, as suggested by Yohe et al. (2004). For high values of the climate-sensitivity parameter to

be consistent with observed data, a slower adjustment towards the equilibrium temperature is required.⁸

Figure 4.11 shows optimal carbon taxes obtained with Bio-DICE, relative to optimal carbon taxes in DICE–2007 (all model runs are 400 years, i.e., until 2405, but we focus on the coming century in our results). The shaded fans again represent varying values for climate sensitivity, between 2 and 10 as before. The four subplots show results for the two different time-preference rates, interacted with the two damage function formulations. All curves lie above unity, meaning that in all runs are optimal taxes higher with Bio-DICE.

Panel A shows optimal carbon taxes with default time-preference rate and damage function. The differences between Bio-DICE and DICE–2007 are relatively small—for a default climate sensitivity of 3, optimal carbon taxes in 2005 are roughly 4% higher with Bio-DICE. This rises to around 9% with a climate sensitivity of 8, which may be seen as unlikely but certainly not impossible. Panel B shows the same results, but with the low time-preference rate of 0.1% per year, meaning that the damages due to the additional future warming in the model are valued higher. This results in a higher optimal-tax differential: for a CS of 3, Bio-DICE gives

⁸In particular, we adjust σ_1 in the temperature-adjustment equation, reproduced below, where T represents atmospheric temperature increase, TL denotes the temperature increase of the lower oceans, and F is the change in radiative forcing relative to pre-industrial conditions

$$T_t = T_{t-1} + \sigma_1 \left\{ F_t - \frac{\eta}{\kappa} T_{t-1} - \sigma_2 [T_{t-1} - TL_{t-1}] \right\}.$$

Climate sensitivity is captured by κ . We use the relationship between κ and σ_1 given in Yohe et al, adjusting the values of σ_1 to apply to the 10-year time periods used in DICE, and shifting the relationship such that σ_1 takes the default value of 0.22 for the default value of $\kappa = 3$. The same approach is used in Below and Persson (2011).

around 13% higher taxes in 2005, or 29% higher for $CS = 8$. Panels C and D represent optimal carbon taxes when climate impacts are more pronounced: here optimal taxes are substantially higher when using Bio-DICE.⁹

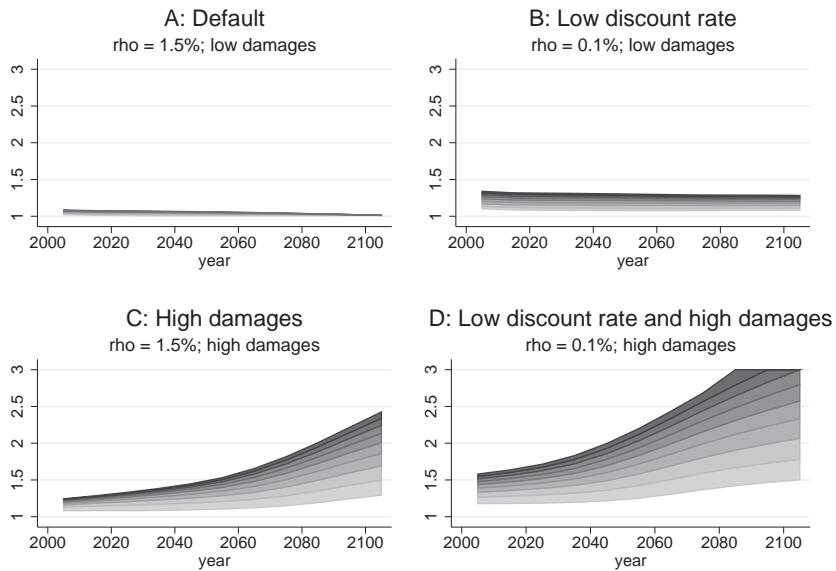


Figure 3.7: Optimal CO₂ taxes in Bio-DICE, relative to DICE-2007

⁹Note that the comparison is always between the two models run with the same parameter values, the only difference being in the carbon cycle formulation. The curve that goes through the upper right-hand corner of Panel D therefore represents the following: the optimal tax on CO₂ emissions over time, measured in USD per ton of carbon, when running Bio-DICE with a climate sensitivity of 8, a time-preference rate of 1.5% per year, and a high-damage function, divided by the optimal tax on CO₂ emissions over time, when running DICE-2007 with these same parameter values.

Figure 3.8 presents results structured in the same way, but for cumulative fossil fuel consumption. Carbon taxes act to reduce climate change, through lowering the amount of fossil fuel burnt in economic activity. Optimal total fossil fuel burnt is therefore an important measure of the strength of optimal climate policy.

In Panel A, the fall in total fossil fuel consumption is barely noticeable. For the default CS = 3, total fossil fuel consumption is less than 1% lower with Bio-DICE, relative to DICE-2007. This figure increases to around 2% for CS = 8. In Panel B, the corresponding numbers are around 5% and 25%, respectively. In the high-damage runs, fossil fuel consumption is more dramatically reduced: it is only around 70% of baseline with CS = 3, and around 53% with CS = 8 in Panel C. In Panel D, the corresponding figures are 52% and 30%.

3.5 Conclusions

The global carbon cycle entails a multitude of processes that interact in complex ways. Its representation in climate–economy models must necessarily be reduced to a couple of equations. However, we suggest an extension of existing carbon-cycle representations to take into account the fact that the strength of carbon sinks is tightly linked to climate sensitivity—a highly uncertain property of the climate system. With such an extended carbon-cycle representation, optimal carbon taxes are higher than with a standard model—vegetation takes up less carbon the more temperatures go up in the future, and this should be taken into account when prescribing CO₂ taxes. How much optimal carbon taxes increase depends on what is assumed about other parameters in the model. Our extension of DICE suggests that the default carbon cycle performs well

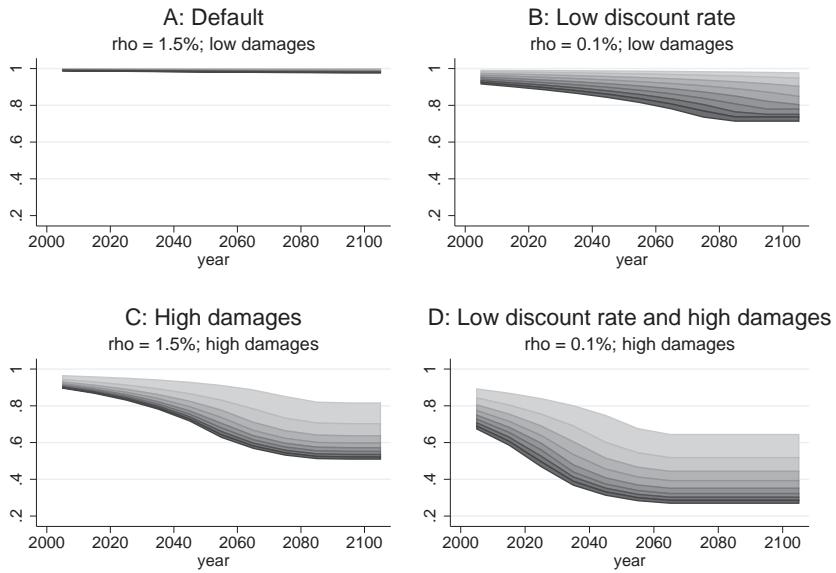


Figure 3.8: Optimal cumulative fossil fuel consumption in Bio-DICE, relative to DICE-2007

under default parameter values for all parameters in the model: Bio-DICE gives an optimal emissions tax that is only around 4% higher for 2005. However, for alternative—and plausible—values of climate sensitivity, time-preference rates, and/or damage functions, optimal climate policies prescribed by the models diverge in a more pronounced way. With non-default values for all three parameters, optimal climate policy differs substantially between Bio-DICE and DICE-2007.

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Chapter 4

Uncertainty, Climate Change and the Global Economy*

4.1 Introduction

Uncertainty about future climate change is an unavoidable fact. It is commonplace to gauge this uncertainty by simulations with different climate models. This is the approach taken, e.g., by the International Panel on Climate Change (IPCC, 2001, 2007) to highlight our imprecise knowledge about the relation between specific atmospheric concentrations of greenhouse gases (GHGs) and global temperature. Such model simulations typically rely on a small set

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of common, and deterministic, emission scenarios – so-called SRES-storylines (Nakićenović et al, 2000) – which are not related to the processes underlying economic growth and energy use in an explicit and reproducible way.¹ Thus, the common methodology focuses only on the uncertainty surrounding specific biogeophysical relations in the entire chain from human activity to climate change and back to human activity. However, the socioeconomic relations behind regional and global economic growth, energy use and emissions are equally fraught with uncertainty as the biogeophysical relations.

A comprehensive assessment of the uncertainties about the important links in the chain from economic conditions to climate change is obviously a monumental task, and this paper is merely a pass at the problem. Our approach is to simultaneously introduce uncertainty about a number of parameters that shape exogenous variables and endogenous relationships in the same simple, but comprehensive, model of the global climate and economy, namely a slightly modified version of the RICE model, developed and described by Nordhaus and Boyer (2000).

We then perform Monte Carlo simulations, i.e., we make a large number of random draws of the full set of parameters and simulate the entire model for each such draw. Each simulation generates time paths for future output, global temperature, climate damages, etc. The collection of all such time paths are then used to derive probability distributions at different points in time for the

¹For a broad, and critical, discussion of the SRES methodology see McKibbin, Pearce and Stegman (2004) or Schenk and Lensink (2007). Webster et al. (2002) and Mastrandrea and Schneider (2004) discuss the use of scenarios vs. a probabilistic approach. In the fifth IPCC assessment report, a new set of scenarios will be used instead – the so-called Representative Concentration Pathways (RCPs). See Inman (2011) for a background on the RCPs.

variables of most interest. Climate sensitivity (the effect on equilibrium global mean temperature of a doubled GHG concentration) remains the single most important determinant of uncertainty about global warming, but well-identifiable socioeconomic developments in major regions of the world – such as population growth, and improvements of overall technology and energy efficiency – drive a non-trivial part of that uncertainty. Closing down uncertainty about climate sensitivity altogether, one is left with an uncertainty range of temperature a hundred years from now, which is close to 4 °C (See Figure 10, where the range is between 2.98 and 6.80 °C.)

Conceptually, our analysis is similar to that of Wigley and Raper (2001) who derive a probability distribution for future global mean temperature in a simple climate model by introducing uncertainty through assigned probability density functions (p.d.f.) for the main drivers of temperature. However, their study stresses uncertainties in the biogeophysical and biogeochemical systems, while emissions are given by a (uniform) p.d.f. over alternative SRES scenarios, rather than alternative socioeconomic developments. A similar analysis is performed in the PAGE model (Hope, 2006) used in the Stern Review (Stern, 2006). Analogously, Murphy et al. (2004) derive a probability distribution for climate sensitivity from the Hadley Centre climate model, by drawing alternative values of the parameters that govern the model's important relations. Mastrandrea and Schneider (2004) use the DICE model – an aggregated version of RICE, used here – to produce probability distributions for temperature increase. Aspects of their methodology is close to ours, but they focus their analysis on climate policy. So do Ackerman et al. (2010), in their study of how uncertainties about the climate system and climate impacts together can lead to catastrophic outcomes in DICE.

In an early analysis, Nordhaus and Yohe (1983) indeed consider uncertainty about socioeconomic determinants of climate change, as do Nordhaus and Popp (1997). But the purpose of these papers is again different (to gauge the value of different types of scientific information). Finally, Webster et al. (2002) derive GHG emission scenarios in a probabilistic manner by introducing uncertainty over important variables in an economic model, but do not evaluate the consequences of these for climate variables.

Section 4.2 of this paper gives a short description of the RICE model and our modifications of it. Section 4.3 explains how we introduce and quantify the uncertainty about model parameters. Section 4.4 presents results for variables of interest in two forms: fan charts, which illustrate how uncertainty develops over the coming century, and histograms, which illustrate uncertainty at a point in time 100 years from now. Section 4.5 concludes.

4.2 The modified RICE model

We need a model that incorporates the global economy as well as the climate system and allows us to parametrically vary assumptions about important relations. For these reasons, we adapt and use the RICE–99 model, as formulated in Appendix D of Nordhaus and Boyer (2000).² Next, we provide an overview of this model and our modifications. The equation numbers, variables, and parameters discussed below refer to a formal description of the model in the Appendix of our paper.

²This monograph gives a general description of the RICE model (chapter 2), and its appendix (pp. 179–187) includes all equations and parameter values of the baseline model.

General description of RICE–99. The world is divided into eight regions (indexed by J) on the basis of geography as well as levels of economic development: United States (USA), OECD Europe (EUR), Other High Income countries (OHI), Russia and Eastern Europe (REE), Middle Income (MI), Lower Middle Income (LMI), China (CHI) and Lower Income (LI).³ Neither trade nor investments flow between regions. Time (indexed by t) is measured in 10-year periods, starting in 1995. In each period, each region produces a homogeneous good with a neoclassical production technology based on capital and labour, but augmented by “energy services” reflecting the carbon content of energy inputs (see equation A.4 in the Appendix). Regional damages from climate change are modelled as an output loss proportional to the value of GDP.

Economic growth in each region is driven by growth of population (A.5) and total factor productivity (TFP) (A.6). Higher economic growth implies more rapidly increasing regional demand for energy. How much this translates into use of exhaustible carbon resources depends on carbon-saving technological change (A.7), as well as regional energy prices. These prices have a regional component, reflecting regional taxes and distribution costs, and a global component, reflecting gradually higher costs of extraction from the global supplies of oil, coal and natural gas (A.10–A.12). Naturally, higher prices curtail energy use.

Energy use in each region and time period creates industrial CO₂ emissions that – together with emissions from changes in land use and changes in the properties of the biosphere – end up in the global atmosphere (A.13). The model incorporates a simple carbon cycle, i.e., carbon flows between atmosphere, biosphere (cum shallow oceans), and deep oceans (A.14). Any CO₂ not absorbed by

³See Nordhaus and Boyer (2000) pp. 28–38 for definitions of regions.

the ocean sinks adds to atmospheric concentration. Via increased radiation (A.15) more CO₂ raises global-mean surface temperature (A.16) in an amount depending on climate sensitivity.⁴ Changes in climate create damages reflecting, e.g., lower agricultural productivity, more frequent storms, or resettlements due to coastal flooding (A.17 and A.18). Damages, as a proportion of gross GDP, are region-specific quadratic functions of global temperatures in the period relative to 1900. Larger damages imply lower welfare. They also create a negative feedback effect, whereby lower growth leads to less energy use, which ultimately reduces temperature.

Along an equilibrium time path of the model, consumers and producers in each region make decentralized utility and profit--maximizing decisions, adjusting savings and investments to the incomes, interest rates, technologies, and market prices they observe and rationally expect to prevail in the future. Specifically, producers adjust their use of carbon-based energy to available technologies and regional energy prices. Along an equilibrium path, regional and global welfare functions (A.1–A.3) are maximized.

RICE can be programmed and solved in two ways. The usual way is to maximize welfare, taking regional damages explicitly into account, so as to derive optimal uses of carbon-based energy, given their adverse effects via global temperature, and to calculate optimal carbon prices. While we do touch upon optimal policies at the very end of the paper, our main purpose is positive (descriptive, to illustrate the effects of uncertainty) rather than normative (prescriptive). For this positive purpose, we do *not* take damages into account in the maximization to illustrate future paths in the ab-

⁴The climate-sensitivity parameter (κ) captures, in a very simple way, the complicated interactions in the earth system – including a number of feedbacks from temperature to warming – that produces a warmer climate as the atmospheric concentration of GHGs goes up.

sence of additional mitigation measures: Business As Usual (BAU) in the jargon of the climate-change literature.

Modifications We make a few adjustments to the RICE model, as follows.

Data for most variables entering the model are now available for the period 1996–2005 so we update initial values by one (ten-year) period and start off in 2005 rather than 1995. Atmospheric temperature for 2005 (T_0 in A.16) comes from the UK Met Office, and atmospheric concentration of CO₂, (M_0 in A.14) is obtained from the Carbon Dioxide Information Analysis Center (CDIAC) and converted into a stock. The concentration of CO₂ in the upper oceans (M_0^U in A.14) is derived from the latter figure. Initial population figures for 2005 (L_0^J and $g_0^{L,J}$ in A.5) come from the UN *World Population Prospects: The 2004 Revision Population Database*. GDP figures for 2005 are collected from the World Bank’s *World Development Indicators* (WDI) database. These are used to calibrate initial levels of TFP, capital stocks, and energy services (A_0^J , K_0^J , and ES_0^J in A.6–A.9), assuming that investments and energy service inputs were chosen optimally in all regions between 1995 and 2005. Finally, we estimate current values of the TFP and energy efficiency growth rate parameters (equations A.6 and A.7), using data from the Penn World Tables (Heston, Summers and Aten, 2002) and the World Bank’s WDI database. These estimates will be discussed in more detail below. The precise numbers assigned to parameters and initial conditions are given in Tables 4A.1 and 4A.3 in the Appendix.

RICE assumes that the rate (all) consumers use to discount the utility of future consumption declines over time, while we reset it to a constant. In particular, we set the (average) social rate of

discount equal to 1.5% per year (with an uncertainty range around it). Specific assumptions about the discount rate are vital when one uses a climate-economy model for the normative purpose of finding optimal paths of mitigation, because abatement costs close in time are traded off against benefits of lower damages much further away in time. For our main positive purpose, to illustrate uncertainty about future outcomes under BAU assumptions, the discount rate is much less important.⁵

Finally, We also try to incorporate scientific findings that the biosphere's ability to absorb CO₂ might change with climate.⁶ At some level of CO₂ concentration in the atmosphere, the biosphere will likely switch from being a CO₂ sink to a CO₂ source. (Oceans too may absorb less CO₂ as climate changes, but these effects are smaller and less certain.) It is estimated that this terrestrial biosphere effect may contribute an additional 40–400 Gigatons of carbon (GtC) into the atmosphere by 2105, most models predicting a number between 100 and 200 GtC.

Ideally, the terrestrial biosphere effect should be added as an additional module to the carbon-cycle part of the model (for such an attempt, see von Below and Ahlström, 2011). Here, we have chosen the simpler solution of just adding an additional flow of emissions into the atmosphere in every period, calibrated to yield a mean additional concentration in 2105 corresponding to 150 GtC. However, this value is highly uncertain, so we impose a probability distribution on it, as we do for many other model parameters. The

⁵The specific assumptions about the discount rate was indeed been one of the major points in the public discussion about the conclusions in the Stern Review (Stern, 2006); see, e.g., Nordhaus (2006), Dasgupta (2007) and Weitzman (2007).

⁶This alteration of the model is based on personal communications with Will Steffen and on Friedlingstein et al. (2006).

specification of these parameter uncertainties is the topic of the next section.

4.3 Specification of uncertainty

We express the uncertainty about individual parameters and exogenous variables in the model as statistical distributions on the forms summarized in Tables 4A.1 and 4A.3. Most distributions are assumed to be Gaussian; the uncertainties about population projections and the terrestrial biosphere effect are deemed to be asymmetric and, therefore, gamma-distributed random variables are used to generate these processes. The probability distribution for the climate-sensitivity parameter is a special case derived from a truncated normal distribution, as discussed below.

Means for most parameters are close to the specific parameter values used in RICE, except that we raise the means of initial TFP growth rates to correspond more closely to the growth experience in the last ten years.

Using the p.d.f. of each one of the assumed distributions, we conduct a Monte Carlo simulation with 10001 independent random draws of the full set of parameters. For each of these draws, we carry out a full dynamic simulation for 400 years: an equilibrium time path of the model, as described above. These 10001 equilibrium paths generate different levels of GDP, emissions, temperatures, etc., which we use to describe the uncertainty about these outcomes.

Of course, each assumption regarding the distribution of an underlying parameter is a subjective assessment, made by ourselves or some collective of scientists. Most of the many relations that contribute to the climate problem are highly uncertain, however, and our objective is to illustrate a way to take this comprehensive

uncertainty into account. We believe that the exercise meaningfully gauges the magnitude of uncertainty at different time horizons. Moreover, it helps illustrate the effects of favorable or unfavorable – from the viewpoint of climate change – circumstances, and which circumstances matter the most. Next, we provide details on the various sources of uncertainty.

Population Population growth is a major source of uncertainty about future output growth. In RICE, regional population trajectories are pinned down by two parameters: initial population growth rates, and the decline rates for population growth ($g_0^{L,J}$, and $\delta^{L,J}$ in A.5). To estimate these parameters, we first notice that the population level in each region J converges to a constant level.⁷ We denote this steady-state level of population L^J , and notice that we can solve for this level from $L^J = L_0^J \times \exp\left(\frac{g_0^{L,J}}{\delta^{L,J}}(1 - e^{-\delta^{L,J}t})\right)$ as $t \rightarrow \infty$. Solving this expression for $\delta^{L,J}$, we can write population at time t in region J as

$$L_t^J = L^J \times \exp\left(1 - \exp\left[-\frac{g_0^{L,J}}{\ln(L^J/L_0^J)}t\right]\right). \quad (4.1)$$

For a given initial population level L_0^J , the population level at any time is then defined by two parameters: the initial population growth rate $g_0^{L,J}$ and the steady-state population level L^J .

To estimate these parameters, we rely on the UN *World Population Prospects: The 2004 Revision Population Database*, which contains country-level population forecasts in five-year intervals up

⁷Kelly and Kolstad (1999) argue that relaxing the common assumption of an eventual stabilization of global population and productivity levels in climate-economy models, greatly increases the severity of climate change. However, their result relies on an implicit assumption of an infinite supply of fossil fuels, the extraction of which has no resource cost.

until 2050 in the form of three different scenarios: low, median, and high. We aggregate these country scenarios up to RICE regions, and estimate the growth parameters based on the each scenario. More precisely, we use non-linear least squares to obtain point estimates for $g_0^{L,J}$ and L^J for each of the three UN scenarios, based on the equation in (4.1). We add an error term, which is allowed to have region-specific heteroskedasticity and autocorrelation. Then, we treat the variance among these three estimates as a measure of the uncertainty of the parameter estimates. For the regions where the low and high estimates are symmetric around the median estimate, we use the median estimate as our point estimate for the parameter in question, and arrive at a measure of the uncertainty by assuming that the low and high estimates are ± 2 standard deviations.

For most regions, however, the low and high estimates are not symmetric around the median estimate, neither for the initial growth rate nor for the steady-state population level. In these cases, we assume that the low, median and high estimates correspond to the 2.5, 50 and 97.5 percentiles of the uncertainty distribution for each parameter. We then assume that the uncertainty distribution is a gamma distribution, and calculate its parameters from the three estimates, from the cumulative distribution function of the gamma distribution. For example, for $g_0^{L,USA}$, we find a location parameter x and a gamma distribution $\Gamma(k, \psi)$, such that when we define $g_0^{L,USA} = x + \gamma$, where $\gamma \sim \Gamma(k, \psi)$, then 2.5% of the draws of $g_0^{L,USA}$ lie below the low estimate for $g_0^{L,USA}$, and so on.⁸

Figure 4.1 shows the median population trajectories for all re-

⁸For EUR, OHI and CHI, population levels are projected to first rise and then fall. Mean population forecasts and the uncertainty around them are therefore entered manually up until 2045 for these regions.

gions and confidence bands around them in the form of fan charts.⁹

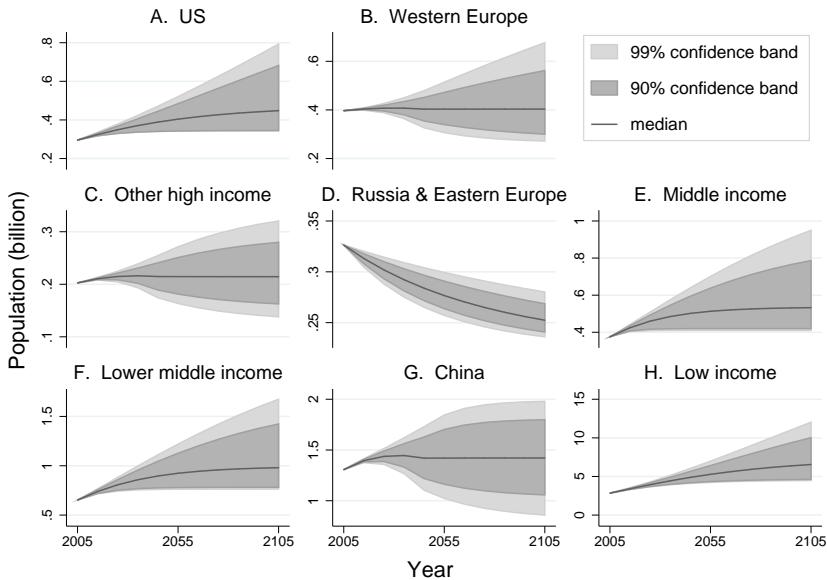


Figure 4.1: Forecasts for regional population levels, L_t^J

TFP Along with population growth, productivity growth is the most important determinant of future output levels. Our estimated TFP growth rates, which are higher than in RICE–99, are calculated in the following manner. Country-level investment data from the Penn World Tables and the perpetual inventory method are used to construct a series for capital stock. These figures, along with data on GDP¹⁰ and population from the same source, allow us to calculate past TFP levels using a standard Cobb-Douglas production function. In these calculations, we use data for countries

⁹Throughout the paper, we choose to focus on the time period between now and 100 years ahead in the charts presented; however, the model simulations run through 40 time periods, i.e., 400 years.

¹⁰Throughout the paper, PPP-adjusted GDP figures have been used.

where data is available for the whole period 1960–2000, except for REE where no data is available before 1992; here we use 1992–2000.

We then aggregate the data up to RICE regions and five year-periods, and use these to form statistical estimates of TFP growth processes for each region with the same functional form used in RICE. To allow for a global component of TFP, we also estimate the same kind of process for the entire world economy. In the end, each region’s TFP growth is a weighted average of the region-specific and global components.

The process for region-specific TFP growth has the same functional form as population growth. Hence, we write down a regression equation similar to (1), namely

$$A_t^J = A^J \times \exp \left(1 - \exp \left[-\frac{g_0^{A,J}}{\ln(A^J/A_0^J)} t \right] \right) + \varepsilon_t . \quad (4.2)$$

Ideally, we would like to estimate both $g_0^{A,J}$ and A^J simultaneously, using equation (2) and non-linear least squares. This is not feasible, however, as the data on past TFP do not follow a time path that is sufficiently close to the functional form we want to estimate. Instead, we take the following approach.

First, we impose that the steady-state values of TFP are the same as the implied steady-state TFP levels in the original RICE model (relative to the initial, i.e., 1995 TFP levels). The available data does not allow us to conclude anything about what levels of TFP might converge to, if at all. As we want to stay close to RICE – in particular, we want to use the same functional form for TFP growth – this shortcut is necessary. Having fixed A^J , we can estimate $g_0^{A,J}$, with non-linear least squares, using (2). This procedure gives us point estimates and standard errors for $g_0^{A,J}$.

In order to gauge the uncertainty about A^J , we turn the same estimation procedure upside down. Thus, we fix $g_0^{A,J}$ at the point estimate found previously, and estimate A^J , using non-linear least squares, from (2). The standard error obtained for A^J through this procedure is our measure of the standard deviation for A^J (whether or not the point estimates from this last regression – which we do not use – are close to the values imposed for A^J based on the original version of RICE.)

Data availability varies across countries, and hence regions. In general, we have used all available data in our estimations. For some regions, a number of years were dropped in the beginning of the time series, whenever this was necessary to allow estimation of (2). This suggests that our uncertainty estimates are, if anything, too low. For one region, OHI, equation (2) could not be estimated at all. Instead, the value of $g_0^{A,J}$ for EUR was used, and uncertainty about the steady-state TFP relative to its initial value was also set equal to that of EUR.

In addition to estimating the parameters $g_0^{A,J}$ and A^J separately for each region J , we also estimate analogously defined global parameters, $g_0^{A,W}$ and A^W . This estimation is carried out with the regression equation in (2), but with a time series for global TFP. Our final assumptions regarding growth rates and steady-state levels for TFP in each region thus consist of a global component and a region-specific component, where the relative weight is determined by historical correlations between global and regional TFP growth. In these calculations, $g_0^{A,J}$ and A^J and are perfectly correlated for each region J . In other words, the random draw in our Monte Carlo simulation that has the highest value for $g_0^{A,J}$ also has the highest A^J .

Figure 4.2 illustrates our TFP forecasts in the form of fan charts

(note the different scales on the y-axes).

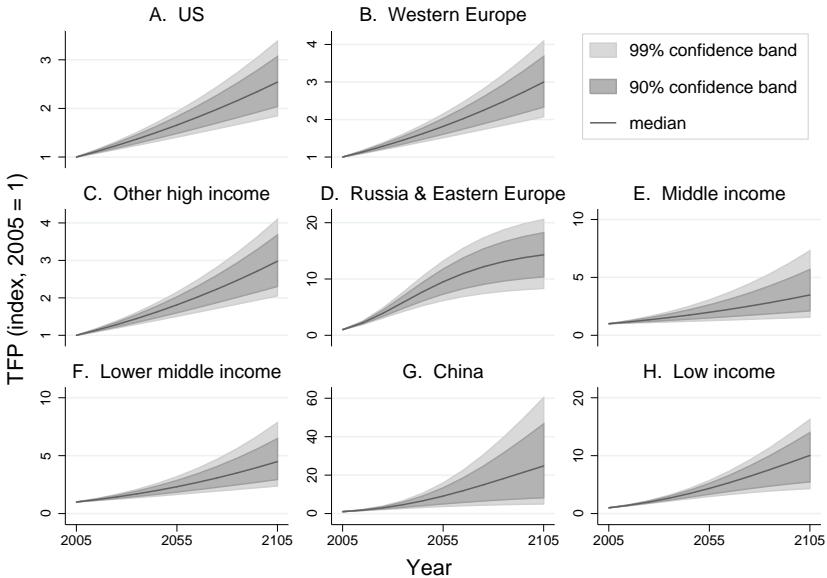


Figure 4.2: Forecasts for regional TFP levels, A_t^J

Energy efficiency Energy efficiency in production is modelled with parameter Z_t^J , which is set at 1 in all regions in the initial period. Then, Z declines following a process similar to population and TFP growth, with an initial (negative) growth rate, $g_0^{Z,J}$, and a decline parameter, $\delta^{Z,J}$. A lower value of Z means higher energy efficiency: less CO₂ is emitted for the same amount of carbon energy used. Since energy efficiency is modelled with the same type of process as TFP, we estimate its parameters in an analogous manner. Exploiting data on the ratio of CO₂ emissions to GDP, carbon intensity, from the World Bank's *World Development Indicators* database, we estimate means and standard deviations

of initial-period growth rates, as well as uncertainty about steady-state levels. Here again, we use non-linear least squares, with the same methodology as for TFP, to estimate an equation similar to (4.1), but with carbon intensity as the dependent variable. Data exists from 1970 until 2006, except for REE, where data is available only from 1992. As in the TFP estimations, as much as possible of the available data is used in the regressions. For MI, LI and OHI, estimation using the methodology described is not feasible. The carbon intensity of the two former regions has been rising up until recently; hence fitting a functional form with a falling carbon intensity doesn't allow for identification. As before, we assign OHI the values found for EUR, whereas MI and LI are given the same values as LMI. The means of the probability distributions for steady states for all regions are again the same as the ones implied in RICE-99.

Figure 4.3 shows the forecasts for the energy efficiency parameter Z_t^J . As the figure shows, energy efficiency improvements are expected to be asymmetric in some regions. This is due to truncation of some of the steady-state uncertainty distributions — carbon intensity can never fall below 0. China, Russia and Eastern Europe are expected to experience the greatest improvements in energy efficiency, while other regions follow roughly similar patterns.

Land use Emissions of CO₂ due to changes in land use arise mainly from deforestation, when carbon of burnt biomass is released as carbon dioxide. In RICE, this process is modeled in similar fashion to other growth processes. Each region has an initial rate of emissions due to land-use changes, and these rates then decline slowly at a rate set at 10% per decade.

We update initial emission rates and introduce uncertainty over them, based on figures in Chapter 7 of the WG1 contribution to

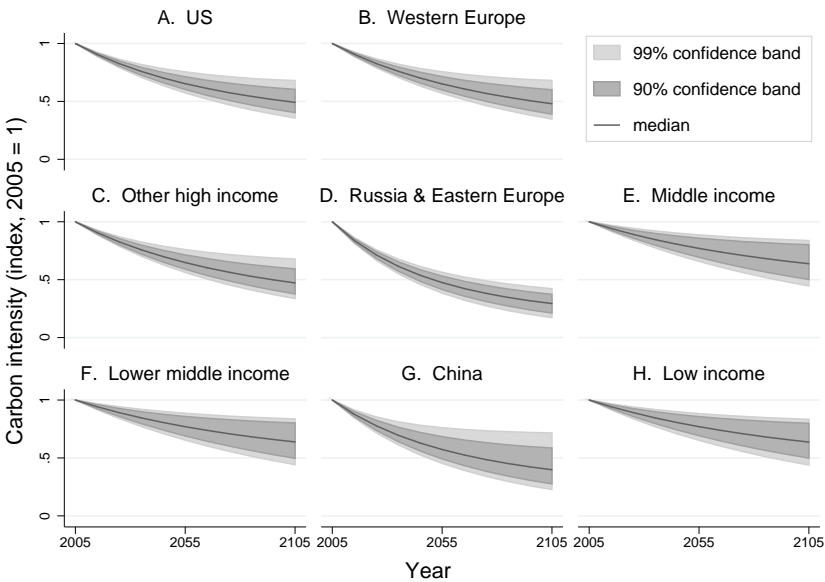


Figure 4.3: Forecasts for regional energy efficiency, Z_t^j

the fourth IPCC Assessment Report (IPCC 2007). In particular, we use the disaggregated (Tropical Americas, Africa and Asia) AR4 estimates for the 1990s given in Table 7.2, interpreting the uncertainty ranges as ± 2 standard deviations.¹¹ The figures for the LMI and especially LI regions are revised upwards; for the other regions, changes are minor. Exact figures are reported in Table 4A.3 in the Appendix.

Terrestrial biosphere As already mentioned in Section 4.2, we add a source of carbon emissions to the atmosphere, representing

¹¹We take Lower Income countries to correspond to Tropical Africa and most of Tropical Asia, attributing the remaining fractions of the figure for Asia to Malaysia, which counts as Middle Income, and to China. The figure for Tropical Americas is divided equally between Middle Income (Brazil) and Lower Middle Income (most other Latin American countries).

the processes whereby the global terrestrial biosphere becomes less prone to absorbing carbon as the climate changes. We incorporate this effect by adding a constant, but uncertain, flow of carbon into the atmosphere in each time period. Based on Friendlingstein et al., we calibrate the uncertainty about this flow such that it will add 40–400 GtC into the atmosphere by 2105, with a median addition of 150 GtC. As before, we use a gamma distribution to capture the asymmetry in the uncertainty. More precisely, the constant flow of carbon TBE_t in each time period is defined as

$$TBE_t = x^* + \gamma^*,$$

where γ^* follows a gamma distribution $\Gamma(k^*, \psi^*)$ with x^* , k^* and ψ^* calibrated so as to yield the desired result.

Climate sensitivity The climate sensitivity parameter, κ , measures the rise in temperature following a doubling of atmospheric CO₂ concentrations. Many estimates of this parameter lie in the region around 3.0, but uncertainty about the true value is substantial and many climate models generate an asymmetric distribution. As explained by Roe and Baker (2007), a distribution with a pronounced right tail is a natural outcome of uncertainty about the various feedback processes whereby higher temperatures raise the level of radiative forcing. Examples of such feedbacks are changes in the formation of water vapor and clouds, or in the earth's albedo (ability to reflect solar radiation). In the RICE model framework, it is natural to portray the uncertainty about such feedbacks as uncertainty about climate sensitivity. We generate the latter following Roe and Baker's (2007) reduced-form approach, postulating

that

$$\kappa = \Delta T_0 \frac{1}{1-f} ,$$

where f denotes an aggregate feedback parameter (the sum of the feedback coefficients from a number of processes) and ΔT_0 climate sensitivity in the absence of feedbacks. We set ΔT_0 deterministically at 1.2 °C and, following Roe and Baker, assume that f is normally distributed with mean of 0.65 and standard deviation of 0.10. To avoid extremely high values for κ , we truncate the distribution by cutting off 1% in the upper tail.¹² Passing this truncated normal through the highly nonlinear transformation (see also Roe and Bakers's Figure 1), we obtain a p.d.f. for κ similar in shape to the weighted p.d.f. reported in Figure 3 of Murphy et al. (2004). The mean and median of this theoretical distribution are about 3.71 and 3.41 respectively. Figure 4.4 plots the frequency of draws, the realized p.d.f. for κ , used in our simulations.

When we vary κ , the original values of the other heat-transfer-equation parameters ($\sigma_1, \sigma_2, \sigma_3$) may no longer appropriately reflect observed data. To remedy this, we vary σ_1 with the realized value of κ , according to a function derived from the data in Yohe et al. (2004, supporting online material, Table S1).¹³

¹²This means that we are excluding the possibility of “runaway climate change”— where feedback effects reinforce each other, resulting in a chaotic and entirely unpredictable climate. Such futures are not readily incorporated into the RICE framework.

¹³In particular, we adjust σ_1 in the temperature-adjustment equation (A.16), where T represents atmospheric temperature increase, T^L denotes the temperature increase of the lower oceans, and F is the change in radiative forcing relative to pre-industrial conditions. Climate sensitivity is captured by κ . We use the relationship between κ and σ_1 given in Yohe et al, adjusting the values of σ_1 to apply to the 10-year time periods used in DICE, and shifting the relationship such that σ_1 takes the default value of 0.226 for the default value of $\kappa = 3$.

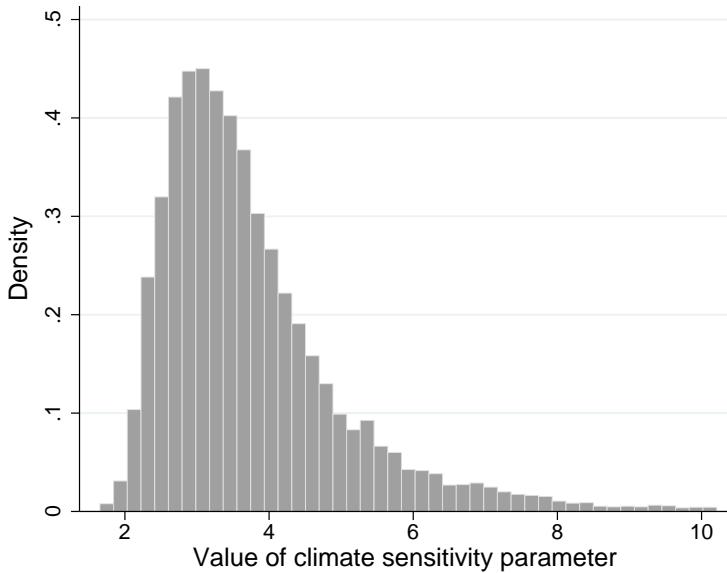


Figure 4.4: Distribution of draws on κ

Other uncertainties As mentioned above, we use a time-invariant (but uncertain) rate of time preference (ρ). The discount rate is assumed to have a normal distribution with standard deviation 0.33 around an average value of 1.5%. This way, random draws almost always fall within the range [0.5, 2.5] with most outcomes within [1, 2].

Uncertainties about the regional coefficient on carbon-energy in the production function β^J , the damage function parameters θ_1^J and θ_2^J , and the global carbon supply parameters ξ_2 , ξ_3 , and C_{MAX} were found to play a very minor role in the exercise carried out here. To keep matters simple, these parameters were kept deterministic.

4.4 Results

This section reports on selected results from our Monte Carlo simulations. To keep the presentation brief and non-taxonomic, we focus on the global variables of most interest.

World GDP Figure 4.5 shows future values of (the logarithm of) world GDP, measured in trillion USD (in 2005 prices).

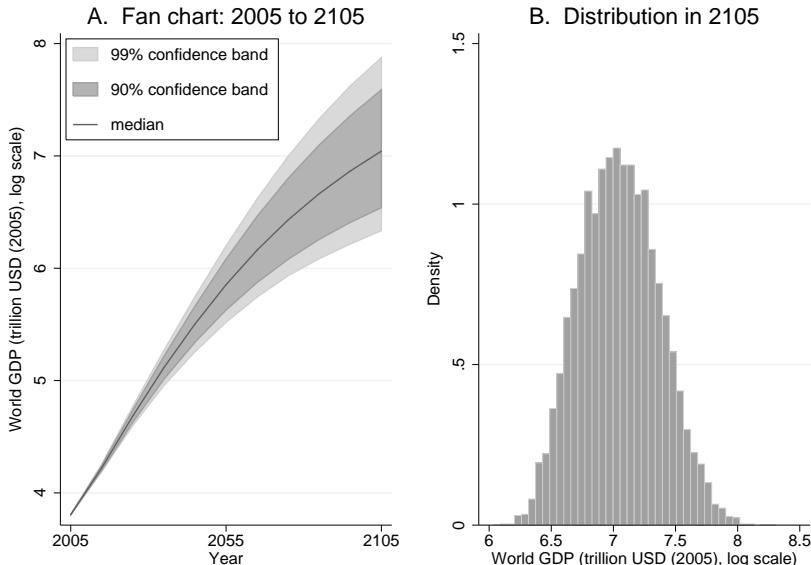


Figure 4.5: World GDP projections

Panel A illustrates the uncertainty with a fan chart, showing the median realization plus 90 and 99% confidence bands over the coming 100 years. Panel B shows a histogram of estimated world GDP 100 years ahead, which corresponds to an (unsmoothed) p.d.f. for that variable. More than half of the uncertainty about future

GDP levels stems from variability in TFP growth.¹⁴ But variability in population growth and other exogenous parameters matter too, as does the fact that we report world GDP *net of* damages caused by rising global temperatures (as defined in equations A.17 and A.18).

Inspection of the simulation data reveals that the realizations in the right tail of the world GDP distribution are due to some combination of high growth rates in the US, China or low-income countries; the US because of its high initial GDP level, and the latter two because of their population size.

Note that the ratio of world GDP at the top and bottom of the 99% confidence interval in 2105 is on the order of 4. This is a very large uncertainty indeed, when it comes to the implied emissions, *ceteris paribus*.

Industrial emissions Since production requires carbon energy as an input, higher GDP generally means higher industrial CO₂ emissions. However, substantial gains in energy efficiency allow incomes to grow without corresponding growth in emissions. Figure 4.6 illustrates future carbon emissions, measured in GtC. As the fan chart shows, uncertainty increases steadily over time, reflecting the increasing uncertainty about economic growth and energy efficiency. Annual emissions in the median BAU realization reach their maximum some seventy years ahead, at about five times their current level just below 10 GtC per year. Emissions then start to decline slowly, because carbon-saving technological change and the effect of higher carbon prices eventually outweigh the increased demand from higher world production. The upper part of the fan

¹⁴A Regression of world GDP in 2105 on the realizations of all 18 TFP growth parameters within the same Monte Carlo draw gives an adjusted R-square of 0.89

chart shows that in 500 of our 10001 simulations (i.e., 5%) industrial emissions peak at well above five times their current level.

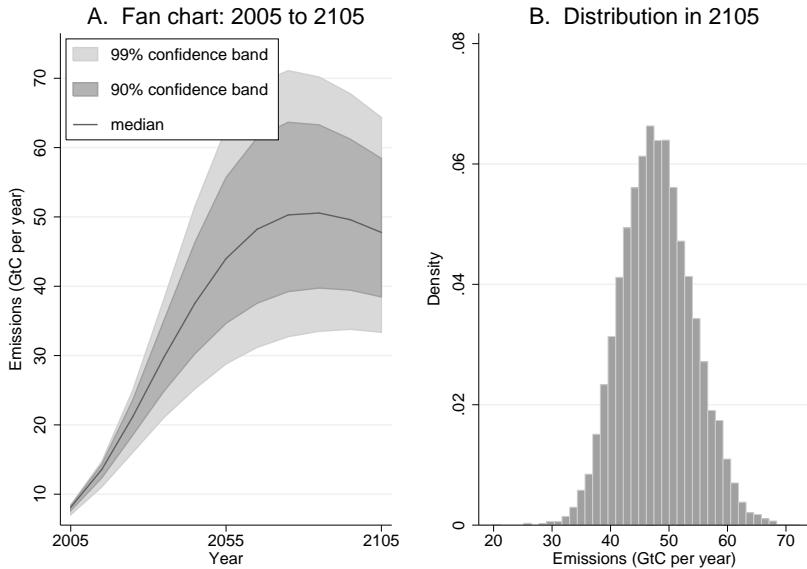


Figure 4.6: Projections for industrial emissions of CO_2

The 2105 histogram illustrates an upward skew in the emissions distribution. The data shows that the extreme realizations in the right tail come about when either China or the group of low-income countries experience large increases in GDP growth but little improvement in their energy efficiency. This is intuitive, given the population size of these regions, and their initial energy efficiency which is relatively poor.

Atmospheric CO_2 concentration Because emissions, even in the low-growth BAU paths, are far larger than the earth's natural absorption capacity, they keep adding to the atmospheric con-

centration of CO₂ measured in parts per million (ppm). This is illustrated in Figure 4.7.

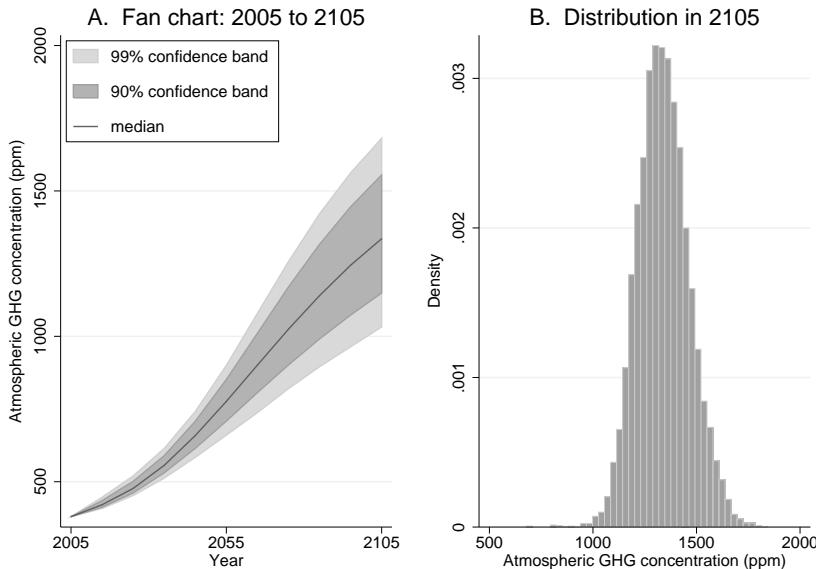


Figure 4.7: Projections for atmospheric GHG concentration

In the model, cumulated industrial CO₂ emissions are closely linked to atmospheric concentration of carbon dioxide. The two are not perfectly correlated, however, given the uncertain terrestrial biosphere effect and uncertain regional changes in land use. Nevertheless, extreme values for CO₂ concentrations reflect the same causes as high industrial emissions. Since the carbon cycle is a slow process, the atmospheric concentrations adjust to emissions only with a long time lag, so we do not see a slowdown in CO₂ concentration growth following the peak in emissions within the time frame of the fan chart.

The 90% confidence interval for 2105 ranges from 1150 to 1550

ppm, which is narrower than the 540–1440 ppm reported by Nordhaus and Yohe (1983, Figure 2.4) in the DICE model, although the median in the present study is considerably higher: 1335 vs. 770 ppm. Using the PAGE model, which does not model the world economy, Hope (2006), reports a much narrower interval (with a lower mean): roughly 700–925 ppm.

Global warming Figure 4.8 shows future increases in global mean surface temperatures, relative to the year 1900, measured in Centigrades (°C). A century from now, the median realization of temperature is around 4.5 °C above today’s temperature, which, in turn, is 0.71 °C above the 1900 level. Such a median temperature hike of over 5 °C relative to preindustrial levels is broadly consistent with the median increase of CO₂ concentration in Figure 4.7 to 1335 ppm from 280 ppm and a median climate sensitivity of approximately 3.4.¹⁵

The 90% confidence interval for temperature increase in 2105 is 4.2–6.6 °C. This range of warming for the next century is of the same magnitude as the range reported elsewhere, albeit derived with very different methods (see e.g., IPCC 2001, 2007). While the PAGE model study has a narrower interval for CO₂ concentrations than this study, the temperature relationship is reversed: the PAGE interval is nearly 4 °C wide, with a mean of about 4.3 °C (Hope 2006, Fig. 5). The reason seems to be that the heat-transfer specifi-

¹⁵Climate sensitivity refers to the long-run effect on temperature of a doubled CO₂ concentration, which is reached only with considerable time lag. This makes the predicted median rise in temperature until 2105 fall short of a predicted long-run increase (see equations A.15–16) of

$$\frac{\log(\frac{1335}{280})}{\log(2)} \cdot 3.4 = 7.7^\circ \text{ C.}$$

cation in PAGE makes atmospheric temperature converge towards its steady-state level much faster than the one in RICE.

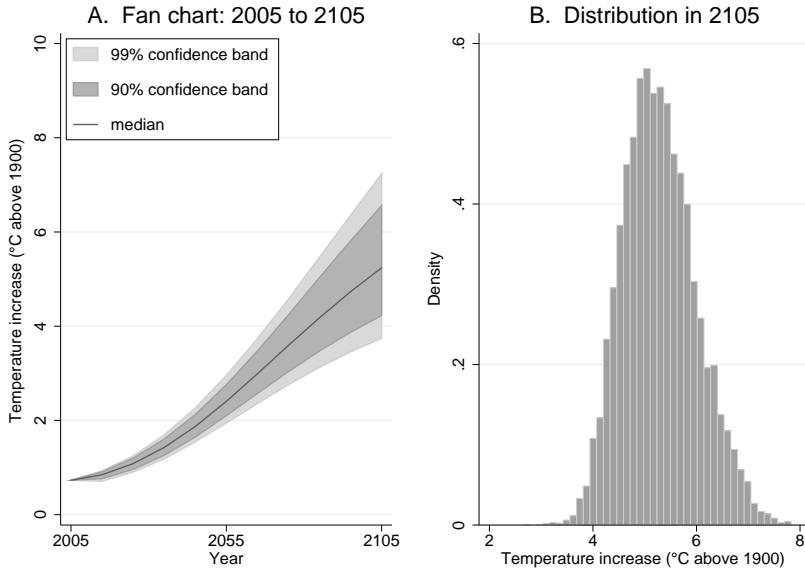


Figure 4.8: Projections for temperature increase

Notice that already the 5th percentile in Figure 4.8 lies clearly above 2 °C of warming in fifty years' time. Indeed, the histogram in panel B shows that nearly all of the 10001 temperature realizations a century from now lie above 2 °C. The European union has considered this temperature as the upper limit for manageable climate change as referred to in Article 2 of the UNFCCC. Even the most optimistic realizations in the leftmost tail for temperature should thus be a matter of serious concern.

Anyone who pays close attention to the optimistic tail, should seriously consider also the pessimistic tail of the distribution for climate change. As the histogram in Figure 4.8 shows, the highest

temperature realizations by 2105 involve a rise above 7 °C. As is well-known the effects of such temperature changes are very hard to predict, but may include eventual sea levels high enough to threaten major cities as London, Shanghai, or New York, and substantial risks of large-scale shifts in the Earth system, such as collapses of the Gulf Stream or the West Antarctic ice sheet.

Sources of uncertainty What causes variability of global temperature in our simulations? The climate sensitivity parameter, κ , is the most important source of uncertainty.¹⁶ This reflects the fact that climate sensitivity is the last link (in the RICE model) in the chain from human activity to global warming.

But socioeconomic uncertainty is very important as well. Figure 4.9 shows the distributions of global temperature after another Monte Carlo simulation with 10001 draws, where climate sensitivity is held constant at its mean value. A hundred years from now, the range for temperature outcomes is about 3.8 °C wide and the highest temperatures are well above 6 °C. The 99% confidence interval is 1.7 °C wide, to be compared with a corresponding confidence interval of 3.5 °C when we allowed for uncertain climate sensitivity in Figure 8.

Alternative futures What realizations of the future lie behind the most severe instances of global warming? As already mentioned, climate sensitivity above its mean is a very important one. But other reasons are more squarely rooted in the human system. One is lower than expected improvements of energy efficiency in regions with high production and dirty technologies: chiefly the US

¹⁶A regression of temperature increase in 2105 on values of draws on κ gives an adjusted R-square of 0.77.

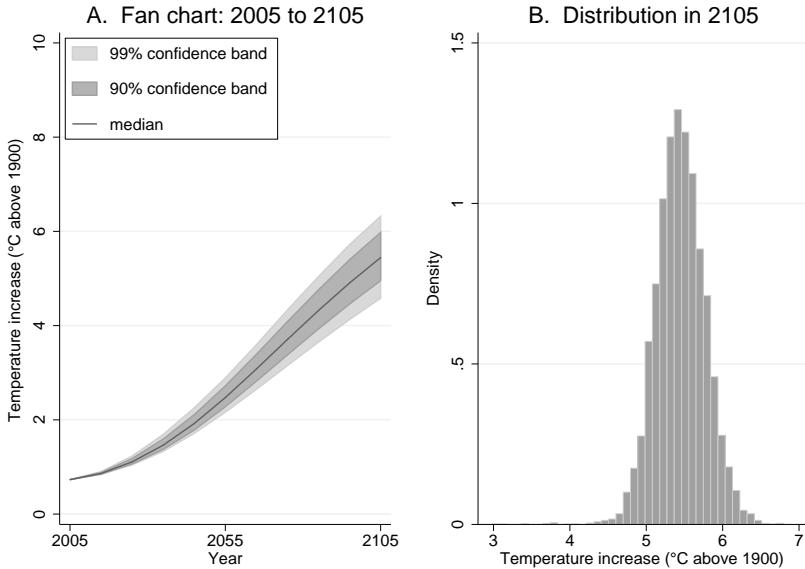


Figure 4.9: Temperature projections under certain climate sensitivity

and China. Another root is higher than expected economic growth in very populous regions, in particular the current low-income countries that host about half of the world population. To put it bluntly, futures in which today's unfortunate manage to permanently break out of poverty (without large improvements in energy-saving technologies) have substantially higher global warming. Ironically, resolution of one of today's most pressing global problems aggravates another one.

Figure 4.10 illustrates the interplay between different sources of climate change. Panel D plots the temperature increase a hundred years from now against the randomly drawn value of the climate-sensitivity parameter (κ). A log curve approximates the relationship well, but the variability around this curve stems from variation

in other parameters. We use the four highlighted observations – labeled 1 through 4 in all plots – to discuss how (sources of) GDP growth and energy efficiency matter for climate change. To make the figure readable, we are displaying only a random sample of 2000 out of the 10001 Monte Carlo draws. Note that the temperature axis has the same scale in all four plots.

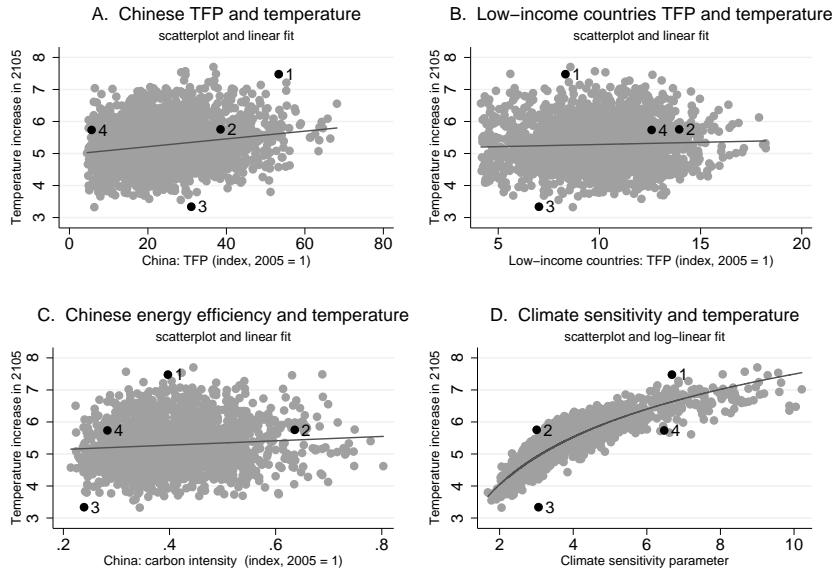


Figure 4.10: Illustration of sources of variability.

Observation 1 is an outlier on the upside as it entails a temperature hike of 7.5 °C. This is clearly associated with a growth spurt in China with TFP at the 98th percentile level, as illustrated in panel A. On top of this carbon intensity in the low-income group of countries also plays a role: its realized value is at the 99th percentile (not pictured). This can be compared to Observation 4, which has about the same climate sensitivity (see panel D) as Observation 1,

but a temperature rise almost 2 °C smaller. This is largely due to how China develops. Here productivity growth is exceptionally slow, but energy-saving technology experiences a significant development: as shown in Panel A, Chinese TFP is at the 1st percentile, and as shown in Panel C carbon intensity is at the 6th percentile. TFP growth in low-income countries is quite strong, at the 84th percentile in Panel B, but China's technological development plays a more important role.

Observation 2 is again a substantial outlier but at a lower level of climate sensitivity. Global warming amounts to 5.6 °C, largely driven by strong TFP growth in low-income countries (94th percentile, see Panel B), as well as very high Chinese carbon intensity (97th percentile, see Panel C). This can be compared to Observation 3, with the same climate sensitivity but 2.2 °C less warming than Observation 2. What drives the result is an extremely favorable development of Chinese energy efficiency (below the 1st percentile, see Panel C), together with a moderate TFP growth globally – in all world regions other than China, TFP levels are at the 15th percentile or lower.

These alternative futures illustrate in a more concrete way than Figure 4.9 how alternative socioeconomic developments may contribute a great deal to the uncertainty about future global warming.

Policy implications How does the uncertainty about the sources of future climate change map into optimal policy? A proper analysis of this question would require us to consider a climate-economy model with uncertain outcomes, and to solve a problem where uncertainty plays an essential role. RICE is not such a model, since each model scenario really assumes a perfect foresight path. With this caveat in mind, let us nevertheless briefly present the results

form two alternative sets of simulations. In those, we run the model in optimization, rather than Business-as-usual mode – for each Monte Carlo draw of the model parameters – and solve for the optimal path of global carbon taxes.

Figure 4.11 shows the distributions of optimal carbon taxes in the wake of full model uncertainty including the important climate sensitivity parameter. In the median model run, the global carbon tax rises from its initial level around 38 USD per ton of carbon, towards a level just below 1000 USD per ton a hundred years hence. Moreover, the distribution of optimal carbon taxes has a clear upward skew: in more than 5% of the runs, the 2105 tax is above 2000 USD per ton.

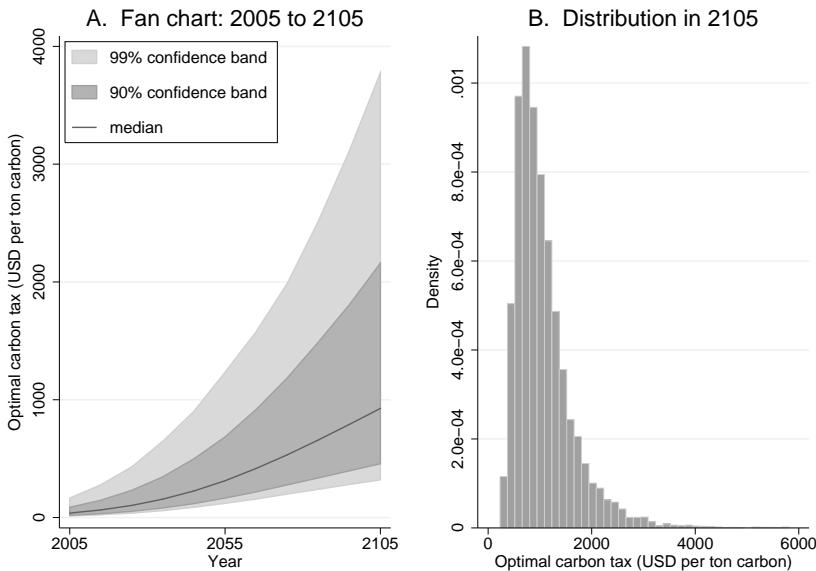


Figure 4.11: Optimal carbon taxes (full uncertainty)

Figure 4.12 shows the same distributions, when there is only

socioeconomic uncertainty. These distributions are almost identical to the ones in Figure 4.11. Evidently, the socioeconomic futures with very high levels of emissions entail very strong incentives for policy intervention.

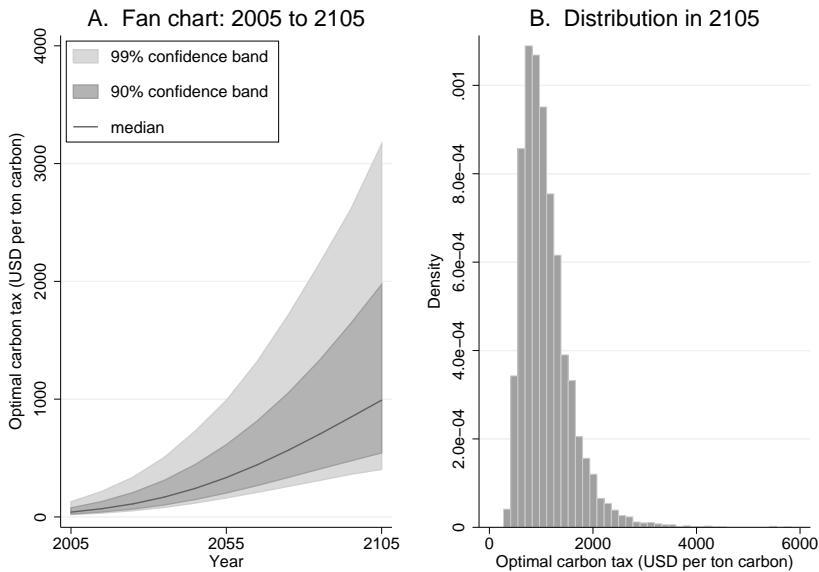


Figure 4.12: Optimal carbon taxes under certain climate sensitivity

4.5 Conclusions

On the methodological side, our paper illustrates a way to analyze uncertainty about future climate change, which includes the most important determinants in the human system as well as the natural system. Our results suggest that uncertainties about relations in the economic system can play a major role. More research, with less stylized assumptions and more comprehensive climate-economy

models with explicit uncertainty, should follow.

On the substantive side, our simulations rely on BAU assumptions regarding energy taxes and other means of mitigating climate change. The results clearly show that – absent serious future mitigation efforts – global warming will be substantial even under very favorable circumstances.

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A4 Appendix

This Appendix begins with a list of the full set of equations in the underlying RICE model. It also includes a list of all the model's variables and the distributions for the parameters we use in the Monte Carlo simulations.

RICE model equations

- $$(A.1) \quad W^J = \sum_t U[c_t^J, L_t^J] R_t$$
- $$(A.2) \quad R_t = \prod_t [1 + \rho]^{-10t}$$
- $$(A.3) \quad U[c_t^J, L_t^J] = L_t^J \{\ln[c_t^J]\}$$
- $$(A.4) \quad Q_t^J = \Omega_t^J \left\{ A_t^J (K_t^J)^\alpha (L_t^J)^{1-\beta^J-\alpha} (ES_t^J)^{\beta^J} - c_t^{E,J} ES_t^J \right\}$$
- $$(A.5) \quad g_t^{L,J} = g_0^{L,J} \exp(-\delta_t^{L,J}), \quad g_0^{L,J} \text{ given}$$
- $$L_t^J = L_0^J \exp \left[\int_0^t g_s^{L,J} \right], \quad L_0^J \text{ given}$$
- $$(A.6) \quad g_t^{A,J} = g_0^{A,J} \exp(-\delta_t^{A,J}), \quad g_0^{A,J} \text{ given}$$
- $$A_t^J = A_0^J \exp \left[\int_0^t g_s^{A,J} \right], \quad A_0^J \text{ given}$$
- $$(A.7) \quad ES_t^J = Z_t^J E_t^J$$
- $$g_t^{Z,J} = g_0^{Z,J} \exp(-\delta_t^{Z,J}), \quad g_0^{Z,J} \text{ given}$$
- $$Z_t^J = Z_0^J \exp \left[\int_0^t g_s^{Z,J} \right], \quad Z_0^J = 1$$
- $$(A.8) \quad Q_t^J = C_t^J + I_t^J; \quad c_t^J = C_t^J / L_t^J$$
- $$(A.9) \quad K_t^J = K_{t-1}^J (1 - \delta_K)^{10} + 10 \times I_{t-1}^J, \quad K_0^J \text{ given}$$
- $$(A.10) \quad c_t^{E,J} = q_t + mku p^{E,J}$$
- $$(A.11) \quad CumC_t = CumC_{t-1} + 10 \times E_t; \quad E_t = \sum_J E_t^J$$
- $$(A.12) \quad q_t = \xi_1 + \xi_2 [CumC_t / CMAX]^{\xi_3}$$
- $$(A.13) \quad LU_t^J = LU_0^J (1 - \delta_{LU})$$
- $$ET_t = \sum_J (E_t^J + LU_t^J) + TBE_t; \quad TBE_t = x^* + \gamma^*$$
- $$(A.14) \quad M_t = 10 \times ET_{t-1} + \phi_{11} M_{t-1} + \phi_{21} M_{t-1}^U, \quad M_0 \text{ given}$$
- $$M_t^U = \phi_{12} M_{t-1} + \phi_{22} M_{t-1}^U + \phi_{32} M_{t-1}^L, \quad M_0^U \text{ given}$$
- $$M_t^L = \phi_{23} M_{t-1}^U + \phi_{33} M_{t-1}^L, \quad M_0^L \text{ given}$$
- $$(A.15) \quad F_t = \eta \{ \ln[M_t/M_t^{PI}] / \ln(2) \} + O_t$$
- $$O_t = -0.1965 + 0.13465 t \quad t \leq 10$$
- $$= 1.15 \quad t > 10$$
- $$(A.16) \quad T_t = T_{t-1} + \sigma_1 \{ F_t - \frac{\eta}{\kappa} T_{t-1} - \sigma_2 [T_{t-1} - T_{t-1}^L] \}, \quad T_0 \text{ given}$$
- $$T_t^L = T_{t-1}^L + \sigma_3 [T_{t-1} - T_{t-1}^L], \quad T_0^L \text{ given}$$
- $$\kappa = 1.2/(1-f)$$
- $$\sigma_1 = \left[1 - \left[1 - \left(\frac{s_1 \kappa}{\kappa - s_2} \right) \left(\frac{\eta}{\kappa} + \sigma_2 \right) \right]^{10} \right] + \left[\frac{\eta}{\kappa} + \sigma_2 \right]^{-1} + s_3$$
- $$(A.17) \quad D_t^J = \theta_1^J T_t + \theta_2^J T_t^2$$
- $$(A.18) \quad \Omega_t^J = 1 / [1 + D_t^J]$$

List of variables and parameters

| Exogenous variables and parameters | |
|------------------------------------|---|
| L_t^J | Population (millions) |
| R_t | Social time preference discount factor |
| ρ | Social time preference discount rate |
| α | Elasticity of output w. r. t. capital |
| β^J | Elasticity of output w. r. t. energy services |
| A_t^J | Total factor productivity (TFP) |
| $g_t^{L,J}$ | Population growth rate (per decade) |
| $g_0^{L,J}$ | Population growth rate in initial period |
| $\delta^{L,J}$ | Rate of decline of g_t^L |
| $g_t^{A,J}$ | TFP growth rate (per decade) |
| $g_0^{A,J}$ | TFP growth rate in initial period |
| $\delta^{A,J}$ | Rate of decline of g_t^A (per decade) |
| A^J | Steady-state level of TFP (relative to 2005) |
| Z_t^J | Energy efficiency |
| Z_0^J | Energy efficiency in initial period |
| $g_t^{Z,J}$ | Energy efficiency improvement rate (per decade) |
| $g_0^{Z,J}$ | Energy efficiency improvement rate in initial period |
| Z^J | Steady-state level of energy efficiency (2005 = 1) |
| $\delta_t^{Z,J}$ | Rate of decline of g_t^Z (per decade) |
| δ_K | Rate of depreciation of capital (per year) |
| K_0^J | Initial capital stock |
| $mkup^{E,J}$ | Carbon services markup (1000 USD (2005) per ton carbon) |
| ξ_1 | Marginal cost of carbon extraction in 2005 |
| ξ_2, ξ_3 | Parameters in cost-of-extraction function |
| $CMAX$ | Point of diminishing returns in carbon extraction (GtC) |
| LU_t^J | CO ₂ emissions from land-use changes (GtC per year) |
| LU_0^J | Emissions from land-use changes in initial period |
| δ_{LU} | Rate of decline of LU_t^J (per decade) |
| TBE_t | Emissions due to the terrestrial biosphere effect |
| x^*, γ^* | Parameters in terrestrial biosphere process |
| η | Increase in forcing due to doubling of CO ₂ concentrations |
| O_t | Forcings from other (exogenous) GHGs |
| κ | Climate sensitivity parameter |
| f | Parameter in the process generating κ (Roe and Baker) |
| σ_1 | Speed of adjustment for atmospheric temperature |
| σ_2 | Coefficient of heat loss from atmosphere to deep oceans |
| σ_3 | Coefficient of heat gain from atmosphere to deep oceans |
| s_1, s_2, s_3 | Heat-transfer equation adjustment parameters |
| θ_1^J, θ_2^J | Damage function coefficients |

List of variables and parameters, contd.

| Initial conditions (temperatures relative to 1900): | |
|--|---|
| M_0 | Initial stock of carbon in the atmosphere (GtC) |
| M_0^U | Initial stock of carbon in the upper ocean (GtC) |
| M_0^L | Initial stock of carbon in lower ocean (GtC) |
| M^{PI} | Preindustrial stock of carbon in atmosphere (GtC) |
| T_0 | Initial atmospheric temperature ($^{\circ}\text{C}$) |
| T_0^L | Initial ocean temperature ($^{\circ}\text{C}$) |
| Carbon cycle transition coefficients (percent per decade): | |
| ϕ_{11} | Atmosphere to atmosphere |
| ϕ_{12} | Atmosphere to upper box |
| ϕ_{21} | Upper box to atmosphere |
| ϕ_{22} | Upper box to upper box |
| ϕ_{23} | Upper box to lower box |
| ϕ_{32} | Lower box to upper box |
| ϕ_{33} | Lower box to lower box |
| Endogenous variables: | |
| W^J | (Regional) Welfare |
| U_t^J | (Regional) Utility |
| c_t^J | Per-capita consumption |
| Q_t^J | Output (trillion 1990 USD per year) |
| K_t^J | Capital stock (trillion 1990 USD) |
| ES_t^J | Energy services from fossil fuels (GtC per year) |
| $c_t^{E,J}$ | Market price of carbon energy (1000 USD per ton) |
| E_t^J | Industrial CO ₂ emissions (GtC per year) |
| C_t^J | Consumption (trillion 1990 USD per year) |
| I_t^J | Investment (trillion 1990 USD per year) |
| q_t | Cost of extraction of carbon energy (1000 USD per ton) |
| $CumC_t$ | Cumulative industrial carbon emissions (GtC) |
| ET_t | Total global carbon emissions (GtC per year) |
| M_t | Atmospheric CO ₂ concentration (GtC) |
| M_t^U | CO ₂ stock in the upper oceans and biosphere (GtC) |
| M_t^L | CO ₂ stock in the upper oceans (GtC) |
| F_t | Increase in forcing relative to preindustrial (W/m^2) |
| T_t | Atmospheric temperature increase since 1900 ($^{\circ}\text{C}$) |
| T_t^L | Temperature increase in lower oceans since 1900 ($^{\circ}\text{C}$) |
| D_t^J | Climate change damages (proportion of output) |

Table 4A.1: Global parameters: updated values and imposed uncertainty

| name | original value | updated value | standard deviation ¹ |
|------------|----------------|---------------|---------------------------------|
| ρ | 0.03 | 0.015 | 0.0033 |
| x^* | — | 0.2129 | — |
| γ^* | — | 2 | 2 |
| f | — | 0.65 | 0.10^3 |
| κ | 2.9078 | 4 | 4 |
| σ_1 | 0.226 | 5 | 5 |
| s_1 | — | 0.008229 | — |
| s_2 | — | 1.313 | — |
| s_3 | — | 0.08989 | — |
| M_0 | 735 | 811 | — |
| M_0^U | 781 | 820 | — |
| T_0 | 0.43 | 0.71 | — |
| ξ_1 | 113 | 137 | — |

¹ Probability distributions are standard normals unless indicated.² Distributed following a gamma distribution $\Gamma(k^*, \psi^*)$, where $k^* = 4.660$ and $\psi^* = 0.7038$.³ The distribution is truncated in the right tail; see discussion in Section 4.3 above.⁴ See discussion in Section 4.3 and Figure 4.4 above.⁵ See equation (A.16).

Table 4A.2: Unchanged and deterministic global parameters

| name | value | name | value | name | value |
|---------------|-------|------------|-------|-------------|---------|
| α | 0.30 | η | 4.10 | ϕ_{11} | 0.66616 |
| δ_K | 0.10 | σ_2 | 0.440 | ϕ_{12} | 0.33384 |
| δ_{LU} | 0.10 | σ_3 | 0.02 | ϕ_{21} | 0.27607 |
| $CMAX$ | 6000 | M_0^L | 19230 | ϕ_{22} | 0.60897 |
| ξ_2 | 700 | M^{PI} | 596.4 | ϕ_{23} | 0.11496 |
| ξ_3 | 4.00 | T_0^L | 0.06 | ϕ_{32} | 0.00422 |
| | | | | ϕ_{33} | 0.99578 |

Table 4A.3: Regional parameters: updated values and imposed uncertainty

| name | USA | EUR | OHI | REE | MI | LMI | CHI | LI |
|----------------|----------------------|------------------------|------------------------|-----------------------|----------------------|----------------------|------------------------|------------------------|
| LU_0^J | 0 (0) | 0 (0) | 0 (0) | 0 (0) | .40 (.058) | .35 (.05) | .05 (.0083) | 1.00 (.15) |
| L_0^J | 295.6 (-) | 396.9 (-) | 202.64 (-) | 326.3 (-) | 375.5 (-) | 652.7 (-) | 1306.3 (-) | 2842.8 (-) |
| $g_0^{L,J}$ | 0.1034 (0.0199**) | -0.0127* (0.0947**) | -0.0082* (0.0914**) | -0.0437 (0.0356**) | 0.1508 (0.0149**) | 0.1481 (0.0217**) | -0.0290* (0.1137**) | 0.2000 (0.0281**) |
| L^J | 468.5 (1128.95**) | 406.0 (504.70**) | 216.6 (138.97**) | 225.0 (44.16**) | 532.6 (473.19**) | 992.4 (900.63**) | 1442.0 (768.52**) | 7278.0 (12490.97**) |
| g_0^{AJ} | 0.1095 (0.0126) | 0.1300 (0.0140) | 0.1300 (0.0140) | 0.9388 (0.0597) | 0.1512 (0.0391) | 0.1894 (0.0287) | 0.6403 (0.0556) | 0.3879 (0.0240) |
| A^J | 11.19 (24.92) | 13.41 (41.98) | 11.74 (36.74) | 11.71 (2.02) | 12.66 (59.57) | 10.13 (59.51) | 10.08 (33.97) | 17.66 (23.98) |
| $g_0^{Z,J}$ | -0.1321 (0.0077) | -0.1365 (0.0098) | -0.1183 (0.0105) | -0.1836 (0.0100) | -0.0614 (0.0102) | -0.0614 (0.0102) | -0.2013 (0.0240) | -0.0614 (0.0102) |
| Z^J | 0.3269 (0.1449) | 0.2373 (0.1754) | 0.1462 (0.1753) | 0.1583 (0.0719) | 0.2397 (1.6245) | 0.2290 (1.6245) | 0.1381 (.2328) | 0.2318 (1.6245) |
| β^J | 0.091 (-) | 0.057 (-) | 0.059 (-) | 0.08 (-) | 0.087 (-) | 0.053 (-) | 0.096 (-) | 0.074 (-) |
| $mkup^{E,J}$ | 472.66 (-) | 608.59 (-) | 402.34 (-) | 46.09 (-) | 322.66 (-) | 50.78 (-) | 13.28 (-) | 69.53 (-) |
| $\theta_{J,1}$ | -0.0026 (-) | -0.001 (-) | -0.007 (-) | -0.0076 (-) | -0.0039 (-) | -0.0022 (-) | -0.0041 (-) | .01 (-) |
| $\theta_{J,2}$ | 0.0017 (-) | 0.0049 (-) | 0.003 (-) | 0.0025 (-) | 0.0013 (-) | 0.0026 (-) | 0.002 (-) | 0.0027 (-) |

Mean values are reported, standard deviations in parentheses, unless otherwise indicated. The values of LU_0^J , L_0^J , $g_0^{L,J}$ and g_0^{AJ} have been updated; original values are not reported. The values given for A^J and Z^J are relative to 2005 levels. All parameters follow normal distributions, truncated when necessary, except where indicated. All rates are per decade. *'Initial' growth rates here refers to 2045, see Section 4.3 for details. **These parameters follow asymmetric (gamma) distributions; the values reported here are the 95% confidence intervals.

Chapter 5

Last In, First Out? Estimating the Effect of Seniority Rules in Sweden*

5.1 Introduction

This paper empirically investigates how employment protection affects firms' employment behaviour. How employment protection affects the labour market functioning is an academically as well as politically controversial subject (see, e.g., OECD, 2004). The

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main motivation for employment protection is to protect workers from unfair dismissals. Employment protection is also welfare arrangement that provides economic security to workers, ultimately increasing the value of work. Opponents argue that more lenient protection would improve the efficiency of the labour market. How employment protection affects firms' employment behaviour is vital to the design of policy and to the understanding of labour market behaviour.

Previous empirical research often relies on cross-country variation by correlating some strictness index measure of employment protection with the employment level. One major challenge with cross-country studies is to obtain comparable measures of strictness, since legislation varies widely across countries (see, e.g., discussion in Howell et al., 2007; Kugler 2007). We therefore argue that it is also important to evaluate certain aspects of the employment protection legislation. One such aspect is seniority rules, which protect workers with long seniority.

Seniority rules exist in several countries (OECD, 2003). In France, Italy, Mexico and the Netherlands, the law stipulates some kind of seniority-based rules regarding dismissals. In Finland and the US, seniority rules are often laid down in collective agreements. In Norway and the UK, seniority rules are not stipulated by law or laid down by collective agreement but often used as an accepted custom. In the Netherlands and in Sweden the seniority rule is formulated as a 'last-in-first-out' (LIFO) principle. In Sweden this LIFO principle is one main cornerstone in the Swedish Employment Protection Act (EPA; Lagen om anställningsskydd, SFS 1982:80, 22 §). The principle states that the worker who was employed last has to go first when a firm downsizes. The LIFO principle was reformed in January 2001 such that employers with ten or fewer

employees were allowed to exempt two workers from the seniority rule.

Like Sweden, most European countries have a more lenient employment protection for firms below a certain size. For example, workers in France at firms with fewer than ten employees are less protected against layoffs. In Italy, workers in firms with fewer than 16 employees are less protected. In Spain, redundancy payments are lower for firms with fewer than 25 employees. Despite the fact that small firms represent a substantial share of all firms and stand for a large share of total employment, there is limited knowledge how such exemption rules affect firms' employment behaviour.¹ Moreover, the consequences of seniority rules on firms' employment behaviour have not been examined at all.

The purpose of this paper is to estimate whether the exemption rule, which implied that firms with ten or fewer employees could exempt two workers from the LIFO principle, had any effects on firm's employment behaviour. Theory suggests that less protection—the exemption rule in this case—increases worker flows through increased hires and separations. The effect on the intensive margin, i.e., the effect on firm's net employment, is therefore a priori ambiguous. The exemption rule may also affect the extensive margin, i.e., the likelihood that firms enter or exit the market. Therefore, we will analyse effects of the exemption rule on workers flows followed by an analysis of effects on the extensive margin.

We use a matched employer-employee panel data set for the period 1996–2005. The break in the policy for firms of size ten provides a natural setting for analysing the impact of the exemp-

¹The overall evidence from the few existing studies suggest very small effects (Bauer et al. 2007; Borgarello et al. 2004; Schivardi and Torrini 2004; Verick 2004. See also the empirical overview in Section 2.

tion rule using a difference-in-difference approach, where treated firms are firms with 2–10 employees which could exempt two workers from the LIFO principle. The control group consists of firms with 11–15 employees. Results clearly show that the key identifying assumption of parallel trends in outcomes between the treatment and control groups is satisfied. We find that both hires and separation probabilities significantly increased for small firms relative to large firms. The reform increased the probability of getting a new hire in a small firm by 1.7 percentage points after the reform. This corresponds to an increase in the share of new hires by 5%. The effect on separations is of equal magnitude. Results are robust to the inclusion of sector-year and region-year effects as well as to firm size-specific cyclical effects.

We relate our effects on hires and separations to the average yearly variation in hires and separations of small firms, which amounts to 1 and 0.5 percentage points, respectively. Thus, the increase in hires due to the reform is below twice the yearly variation in the share of new hires. For separations the reform effect is just over three times this variation. This suggests that there are important effects on workers flows but they are not overwhelmingly large. As regards the extensive margin, we find no effects.

The paper contributes to the literature on employment protection and firms' employment behaviour by focusing on the effect of a seniority rule on firms' behaviour. Knowledge of how exemption rules in general affect firms' employment behaviour is rare.² Moreover, many studies on employment protection and firm behaviour often rely on small and un-representative data sets (see Schivardi

²Two previous studies using the LIFO reform in January 2001 found that individual sick reporting decreased at firms which could exempt two workers from the seniority rule (see Lindbeck et al. 2006, Olsson 2009).

and Torrini 2004). This makes it difficult to generalise from results and it is not always clear whether non-robust results are due to truly insignificant effects or due to a small number of observations. This is not the case in our paper since we have access to data on the whole population of firms and workers.

The remainder of the paper is organized as follows. In Section 2 we present an overview of the theory and empirical literature on worker flows. Section 3 describes the employment protections legislation and the LIFO principle in Sweden. Data and the empirical strategy are outlined in Sections 4 and 5, respectively. Results are presented in Section 6 and conclusions are given in Section 7.

5.2 Theory and empirical literature on worker flows

5.2.1 Theoretical background on employment protection

Legislation often states that a layoff must be based on objective grounds, and the criteria for objective grounds are formulated in the legislation. Dismissal legislation also includes other more direct costs for layoffs such as redundancy pay, notice periods and seniority rules, which restrict the employers' influence over whom to lay off.

Besides protecting workers from unfair dismissals, it is often argued that the main purpose of dismissal protection is to protect workers from income fluctuations generated by job losses. This is the insurance argument for employment protection, where insurance improves worker welfare. The reason why legislation is re-

quired to provide insurance is analogous to the argument in favour of for example social insurance—insurance markets affected by moral hazard and adverse selection do not provide sufficient coverage (Pissarides, 2001). Furthermore, employment protection might also improve the employer-employee relationship (motivation, willingness to co-operate etc.), which in turn could enhance productivity. Dismissal protection might also raise worker productivity due to improved training incentives, on the employer as well as on the worker side, which increase human capital (Mortensen and Pissarides, 1999). Lindbeck (1994) discusses seniority rules, suggesting that they are used to protect workers with high seniority, who have become less productive in old age, from being made redundant. Employment protection may influence a wide range of outcomes such as labour force participation, employment, employment volatility, firm entry and exit, productivity, wages, GDP growth, innovations, etc. The brief overview below will focus solely on the theoretical predictions on workers flows.

Lay-off costs are often modelled as a tax on layoffs. Lazear (1990) argues that such taxes can be avoided by an efficient labour contract where an *ex ante* transfer—such as a wage reduction—is made from the worker to the employer. In practice, however, with imperfect labour markets and rigid wages (including minimum wages and wages set by collective agreements), dismissal legislation will impose adjustment costs for the employer. As such, theory predicts that lay-off protection decreases hires as well as separations. Since fewer workers are hired, this reduces the exit rate from unemployment. At the same time, fewer workers enter unemployment through reduced separations. Taken together, the net effect on the employment level (or unemployment) is therefore *a priori* ambiguous. The predicted effect on worker flows, on the other hand, is

unambiguously negative.

Seniority rules are similar to other forms of dismissal protection, in that they resemble lay-off taxes. Introducing a LIFO principle will make it more costly to lay off any worker other than the one who was employed last. Specifically, the cost consists in having to lay off also the more recently hired employees, who may be quite valuable to the firm, or alternatively having to negotiate with the union, which will likely entail time as well as monetary costs. It is not difficult to think of situations where employers may want to keep the worker who is ‘last in’, and instead lay off workers with longer tenure. Firms subject to a LIFO requirement should therefore be more careful in their hiring decisions, in order to avoid getting stuck with low-quality matches that are costly to lay off. Ex ante uncertainty about worker quality may play an important role here: if a worker’s productivity and/or match quality is subject to uncertainty which takes quite some time to be resolved, bad matches may be identified as such only after they are no longer the last employed worker. Alternatively, one may think of a setting where workers’ match quality can experience random changes over time, like in the model developed in Kugler and Saint-Paul (2004).

Theory also predicts that dismissal protections have differential effects on different groups of workers (Bertola et al. 2007). Redundancy pay and notice periods often increase with seniority, which means higher lay-off costs for workers with longer seniority, such as older workers. Kugler and Saint-Paul (2004) present a model where higher lay-off costs lead to worsened employment opportunities for job seekers who appear more risky, from the perspective of the employer. It may be relatively more difficult to verify the productivity of workers with a lower attachment to the labour market, such as young, immigrant, female and disabled workers. For example, it

may be more difficult to assess the productivity of younger workers with little labour market experience; employers may find it hard to evaluate degrees taken in other countries; and employers may be more uncertain about women's presence at work since they, on average, have longer periods with parental leave and, on average, higher sickness absence than men (this holds at least for Sweden). Workers with more uncertain productivity have smaller chances of being hired if risk averse employers see them as a more risky investment. Taken together, these theoretical considerations suggest that the exemption rule could improve employment opportunities for younger, female and foreign born workers. For older workers, the exemption rule might instead increase separations.

5.2.2 Empirical literature on worker flows

Empirical evidence on the impact of employment protection on the employment level and worker flows does not clearly support the theoretical predictions (see surveys by Addison and Teixeira, 2005, and Kugler, 2007). A vast majority of the empirical literature follows Lazear (1990) in exploiting cross-country variation in index values for the strictness of employment protection legislation. The only robust empirical finding in this literature is that more strict employment protection reduces flows into and out of unemployment. The results concerning aggregate employment are not robust—estimated effects point in different directions. A number of studies, however, suggest that dismissal protection reduces employment and increases unemployment for younger workers and in some cases also female workers (see e.g., Bassanini and Duval 2006, Bertola et al. 2007; Botero et al. 2004; Heckman and Pagés-Serra 2000; Skedinger 1995).

In addition to the problem of finding comparable measures of strictness across countries, cross-country studies suffer from other identification problems. It is difficult to handle other important differences than differences in legislations between countries which may help to explain the estimated relationship between employment protection and worker flows. Some of the aggregated studies therefore exploit time variation within countries. Employment protection usually shows very little variation over time, however. It is also the case that fluctuations in employment and the unemployment rate might cause changes in legislation, making employment protection endogenous due to reversed causality.

In recent years there have been an increasing number of studies examining the impact of employment protection at the firm or worker level. These studies either exploit reforms that change the dismissal legislation for firms under a certain number of workers, or changes in legislation that occur at different points in time across regions. Kugler and Pica (2008) exploit a reform in Italy where firms below size fifteen were exempted from legislation prior to 1990 but were subject to the legislation from that year. According to their results, worker flows decreased for smaller firms relative to large firms when they were made subject to the legislation. Kugler (2004), exploiting a reform in Colombia, found that the flows in and out of unemployment increased when employment protection was more liberal. Results from Autor et al. (2007) support this finding. Based on US data they show that worker flows decreased in states that implemented a stricter employment protection than the so-called employment-at-will principle. There are exceptions to these results, however. Martins (2009) found no effects on worker flows when studying a reform in Portugal in 1989, where firms with at most twenty workers get more lenient protec-

tion legislation. Germany changed its dismissal legalisation at two times during the 1990s. Until 1996, firms with five or fewer workers had more lenient protection legislation. In 1996, this exemption was extended to firms with at most ten workers. In 1999, the lower threshold of five workers was re-introduced. German studies exploiting these reforms find no or very small effects on worker flows (see Bauer et al., 2007).

Taken together, results exploiting reforms using micro-data in different countries in order to estimate effects on worker flows are mixed. It should be emphasized, however, that it is not always straightforward to compare results from different countries, as it is in general difficult to calculate how the reform really changed the costs for firms. If changes in firms' adjustment costs are small it is reasonable to find small reform effects.

As regards studies focusing on effects on the employment level, results are mixed. Some studies show that stricter employment protection reduces the employment level (see e.g., studies by Autor et al. (2004, 2006) on US data, Kugler et al. (2003) who use data from Spain, Martins (2009) who uses data from Portugal, and Schivardi and Torrini (2004) using data from Italy). Miles (2000), on the other hand, shows no employment effects using data for the US. Autor et al. (2007) find positive effects for the US, and a German study by Verick (2004) also shows positive effects.

5.3 Employment protection and LIFO in Sweden

5.3.1 The Employment Protection Act

The 1982 EPA stipulates that the default type of employment contract is a permanent contract. Fixed-term contracts are allowed if warranted by the nature of the work to be done, and trial periods of up to six months are allowed in connection with permanent contracts. Workers may be fired for gross misconduct, or they may be laid off, either because of ‘shortage of work’ or due to reasons pertaining to the worker personally. The latter is rarely used in practice, and instead it is ‘shortage of work’ that is the principal justification for laying off workers in most cases. A newly employed worker has a minimum notice period of one month, and this increases by one additional month for every two years of tenure, up to a maximum of six months’ notice after ten years of tenure. When a firm decides to downsize, i.e., to lay off employees due to ‘shortage of work’, it cannot pick and choose at will, but must follow the LIFO principle—in other words, if downsizing by n employees, it is the n workers who most recently joined the firm that must be laid off. In addition, an employee who has been laid off due to ‘shortage of work’ has priority in reemployment for nine months following layoff (subject to having worked at least 12 months with the firm).

Several provisions in the EPA make the LIFO principle less stringent than what a first impression suggests. First, the share of temporary contracts has increased substantially during the last ten-year period. Thus, the employer has the possibility to screen new workers for a significant period of time, which makes hiring less risky.

Second, the EPA states that if the firm is bound by collective agreements, the workforce should be divided into groups based on their trade union affiliation, and the LIFO principle then applies to each such group separately. More importantly, however, employers can to a large extent circumvent the LIFO principle and keep a valuable worker through negotiations with the union (Calleman, 2000). Collective agreements often stipulate that the employer and the union can negotiate about even stricter divisions of worker groups based on ‘similar work tasks’. An individual who is redundant with respect to his current work tasks should be offered alternative work before being laid off, but the law explicitly states that he must be qualified enough for alternative tasks—and whether this is the case is at the discretion of the employer. In particular, this last provision implies the following. Suppose a firm has ‘shortage of work’ with respect to task *X*, but not to task *Y*. Workers *A* and *B* are the ones with shortest seniority performing tasks *X* and *Y*, respectively, and *B* has shorter seniority than *A*. In general, the firm should lay off worker *B* in this case, shifting worker *A* from task *X* to task *Y*—but the employer can still lay off worker *A* if he is judged not to be qualified enough for task *Y* (Wilhelmsson 2001, p. 4). Since the legislation is negotiable, it is always possible for the firm and the union to define ‘similar work tasks’ in a very narrow way. As such, a worker who is considered valuable for the firm can be defined as belonging to a clientele of workers not affected by the LIFO principle. Moreover, it is not hard to imagine situation where it is in both the union’s and the firm’s interest to let a relatively newly hired person stay if his or her contribution to the firm is extremely valuable.

5.3.2 Reform of the LIFO requirement

A change in the EPA provision regarding the LIFO principle entered into force on 1 January 2001. After the reform, firms with 10 or fewer employees are allowed to exempt two workers from LIFO considerations, i.e., it can assign ‘key worker’ status to two individuals, who will then escape layoff even if they ought to have been the one to go if LIFO were followed strictly. The chronology of the implementation of the reform is outlined in Lindbeck et al. (2006). Their Table 5.1 makes it clear that it is not likely that the reform was anticipated by actors in the labour market to any great extent—the reform was initiated and implemented against the will of the Social Democratic government, through a coalition between the liberal-conservative opposition and the Green Party, and it was unclear until late in 2000 exactly which firms would be eligible for this loosening of the LIFO requirement.

When determining the size of a firm’s work force in connection with a shortage-of-work situation, all employees are given the weight of 1 (e.g., part-time workers, temporary workers etc.)—with the exception of employees ‘in a managerial position’.³ This will be discussed further in Section 4 below.

5.3.3 Related legislation

When relying on a reform that applies differently across firm sizes, we want to be sure that no other legislation exists that could influence our results. The Gender Equality Act (GEA; Jämställdhetslagen, SFS 1991:433), which regulated gender equality in the workplace, could potentially pose a problem in this respect. The GEA was in

³A couple of other narrowly defined groups are also excluded in the work-force count; see SFS 1982:80 for details.

force from 1991 until 2008, when it was replaced by the more general Anti-Discrimination Act. From 1994 until 2008, it required firms with 10 or more employees to produce annually a ‘gender equality action plan’. This requirement was strengthened in 2001, at the same time that the loosening of the LIFO provision was introduced.

Firstly, note that the cutoff level differs across the two policies: firms with ten or fewer employees could exempt two ‘key workers’ after the 2001 reform, whereas firms with ten or more workers were required to provide an action plan each year. Secondly, and importantly, we would expect the strengthening of the action plan requirement to result in a greater propensity for larger firms to employ women, if anything. Such an effect would serve to bias downwards any effect of an increase in small firms hiring females due to the reform under study. We do find such an effect in our empirical analysis, which we may therefore consider as a lower bound for a true effect.

5.4 Data description

Data comes from the IFAU database, which consists of several data sets; one is the LOUISE from Statistics Sweden, which includes yearly register information on the population aged 16 and older. The IFAU database also includes the Employment register with annual information on all Swedish firms, containing monthly start and end dates of all employments, along with identifiers for employers and employees. From these data sets we can construct an employer–employee unbalanced panel of the population of workers for the period 1996–2005. By using the information on the workers’ monthly start and end dates of employment and firm identifiers, we can measure when workers are hired and separated from a firm in

a particular year, as well as the date of incorporation and termination of a firm.⁴ We define firm size on an annual basis taking the average of firms' monthly employment.

When counting the number of employees, those who have a 'managerial position' should not be counted when defining the size of a firm's work force. We cannot identify which employees are managers, but we take this issue into account when constructing firm size figures in the following manner. Some 12 % of firms in our sample have one or several 'entrepreneurs' associated with them. These 'entrepreneurs' are available in our data, and are never counted as employees. For firms with one or more 'entrepreneurs', we define firm size simply as the total number of employees in each month. For firms with no 'entrepreneurs', we argue that at least one of the employees must act as a manager; hence we reduce the baseline monthly firm size figure by one for all these firms.

Thanks to the individual register we also have information on the age, gender and immigrant status for all workers (we define immigrants as individuals born outside of the Nordic countries). Moreover, since the Employment register is available to us back to 1991 we can trace whether workers have been employed in the same firm since that year. Thus, we can construct a measure of worker tenure which is censored at 60 months in 1996. We restrict the population of firms used in the analysis to firms with 2–15 employees, whereof around 91% belong to the private sector. The choice of the upper limit for firm size is a matter of finding an adequate control

⁴The phrase 'monthly start and end dates of all employments' should be understood as follows: within each yearly Employment register dataset, each employment is identified with its start and end months within the year. If the employment was continued from the preceding year, and continued into the following year, start and end months will be given as January and December respectively.

group to small firms with 10 or fewer employees, satisfying the key identifying assumptions of the econometric model. The analysis is further restricted to workers aged 18–64. There is no information in the data on whether the employment contract is on a temporary or a permanent basis. This is not a problem when defining the firm size, since the EPA stipulates that all types of contracts should be taken into account when defining firm size. Note, however, that the seniority rule is only relevant for workers on permanent contracts. Furthermore, the seniority rule is only of importance when separations are involuntary, but in the data we cannot separate whether separations are voluntary, fires, or layoffs. It is therefore possible that voluntary separations to some extent disguise effects of the exemption rule. We investigate this issue by only looking at firms with high yearly separation shares (higher than the 75th percentile within the distribution of firm separation shares). For this group of firms, the average number of separations that consist of involuntary layoffs are likely to be higher than in the full sample of firms.

Theory predicts increased worker flows, through increased hires and separations, as a result of introducing the exemption rule. Therefore, we start by analysing the effect of the exemption rule on the probability that a worker gets hired or separated from a firm. Since both hires and separations might increase, the net effect on employment is *a priori* ambiguous. To examine the effect of net employment, i.e., the intensive margin, we analyse the difference between the number of hires and separations divided by firm size. Thus, a firm of size 10 with 3 hires and 2 separations has an increase in job flow by 10%. To estimate effects on the extensive margin we estimate the probabilities that a firm enter and exit the market, respectively.

We will use two types of data structures. When estimating ef-

fects on hires and separations we work with individual data. When estimating the effects on firms' net employment and entry and exit probabilities we work with firm-level data.⁵ Table 5.1 shows descriptive statistics of workers, separately by firm size, before and after the 2001 reform. Small firms, which are affected by the reform, are firms with 2–10 employees. Large firms, defined as firms with 11–15 employees, were not affected by the reform. We see that the probabilities of hires as well as separations fell in both small and large firms after the reform. When analysing job flows and reform effects on the extensive margin we use population data on the firm-year level. Table 5.2 reports descriptive statistics on firm characteristics by firm size, before and after the 2001 reform.

5.5 Estimation strategies

To motivate the empirical strategy we show the yearly development of worker flows as well as firm entry and exit probabilities during the period 1996–2005, separately for small and large firms. Figures 5.1 and 5.2 show the development of hire and separation probabilities, respectively. As shown by these figures, small firms have lower hire and separation probabilities than large firms, but there are some signs of convergence after the 2001 reform. Preliminary results therefore suggest that the exemption rule affected employer

⁵Working with the population of employees and firms for a 10-year period is computationally very demanding, especially for certain econometric specifications. We therefore work with 10-percent random samples of the population of individuals and firms. We have verified that these samples yield the statistically the same means of workers and firms characteristics as the population data. We have also performed estimations based on the baseline econometric specification with the full population. This gives statistically the same result as with the 10-percent sample.

Table 5.1: Workers descriptive statistics by small and large firms, before and after the 2001 reform

| | Small firms | | Large firms | |
|---------------------------------|------------------|------------------|------------------|------------------|
| | 2–10 employees | | 11–15 employees | |
| | Pre-reform | Post-reform | Pre-reform | Post-reform |
| Age | 38.13 (12.64) | 39.20 (13.04) | 37.16 (12.58) | 37.92 (12.91) |
| Female (0,1) | 0.382 (0.486) | 0.381 (0.486) | 0.374 (0.479) | 0.380 (0.485) |
| Immigrant (0,1) | 0.068 (0.251) | 0.080 (0.271) | 0.064 (0.244) | 0.075 (0.263) |
| At least 60 months tenure (0,1) | 0.174 (0.373) | 0.181 (0.380) | 0.158 (0.362) | 0.165 (0.368) |
| Firm size | 5.59 (2.52) | 5.64 (2.52) | 12.84 (1.39) | 12.84 (1.39) |
| Hires (0,1) | 0.343 (0.464) | 0.326 (0.458) | 0.373 (0.479) | 0.341 (0.469) |
| Separations (0,1) | 0.346 (0.465) | 0.328 (0.459) | 0.367 (0.477) | 0.333 (0.467) |
| <i>No. of individuals</i> | 317,921 | 321,165 | 109,607 | 113,914 |

Notes: Individuals in firms with 2–15 employees are included. The pre-reform period is 1996–2000, and the post-reform period is 2001–2005. Standard deviations are in parentheses.

Table 5.2: Firm descriptive statistics by small and large firms, before and after the 2001 reform

| | Small firms | | Large firms | |
|---------------------|-------------------|-------------------|------------------|------------------|
| | 2–10 employees | | 11–15 employees | |
| | Pre-reform | Post-reform | Pre-reform | Post-reform |
| Net employment | -0.009 (0.491) | -0.009 (0.481) | 0.007 (0.352) | 0.011 (0.319) |
| Entry rate | 0.069 (0.249) | 0.058 (0.230) | 0.037 (0.188) | 0.035 (0.184) |
| Exit rate | 0.054 (0.223) | 0.051 (0.218) | 0.038 (0.191) | 0.035 (0.184) |
| Firm size | 4.32 (2.36) | 4.39 (2.38) | 12.64 (1.38) | 12.68 (1.37) |
| <i>No. of firms</i> | 62,187 | 62,868 | 7,438 | 7,852 |

Notes: See Table 5.1. Net employment is the difference between hires and separations divided by firm size.

behaviour.⁶ Most importantly, however, small and large firms seem to have parallel trends prior to the reform, which supports the idea of using a difference-in-differences approach to statistically estimate the causal effect of the reform. The parallel-trends assumption will be more closely examined in the empirical analysis.

To investigate the possibility that the exemption rule affected firms' propensity to enter or exit the market, Figures 5.3 and 5.4 show the development of entry and exit rates for small and large firms. Small firms enter and exit the market to a larger extent than large firms, which is reflected by the higher exit and entry rates by small firms. It is difficult to see any evidence of reform effects in these figures; small and large firms seem to have parallel trends before the reform however.

5.5.1 Worker flows: hires and separations

Basic estimations

Using yearly individual cross-sectional data for the period 1996–2005, the following linear probability difference-in-differences (DD) model can be formulated:

$$Y_{igt} = \alpha + \lambda_t + \phi_r + \theta_s + \beta X_{it} + \pi D_{gt} + \delta (D_{gt} + \text{Post}_t) + \varepsilon_{igt}, \quad (5.1)$$

⁶One issue is whether firms engaged in strategic behaviour in order to use the exemption rule. This would happen if firms with more than ten employees downsized in order to use this rule; or if firms with ten or fewer employees avoided expanding their workforce above the threshold of ten. According to the analysis in a previous version of this paper (von Below and Skogman Thoursie, 2008) such behaviour was not present. This is consistent with other studies which focus directly on threshold effects when firms of different sizes have different degrees of employment protection (Borgarello et al. 2004, Schivardi and Torrini 2004 and Verick 2004).

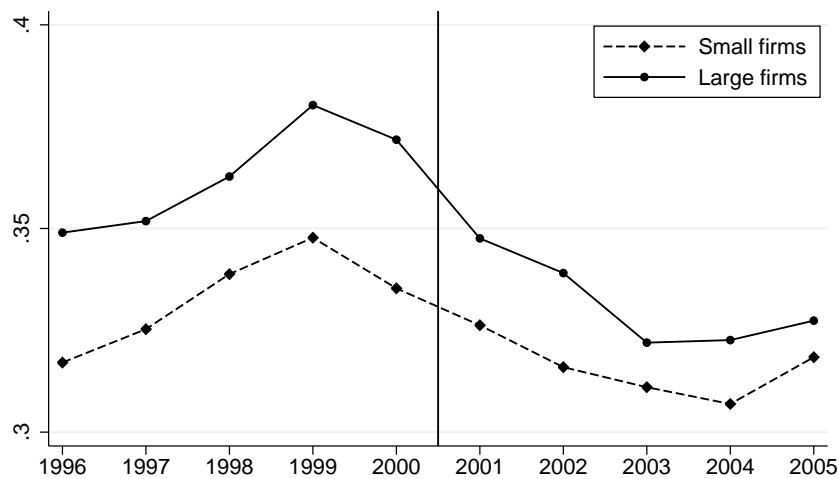


Figure 5.1: Yearly hire probabilities for small and large firms

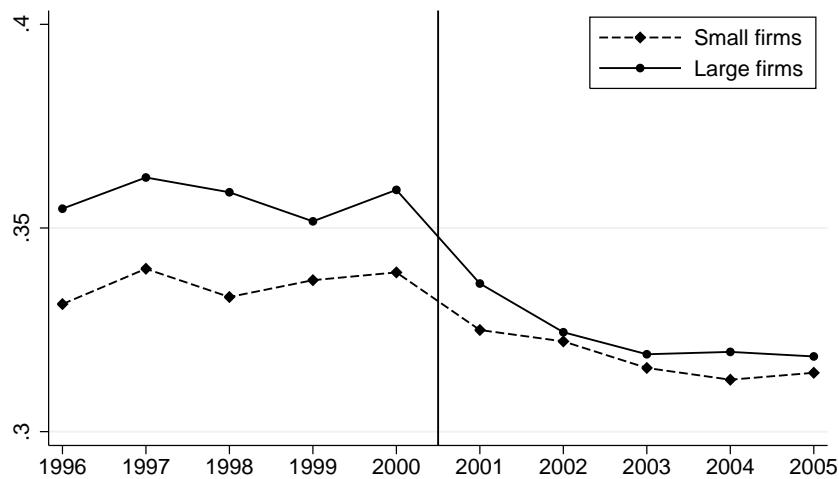


Figure 5.2: Yearly separation probabilities for small and large firms

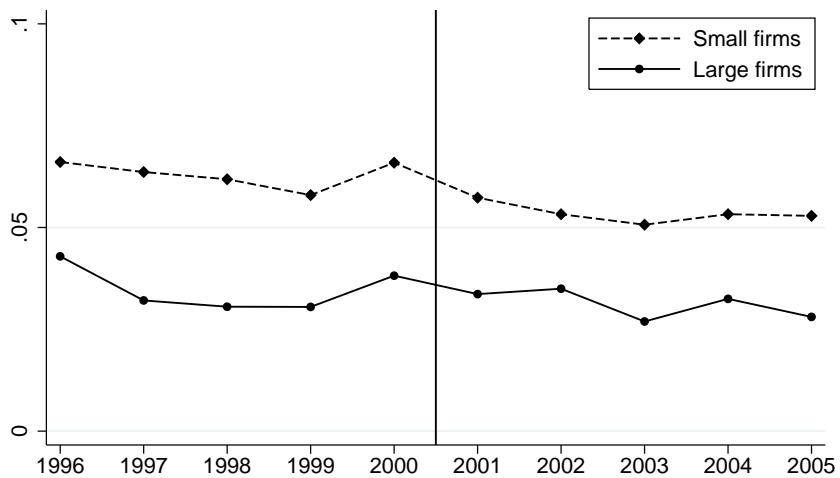


Figure 5.3: Yearly entry probabilities for small and large firms

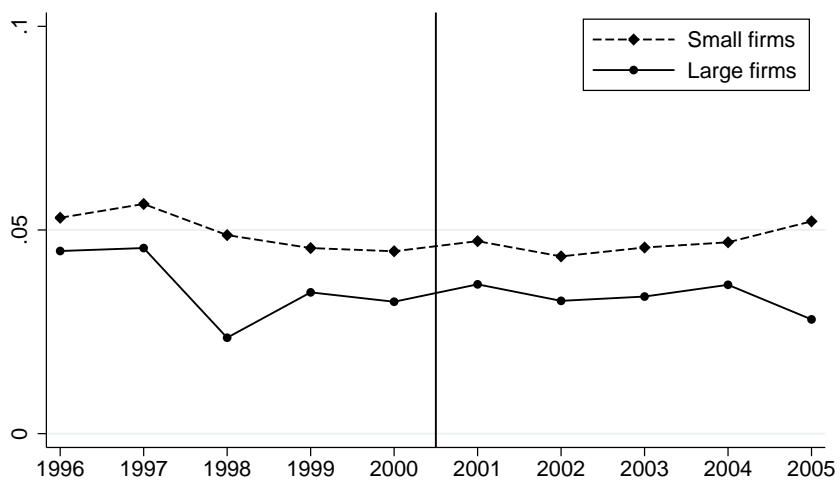


Figure 5.4: Yearly exit probabilities for small and large firms

where Y_{igt} equals 1 if worker i is hired (separated) in a firm of size g in year t ($g = 1$ if small firm with 10 or fewer employees and 0 if large with more than 10 employees). Year, region and sector effects are represented by λ_t , ϕ_r and θ_s , respectively. The vector X_{it} includes worker characteristics (age, gender and immigrant status). All individual characteristics are entered as categorical variables, implying that the model does not rely on any functional-form assumptions with respect to these variables. D_{gt} is a dummy variable taking the value 1 if the worker in year t is employed in a small firm, 0 otherwise. Postt is a dummy variable taking the value 1 from 2001 (the reform year) and onwards. The variable of interest is the interaction between the small-firm dummy and the post-reform dummy, where δ captures the causal effect of the exemption rule under the assumption that small and large firms have parallel trends in the outcome variable. In the empirical analysis we will also allow for sector-year and region-year effects to control for potential differences in time trends in certain sectors or regions across small and large firms. In order to allow business cycles to affect small and large firms differently, we also control for size-specific cyclical effects by interacting the growth rate of gdp with the small-firm dummy variable.

When individuals within certain groups are correlated, OLS standard errors might be grossly understated if the regressor of interest varies only at the group level (Moulton 1986). This means that OLS standard errors from equation (5.1) are downward biased if observations within treatment-years are correlated. To solve this problem we model correlation within group-years by assuming that the error term also consists of a group-year error, such that $\varepsilon_{igt} = \nu_{igt} + \eta_{gt}$, where η_{gt} is a random error component specific to group g in year t (both errors are assumed to be homoscedastic

and η_{gt} are uncorrelated across group-years). Using clustered standard errors is not appropriate in this case since that would require a large number of group-years. Instead, we apply the two-step approach suggested by Donald and Lang (2007). In the first step we construct covariate adjusted group-year effects by estimating:

$$Y_{igt} = \mu_{gt} + \phi_r + \theta_s + \beta X_{it} + \nu_{igt}, \quad (5.2)$$

where $\mu_{gt} = \alpha + \lambda_t + \pi D_{gt} + \delta (D_{gt} + \text{Post}_t) + \eta_{gt}$. The estimated group-year effects, g_t , are group-year means of the outcome adjusted for individual, sector and region variables. In the second step, we regress these estimated group-year effects on all variables that vary at the group and year levels using the following equation:

$$\hat{\mu}_{gt} = \alpha + \lambda_t + \pi D_{gt} + \delta (D_{gt} + \text{Post}_t) + u_{gt}, \quad (5.3)$$

where $u_{gt} = \eta_{gt} + (\hat{\mu}_{gt} - \mu_{gt})$. Since this equation is formulated at the group-year level, correlated errors within group-years taken into account. As pointed out by Donald and Lang (2007), homoskedasticity of u_{gt} is a natural assumption when the number of observations in each group is large, which is true in our case. This point demonstrates that in many circumstances, the most efficient estimator is the unweighted OLS estimator. When estimating the treatment effect we difference equation (5.3) across the two groups (small and large firms) and run OLS on the following equation:

$$\Delta \hat{\mu}_{gt} = \pi + \delta \text{Post}_t \Delta u_{gt}, \quad (5.4)$$

where $\Delta \hat{\mu}_t = \hat{\mu}_{1t} - \hat{\mu}_{0t}$ (Δu_t is analogously defined and assumed to be independent and identically distributed). This estimation is based on 10 yearly (T) observations and is equivalent to a group

fixed-effect model.⁷

When controlling for size-specific cyclical effects we rely on individual-level data and estimate equation (5.1). The reason is that we could not get an estimate of all the group-year means due to collinearity problems. Estimations based on individual-level data turned out to be robust to whether size-specific cyclical effects are controlled for or not (results are available from the authors). For this reason, we will not report results when size-specific cyclical effects are controlled for. Instead, only results from the two-step approach are reported.

To investigate if the exemption rule had differential impacts on separations for workers with different tenure lengths, we apply a triple difference-in-differences model (DDD). Differential trends in the probability of a separation for long- and short-tenure workers in small firms are compared with the corresponding difference in large firms. At the individual level, the DDD model is based on the following equation:

$$\begin{aligned} Y_{igkt} = & \alpha + \lambda + \beta X_{it} + \gamma_{gt} + \tau_{kt} + \pi D_{gt} + \kappa LT_{kt} + \rho D_{gt} \times LT_{kt} \\ & + \delta (D_{gt} \times LT_{kt} \times Post_t) + \varepsilon_{igkt} \end{aligned} \quad (5.5)$$

where Y_{igkt} equals 1 if worker i in a firm of size g with tenure level k is separated in year t ($k = 1$ if long tenure of at least 60 months and 0 otherwise). γ_{gt} captures firm-size specific time effects, and τ_{kt} captures tenure specific time effects. LT_{kt} is a dummy variable taking the value 1 if the worker has long tenure, 0 otherwise (region and sector effects are included in estimations, but are not written out in the equation). The DDD estimate, δ , captures the

⁷Note that we could also have specified a full set of firm size dummies in Eq. (5.1), rather than only including a dummy variable for small firms. This would only affect the interpretation of the estimated intercept in Eq. (5.4).

outcome change between long- and short-tenure workers in small firms relative to the corresponding change in large firms. Thus, this answers the question whether there is a differential effect of the reform on separations for workers with long and short tenure. To account for correlated errors within groups we estimate 40 size-tenure-year ($2 \times 2 \times T$) specific group means by using the two-step approach as described above. Our DDD estimate is obtained by running OLS on the following model:

$$\Delta\hat{\mu}_t = \rho + \delta \text{Post}_t + \Delta u_t \quad (5.6)$$

where $\Delta\hat{\mu}_t = \hat{\mu}_{11t} - \hat{\mu}_{10t} - (\hat{\mu}_{01t} - \hat{\mu}_{00t})$.

To investigate the dynamics of treatment effects and to evaluate the parallel-trends assumption we estimate a treatment-year interaction DD model on individual data:

$$Y_{igt} = \alpha + \lambda_t + \phi_r + \theta_s + \beta X_{it} + \pi D_{gt} + \sum_{t=1997}^{2005} \delta_t (D_{gt} \times \lambda_t) + \varepsilon_{igt} \quad (5.7)$$

where the δ_t is the yearly change in Y (hires and separations) for small relative large firms where 1996 constitutes the reference year. The reason why we rely on individual data here is that it is difficult to obtain yearly treatment effects based on data at group-year levels. We also estimate yearly treatment effects using the triple DD model in order to see how separation probabilities changed for long tenured workers compared to short tenured workers.

Heterogeneous effects

The exemption rule could have differential effects depending on the firm size. Choosing two ‘key workers’ provides relatively more flexibility for a firm with three employees than for a firm with eight

employees. If the firm with eight workers would like to lay off four workers, then the choice of the third and the fourth worker is as restricted as for a firm with more than 10 employees. Instead, the firm with three employees has no restrictions as it can choose the marginal worker it wants to lay off, assigning ‘key-worker’ status to the other two. To allow for separate firm-size treatment effects we estimate the following equation on individual data:

$$\begin{aligned} Y_{ift} = & \alpha + \lambda_t + \phi_r + \theta_s + \beta X_{it} + \sum_{f=2}^{14} \pi_f \text{Size}_{ift} \\ & + \sum_{f=2}^{14} \delta_f (\text{Size}_{ift} \times \text{Post}_t) + \varepsilon_{ift} \end{aligned} \quad (5.8)$$

where Size_{ift} is a dummy variable taking the value 1 if the individual works in a firm of size f (0 otherwise). δ_f measures the change in outcome before and after the reform for firms of size f compared to the corresponding change for firms of size 15, which constitutes the reference firm size group.

We also investigate whether there are additional heterogeneous effects. According to the theoretical discussion in Section 2, the exemption rule could potentially improve employment prospects for young, immigrant and female workers. For this reason we will perform separate analyses for young (aged 18–25), female and immigrant workers.

An interesting question is whether there are differential effects depending on whether workers are unionised or not. Information on union status is unfortunately not available in our data. However, a related question is how the exemption rule affected firms who have not signed collective agreements. For these firms there is no union to negotiate with. This means that, formally, the EPA

is supposed to hold without the possibility to negotiate about the clientele of workers. On the other hand, for small firms with few workers unionised it is possible that the employer will just ignore the seniority rule without experiencing any sanctions. It is well known that collective agreements are rare in the hotel and restaurant industry. For this reason we have also estimated a reform effect on a sub-sample only consisting of restaurants and hotels. Results show that the effect on hires and separations are insignificant for these industries. Nor are there any differential effects on separations for long and short tenured workers. One interpretation is that firms with no collective agreements to a larger extent decide whom to hire and lay off, without taking the legislation into consideration.

5.5.2 Firms' changes in employment, entry and exit

To examine the net effect on yearly employment we define the following difference-in-differences model based on firm-year cross-section data:

$$\Delta E_{jgt} = \alpha + \lambda_t + \phi_r + \theta_s + \pi D_{gt} + \delta (D_{gt} \times \text{Post}_t) + (\nu_{jgt} + \eta_{gt}) \quad (5.9)$$

where ΔE_{jgt} is the difference between hires and separations divided by firm size for firm j in year t .

In order to investigate the effect of the exemption rule on the extensive margin, we estimate the effect of the exemption rule on the probabilities that a firm enters and exits, respectively. These estimations are based on the following model:

$$e_{jgt} = \alpha + \lambda_t + \phi_r + \theta_s + \pi D_{gt} + \delta (D_{gt} \times \text{Post}_t) + (\nu_{jgt} + \eta_{gt}) \quad (5.10)$$

where e is a dummy taking the value 1 if the firm j enters (exits) the market in year t . To account for correlated errors within group-years, we use the Donald and Lang (2007) two-step approach described above.

5.6 Results

5.6.1 Effects on hires and separations

Panels A and B of Table 5.3 show the estimated reform effects based on equation (5.4) on hires and separations, respectively. Panel C reports the estimated reform effects based on equation (5.6), i.e., the triple difference-in-differences (DDD) model. Column 1 reports results from the basic specification, controlling for age, gender and immigrant status, where all these variables are entered as categorical variables. Column 2 adds controls for region and sector effects and Column 3 adds region-year and sector-year effects.

Results show that both the hire and separation probabilities significantly increased for small firms relative to large firms after the reform. The effect is robust to all specifications, even though the estimated effect on hires decreases slightly when sector and region, and sector-year and region-year are controlled for. Taking the point estimates for hires and separations from Column 1 suggests that both increased by 1.7 percentage points after the reform. This corresponds to an increase in the share of hires for small firms by 5% (from 34.3 to 36%) and an increase of almost 5% for separations.

Since there are no previous studies directly estimating the effect of allowing firms to exempt two workers from the LIFO principle, there are no other effects to compare our results with. Are the effects we have found small or large? One way to relate the es-

timated effects on hires and separations is to compare them with the average yearly variation in hires and separations of small firms, which amount to 1 and 0.5 percentage points, respectively. Thus, the increase in hires due to the reform is below twice the yearly variation in the share new hires. For separations the reform effect is just about three times this variation. This suggests that there are important effects on worker flows, but they are not overwhelmingly large.⁸

Panel C of Table 5.3 suggests that the increase in separations due to the reform is smaller for workers with long tenure compared to workers with short tenure, as the estimated effect using the triple difference-in-differences is significantly negative when using Models 2 and 3. This result is perhaps counter-intuitive if we believe that the exemption rule would make it easier for firms to lay off workers with long tenure. One possibility is that workers with more than five years of tenure are difficult to replace even if two workers can be exempted from the LIFO principle. For example, consider a firm with four employees planning to lay off one worker after the reform. Even if two ‘key workers’ can be exempted, it might still be difficult to lay off the worker with more than five years of tenure among the two remaining workers. It could also be the case that workers with long tenure are on average more valuable to firms than short tenure workers. Long-tenure workers have accumulated a large amount of firm-specific human capital. They might also have established stronger bonds with the employer. For these reasons,

⁸To quantify the effects we perform the following calculations. The total number of employees in small firms was about 3,000,000. The share new hires was approximately 34 %, implying that roughly 1,000,000 are new hires each year. The increase in the probability of hires and separations by 1.7 percentage point each then amount to around 17,000 individuals being hired and separated a year. For hires (separations) the average yearly variation in hires is 10,000 (5,000).

effects on separations might be stronger for workers with tenure between 1 and 5 years. To investigate this we allow for differential triple difference-in-differences estimates for workers with 2, 3, 4 and at least 5 years tenure. The reference category is at most 1 year tenure. Results show that the increase in separations is smaller for all tenure categories longer than one year (results are available from the authors). Thus, results show that the exemption rule increased separations in general, but more so for short tenured workers.⁹

5.6.2 Evaluating dynamic reform effects

To investigate dynamic effects of the reform and to evaluate the parallel-trends assumption more carefully than what inspection of Figures 5.1 and 5.2 allows, we estimated the yearly changes in worker flows between small and large firms based on equation (5.7). The estimated yearly effects on hires (separations) with corresponding 95% confidence bands are plotted in Figure 5.5 (Figure 5.6). As evident in Figure 5.5, there is a significant reform effect the same year as the introduction of the exemption rule i.e., in 2001, and the effect seems to increase over the years after 2001. The figure clearly shows that there are no effects in any year before the reform, which strongly supports the parallel-trends assumption. For separations there is a similar pattern with an immediate reform effect in 2001 and a slight increase in the reform effect in 2002 (see Figure 5.6). As for hires, the pre-reform years show no significant effects.

⁹To examine the possibility that voluntary separations to some extent disguise effects of the exemption rule, we also estimated the reform effect on separations on workers belonging to firms with yearly separation shares higher than the 75th percentile within the distribution of firms' separation share. The reform effect on separations for this group of workers is 0.01, i.e., an increase by 1 percentage point. In this sub-sample, the average share of separations for individuals in small firms prior to the reform is 73%, implying a really small effect for this group of firms.

Table 5.3: Estimated effects of the 2001 reform on the hires and separation probabilities.

| | Model (1) | Model (2) | Model (3) |
|---|---------------------|---------------------|---------------------|
| <i>A. Hires</i> | | | |
| DD Reform effect | 0.017*** (0.003) | 0.014*** (0.003) | 0.014*** (0.003) |
| Baseline fraction of hires | 0.343 | 0.343 | 0.343 |
| Percent effect (%) | 5 | 4.1 | 4.1 |
| <i>B. Separations</i> | | | |
| DD Reform effect | 0.017*** (0.003) | 0.017*** (0.003) | 0.017*** (0.003) |
| Baseline fraction of separations | 0.346 | 0.346 | 0.346 |
| Percent effect (%) | 4.9 | 4.9 | 4.9 |
| <i>C. Separations on long vs. short seniority</i> | | | |
| DDD Reform effect | -0.009 (0.006) | -0.012* (0.006) | -0.012* (0.006) |
| Year effects | Yes | Yes | Yes |
| Region | No | Yes | Yes |
| Sector | No | Yes | Yes |
| Region-year | No | No | Yes |
| Sector-year | No | No | Yes |
| <i>Observations</i> | 10 | 10 | 10 |

Notes: Panels A and B report the difference-in-differences estimates based on equation (5.4) and Panel C reports the triple difference-in-differences estimate based on equation (5.6). Standard errors are reported in parentheses. ***/**/* denote significant at the 1/5/10% significance levels. The underlying dependent variable for Panel A is a dummy for whether the employee is a new hire. The underlying dependent variable for Panels B and C is a dummy for whether the employee is a separation. All specifications control for age, gender, immigrant status and firm size, by including a dummy variable for each category. Region refers to 24 counties entered as dummy variables. Sector is defined on a 2-digit level, implying 100 sectors entered as dummy variables. The baseline fraction is the share new hires and separations during the pre-reform period for small firms.

Note that the estimated yearly treatment effects here, in contrast to the results presented in Table 5.3, are based on individual data and do not take care of the problem of correlated errors within group-years. Thus, the 95% confidence bands in Figures 5.5 and 5.6 may be too tight. However, we have also estimated all reform effects presented in Table 5.3 based on individual data and on equation (5.1). Standard errors using individual data are remarkably similar to those reported in Table 5.3. In the light of this, the confidence bands reported in Figures 5.5 and 5.6 may still be rather accurate.

When estimating the triple DD model but allowing for yearly treatment effects we find that the decrease in separations for long tenured workers relative to short tenured workers started already in 1997 (results are available from the authors). We therefore conclude that estimated based on the triple DD must be interpreted with caution since the parallel-trend assumption seems to be violated.

5.6.3 Heterogeneous effects with respect to firm size

Next, we turn to the investigation of whether the effect of the reform differs depending on firm size. The estimated firm-size-specific reform effects on hires and separations, respectively, based on equation (5.8), are plotted in Figure 5.7. We do not report confidence bands here, but underlying estimations show that for hires, effects are only significant for small firms with 2–5 employees. This suggests that the exemption rule only affected hiring behaviour for very small firms. One could argue that there are potential measurement errors in our firm size variable, implying that some firms defined as having 11 or 12 employees actually are small firms and that some firms with 9 or 10 employees actually are large firms.

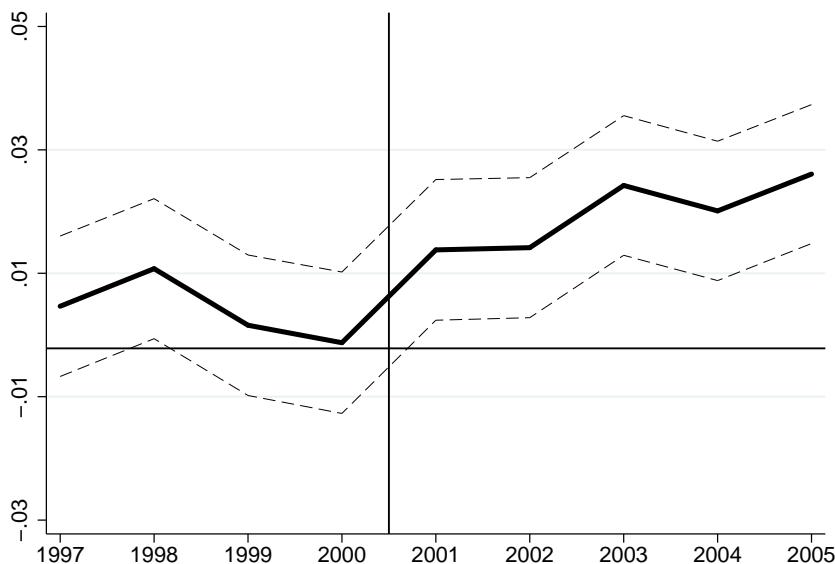


Figure 5.5: Estimated year effects on hires probabilities with corresponding 95% confidence bands

This could partly explain why we do not observe any reform effects at firm sizes close to the firm-size threshold of 11. On the other hand, as regards separations, reform effects are significant for all small firm sizes (2–10). Note that the firm-size specific effects are estimated based on individual data implying that standard errors may be underestimated due to correlated errors within group-years. However, as discussed in the previous subsection, individual data and group-year data gave standard errors of very similar size when estimating general reform effects.

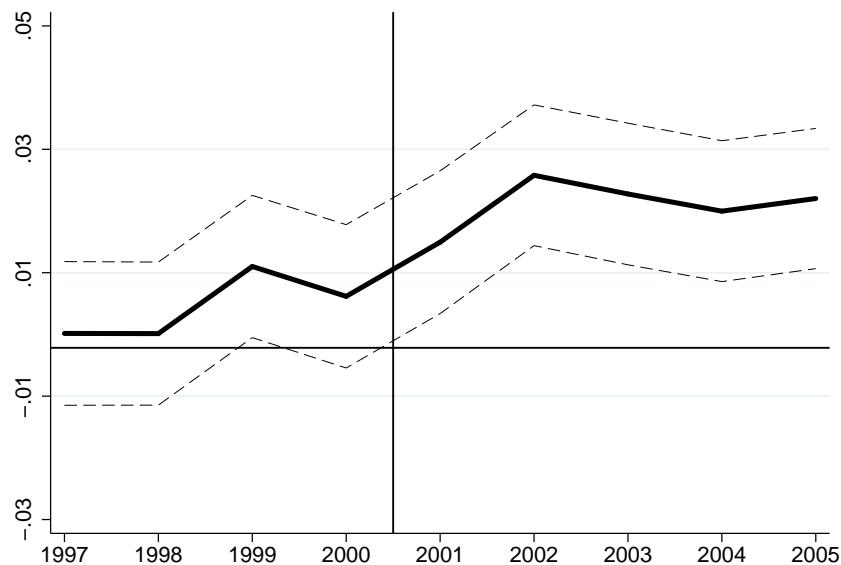


Figure 5.6: Estimated year effects on separation probabilities with corresponding 95% confidence bands

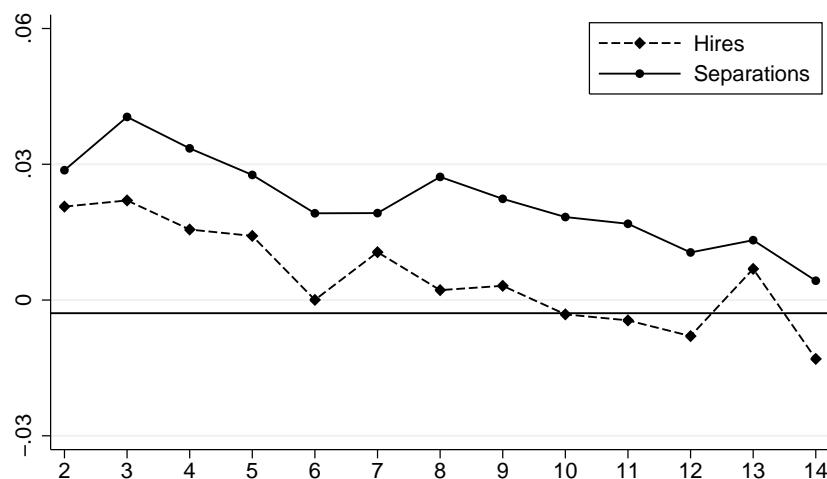


Figure 5.7: Estimated firm size-specific reform effects on hires and separation probabilities

5.6.4 Heterogeneous effects with respect to individual characteristics

Table 5.4 shows results from separate analyses for young, old, immigrant, native, female and male workers, respectively. All estimations are based on equation (5.4) and the specification used in Column 2 of Table 5.3. Results on hires are consistent with the prediction that the exemption rule increases hires for younger and female workers, since the percentage effects are largest among these groups. The coefficients on separations (Panel B) are significant and relatively high for young and female workers, which also fits with the theoretical predictions discussed earlier. The coefficients on hires and separations tend to be of the same magnitude for most groups, which suggests that turnover has increased—particularly for young workers—but that total employment is likely unaffected. The exception seems to be immigrant workers where there is only an effect on hires but not on separations. Note that there are no significant effects for old workers. This is consistent with the above finding that the reform effect is smaller for workers with long tenure compared to workers with short tenure, since old workers have longer tenure on average.

5.6.5 Firms' net employment changes, entry and exit

Table 5.5 shows the estimated reform effects on the intensive and extensive margins. Panel A shows the effects on firms' net employment, i.e., the intensive margin. Panels B and C report effects on the firm entry and exit probabilities i.e., the extensive margins. Results show that there is no effect on net employment (results

Table 5.4: Estimated effects of the 2001 reform on the hires and separation probabilities for different groups

| | Age 18–25 (1) | Age 55–64 (2) | Immigr. (3) | Natives (4) | Females (5) | Males (6) |
|-----------------------|---------------------|---------------------|-------------------|---------------------|---------------------|---------------------|
| <i>A. Hires</i> | | | | | | |
| Reform effect | 0.030*** (0.006) | 0.006 (0.004) | 0.017* (0.009) | 0.014*** (0.003) | 0.017*** (0.004) | 0.012** (0.004) |
| Baseline | 0.546 | 0.198 | 0.429 | 0.337 | 0.357 | 0.334 |
| Percent effect (%) | 5.5 | 3.0 | 4.0 | 4.1 | 4.8 | 3.6 |
| <i>B. Separations</i> | | | | | | |
| Reform effect | 0.030*** (0.007) | 0.003 (0.002) | 0.005 (0.009) | 0.019*** (0.003) | 0.023*** (0.004) | 0.014*** (0.003) |
| Baseline | 0.549 | 0.224 | 0.432 | 0.339 | 0.364 | 0.334 |
| Percent effect (%) | 5.5 | 1.3 | 1.2 | 5.6 | 6.3 | 4.2 |
| <i>Observations</i> | 10 | 10 | 10 | 10 | 10 | 10 |

Notes: Estimations are based on the specification used in Model 2 of Table 5.3. For more information see Table 5.3.

are robust to all specifications). This is consistent with the results above where the probabilities of hires and separations were found to increase by the similar amounts. Thus, the reform affected the employment turnover, but the net effect on employment is zero. Estimating yearly treatment effects on net employment, in an analogous way as we did for hires and separation based on equation (5.7), all year effects are insignificant.

As regards the entry probability, results show negative effects which seems to be the opposite sign to what we would expect (see Panel B). However, when estimating year effects we conclude that the only significant effect appears in year 2005, saying that the entry probability decreased for small relative to large firms in that year. Thus, the negative effects reported in Panel B of Table 5.5 are driven by one year, four years after the reform. Results reported in Panel C show that there were no effects on the firms' exit probabilities. This is also supported when estimating year effects

where all such effects are insignificant.

Taken together, results show that the exemption rule introduced in 2001 had no effects at all on the extensive margin (for this reason, percentage effects are not reported in Table 5.5). Nor were there any net employment effects since the increase in hires and separations are equal in magnitude and cancel out when defining net employment.

5.7 Discussion and conclusions

How employment protection affects firms' employment behaviour is vital to the design of policy and to the understanding of labour market behaviour. This paper empirically investigates how a certain component of the employment protection legislation affects firms' employment behaviour. Previous empirical research often relies on cross-country variation by correlating some strictness index measure of employment protection with the employment level. We argue that it is also important to evaluate certain aspects of the employment protection legislation such as the seniority rule. Consequences of seniority rules on firms' employment behaviour have not been examined in the previous empirical literature.

In Sweden the seniority rule states that the worker who was employed last has to go first when a firm downsizes, i.e., the so-called LIFO principle. This principle has received much attention, both from a political and an academic point of view—where opponents argue, e.g., that unemployment will result because employers become more reluctant to hire new workers. For this reason, the LIFO principle was reformed in January 2001 such that employers with ten or fewer employees were allowed to exempt two workers from the seniority rule. Using an employer-employee unbalanced panel

Table 5.5: Estimated effects of the 2001 reform on the firms' net employment change and firm entry and exit probabilities

| | Model (1) | Model (2) | Model (3) |
|-----------------------------|---------------------|---------------------|---------------------|
| <i>A. Net employment</i> | | | |
| DD Reform effect | -0.004 (0.008) | -0.007 (0.006) | -0.006 (0.006) |
| <i>B. Entry probability</i> | | | |
| DD Reform effect | -0.006** (0.002) | -0.011** (0.005) | -0.011** (0.005) |
| <i>C. Exit probability</i> | | | |
| DD Reform effect | 0.0001 (0.004) | -0.0001 (0.004) | -0.0001 (0.004) |
| Year effects | Yes | Yes | Yes |
| Region | No | Yes | Yes |
| Sector | No | Yes | Yes |
| Region-year | No | No | Yes |
| Sector-year | No | No | Yes |
| Observations | 10 | 10 | 10 |

Notes: The underlying equations are equation (5.9) for Panel A and equation (5.10) for Panels B and C, respectively. However, results reported are based on equation (5.4), i.e., the two-step approach provided by Donald and Lang (2007). The dependent variable in Panel A is the difference between hires and separations divided by firm size. The underlying dependent variable in Panels B and C is a dummy variable for whether a firm enters or exits the market, respectively. For more information, see Table 5.3.

data for the period 1996–2005, we can estimate whether these small firms changed their employment behaviour due to the reform by applying the differences-in-difference estimator.

We find that both the hires and separation probabilities significantly increased for small firms relative to large firms. The reform increased the probability of being a new hire in a small firm by 1.7 percentage points after the reform. This corresponds to an increase in the share of new hires by 5%. The effects for separations are equal in magnitude. Consequently, we find no effect on firms' net employment. The increase in hires due to the reform is only present for the really small firms with 2–5 employees. Effects on both hires and separations are found to be larger for young workers. As regards effects on the extensive margin we find no effects. One way to relate the estimated effects on hires and separations is to compare them with the average yearly variation in hires and separations of small firms, which amounts to 1 and 0.5 percentage points, respectively. Thus, the increase in hires due to the reform is below twice the yearly variation in the share new hires. For separations the reform effect is just above three times this variation. This suggests that there are important effects on worker flows but they are not overwhelmingly large.

That effects are not overwhelmingly large is not surprising when considering how the legislation actually works—employers had great possibilities to circumvent the legislation even before the introduction of the exemption rule, as discussed in Section 3 above. Furthermore, part of the effects found in this paper may be related to informational asymmetries. If employers and employees have imperfect information about the possibilities for firms to keep productive workers, legislation may in part give a false signal that workers are more protected than what actually is the case. If knowledge of

how the seniority rule works is positively correlated with firm size, this might explain why the reform only affected new hires for the really small firms. If employees believe that they are more protected than what is actually the case, they might hesitate to try new jobs with low seniority. If older workers are better informed than young workers, this might to some extent explain why effects are larger for young workers—perhaps younger workers thought it was more important before the reform to stay on the job and accumulate seniority.

Overall, our results support the hypothesis that seniority rules lower mobility by reducing workers flow into and out of employment. At the same time, we do not find any effects on firms' net employment, nor on the extensive margins. This, together with the finding that the exemption rule only affected hires for the really small firms (i.e., firms of sizes 2–5) suggests that an extension the exemption rule to firms with more than 10 employees would not generate any substantial increases employment.

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