SVERIGES RIKSBANK
WORKING PAPER SERIES

369

The Consequences of Uncertainty: Climate Sensitivity and Economic Sensitivity to the Climate

John Hassler, Per Krusell and Conny Olovsson

March 2019

WORKING PAPERS ARE OBTAINABLE FROM

www.riksbank.se/en/research
Sveriges Riksbank • SE-103 37 Stockholm
Fax international: +46 8 21 05 31
Telephone international: +46 8 787 00 00

The Consequences of Uncertainty: Climate Sensitivity and Economic Sensitivity to the Climate

John Hassler[*], Per Krusell,[†] and Conny Olovsson[‡][§]

Sveriges Riksbank Working Paper Series

No. 369

March 2019

Abstract

We construct an integrated assessment model with multiple energy sources—two fossil fuels and "green energy"—and use it to evaluate ranges of plausible estimates for the climate sensitivity as well as for the sensitivity of the economy to climate change. Rather than focusing on uncertainty explicitly, we look at extreme scenarios defined by the upper and lower limits given in available studies in the literature. We compare optimal policy with laissez faire and we point to the possible policy errors that could arise. By far the largest policy error arises when the climate policy is "overly passive"; "overly zealous" climate policy (i.e., a high carbon tax applied when climate change and its negative on the economy are very limited) does not hurt the economy much as there is considerable substitutability between fossil and non-fossil energy sources.

Keywords: Climate change, integrated assessment model, uncertainty.

---

[*] IIES, Stockholm University, S-106 91 Stockholm, University of Gothenburgh, CEPR and SEM. john@hassler.se

[†] IIES, Stockholm University, University of Gothenburg, CEPR and NBER. per.krusell@iies.su.se

[‡] Sveriges Riksbank. conny.olovsson@riksbank.se

[§] The opinions expressed in this article are the sole responsibility of the authors and should not be interpreted as reflecting the views of Sveriges Riksbank.

1 Introduction

The economy-climate nexus involves three large blocks: how the economy works, how the climate is determined, and how emitted carbon circulates between different reservoirs (the carbon cycle). These blocks interact. The key links are that the economy feeds carbon dioxide into the atmosphere where it enters the carbon circulation system, atmospheric carbon that then constitutes a key input into the determination of the climate, which in turn affects how our economies work; hence, human welfare is affected. The description of the joint system is often referred to as *integrated assessment modeling* and in this paper we employ an integrated assessment model to address one of the key questions in this area: uncertainty. In particular, there is imperfect knowledge of the climate system, about the carbon cycle, and about the economic damages caused by climate change, as well as about how these systems interact. We focus on two of these uncertainties here: the climate system and the economic damages.

A key feature of our analysis is that, unlike the literature on this issue so far, we do not formally model uncertainty. Rather, we look at the range of estimates and focus on the extremes. The extremes are naturally defined as upper and lower bounds of intervals given in the literature. (True tails events, occurring with extremely low probability, are not considered here.) First, we look at how sensitive global temperature is to carbon dioxide in the atmosphere and select two extreme values: an upper bound and a lower bound. These are selected from IPCC's 2013 report, which states a range of values for *climate sensitivity* — the change in the global mean temperature after a doubling of the atmospheric carbon dioxide concentration — within which the outcome will "likely" land, i.e., with a probability that the IPCC considers to be higher than around 2/3. For economic damages, we rely on the recent meta-study by Nordhaus and Moffat (2017) and similarly select upper and lower bounds. We then combine these into four distinct possibilities, thus combining the bounds into four logically possible outcomes. We find this approach more easily interpretable, and arguably even more relevant, than an approach which formally looks at uncertainty, since we perceive the main issue to be a concern with extreme outcomes (both good ones and bad ones) rather than with random fluctuations within the range defined by the extreme cases. Thus, we do not think that it is the imperfect consumption smoothing that is worrisome in the climate-economy area but rather fears of a highly damaging outcome, either because insufficiently aggressive policy is undertaken when the damages of emission turn out to be large, or because of policy that is too aggressive when carbon emission by itself (through climate change) does not harm economic welfare much.[1]

Our integrated assessment model is based on Golosov et al. (2014). It is also related to recent work where we endogenize technology: Hassler, Krusell, and Olovsson (2017) and, with more detail on energy supply, Hassler et al. (2017). Our framework is highly tractable and yet quantitatively specified, i.e., it is specified based on a specific (optimal neoclassical growth) structure that can be straightforwardly tied to empirical estimates of utility- as well as production-function based parameters. The model is augmented to include some richness on the side of energy supply and in order to include a carbon cycle and a climate model. One of the key features of this framework is that it captures the sensitivity of climate to atmospheric carbon dioxide concentration *jointly* with the economic damages inflicted by global warming in *one parameter*: γ. This parameter has a concrete interpretation: the percentage loss in the flow of world GDP from a one-unit increase in the carbon dioxide concentration in the atmosphere (thus baking together how carbon creates warming, which in turns causes economic damages). In the calculations, "one unit" is expressed as 1,000 gigatonnes of carbon (GtC) in the global atmosphere. Hence, we will look at four values of γ defined by the four combinations of high and low climate sensitivity and high and low economic sensitivity. Conveniently for policy analysis, the optimal carbon tax is proportional to γ.

To begin with, then, one interesting issue is whether the uncertainty, as expressed by the ranges in the two studies we refer to (IPCC and Nordhaus-Moffat), generates a larger span of values for γ due to the uncertainty about climate sensitivity than that due to uncertainty in economic sensitivity, or the other way around. We find the following: low-low (climate-economic) sensitivities deliver a γ of 0.27, low-high gives a value of 1.79, high-low yields 1.44, and high-high 10.39. Thus the effects are not additive—they interact nonlinearly somewhat—but, roughly speaking, the difference between high and low climate sensitivities amount to a factor of about 5.5 in the γ, whereas the uncertainty due to economic sensitivity approximately amounts to a factor of 7 in γ. Thus, these are of the same order of magnitude. Clearly, it is hard to argue that the bounds selected from the two studies represent exactly the same amount of uncertainty, but we note at least that there is significant economically relevant uncertainty both about the climate and about the economy. Our priors were that the former would be swamped by the latter, which turned out not to be correct.

When we compute optimal taxes we obtain values that are in line with numbers in the

---

[1] For examples of studies of risk and uncertainty, see for example Lemoine (2010), Jensen and Traeger (2014), Cai, Judd and Lontzek (2013), Gollier (2013) and Weitzman (2011).

literature and we then use these to simulate eight scenarios: for each of the four γ cases, we look both at the laissez-faire market outcome and at optimal policy. We see, in brief, that the negative welfare effects of carbon emission are sizable, unless both the climate and economic sensitivities are low. We also see, however, that the optimal tax is quite potent in containing climate change and its economic effects. In terms of energy supply, we see that coal use will grow significantly in all of the scenarios, the one exception being the worst outcome—with both sensitivities being high and under the corresponding optimal tax. Finally, we look at the kinds of errors that arise if one adopts a climate policy in a way that is poorly matched to the actual sensitivities. Here we see that the negative consequences of erroneously adopting a high tax—computed optimally based on the assumption that both the climate and economic sensitivities are high) are not very large, chiefly because energy substitution is quite effective: using green energy (which would be the equilibrium implication of a high tax on carbon—when coal really should be used more is not very costly for the economy as the two are rather close substitutes. On the other hand, incorrectly adopting a low tax—that is appropriate if both sensitivities are low when they are actually high—is very costly.

In Section 2 we describe the economy-climate model. Section 3 then shows how we calibrate the model and Section 4 covers the results. We offer some concluding remarks in Section 5.

2 Model

In the following, we describe our benchmark model, block by block, and then discuss the tax assumptions implemented in the market economy.

2.1 Economy

Overall, our framework is an integrated model of the economy and the climate: these two systems have a feedback between them. As such, it is a close relative of Nordhaus's DICE and RICE models described in Nordhaus and Boyer (2010) and later updates. However, and for focus, we consider a world economy that is highly stylized in a number of ways and, in that sense, is much simpler than some of the existing leading models. First, the world has two regions, defined by whether they are oil-consuming or oil-producing. Second, we look at three types of energy sources: oil, which is produced at zero marginal cost, coal, which is produced at a constant marginal cost measured in terms of the final good, and "green", which is also produced at a constant marginal cost. The amount of oil is finite and the amounts of coal and green are infinite (for coal, this is a simplification but not a severe one since there is a very large amount of coal and, hence, a very small associated rent). Third, the only trade between the regions is intratemporal: oil for consumption (there is a homogeneous consumption good). We take technology trends as given and only consider policy in the form of a carbon tax, which if used properly would suffice to render the world equilibrium Pareto optimal. The implications of endogenous technical change in a similar setting is explicitly analyzed in Hassler et al. (2017), which in turn builds on the simpler endogenous-technology in Hassler, Krusell, and Olovsson (2017). We use a simple utility and production-function specification in order to obtain closed-form solutions as far as possible.

Both regions are inhabited by representative consumers; these have preferences given by

$$E_0 \sum_{t=0}^{\infty} \beta^t \log(C_t). \tag{1}$$

From now on, we use C_t to denote consumption in the oil-consuming region and $C_{o,t}$ to be consumption in the oil-producing region.

The oil-consuming region has an aggregate production function for the final good Y_t that is given by

$$Y_t = A_t L_t^{1-\alpha-\nu} K_t^{\alpha} E_t^{\nu}$$

where A_t is total-factor productivity (TFP), L_t is labor used in final-good production, K_t is the capital stock, and E_t is energy services.

The assumption that the elasticity of substitution between energy and the other inputs (capital and labor) is unity is hard to defend when a time period is short—then, a much lower elasticity is called for. However, for longer time periods—and indeed our focus here is a long-run one—the Cobb-Douglas assumption does not appear unreasonable. In fact, as demonstrated for this particular application in Hassler, Krusell, and Olovsson (2017), one can express the higher long-run substitutability between inputs in terms of endogenous technology choice. Suppose, namely, that the production function is of a CES form between energy services and a Cobb-Douglas capital-labor composite and that technology choice involves the ability to choose "input saving" in the form of two technology parameters multiplying these two inputs, subject to a constraint. Then if that constraint is specified as a log-linear relationship, the outcome is a reduced-form production function in the basic inputs that is Cobb-Douglas, regardless of the degree of short-run substitutability between these inputs.[2]

Energy services, in turn, are provided by firms that act competitively with a constant-returns-to-scale production function in n distinct energy inputs:

$$E_t = \mathcal{E}(e_{1,t}, \ldots, e_{n,t}) = \left(\sum_{k=1}^{n} \lambda_k \left(e_{k,t}\right)^{\rho} \right)^{\frac{1}{\rho}}. \tag{2}$$

Here, $e_{1,t}$ is the import of oil in period t. The other energy sources $\{e_{2,t}, \ldots, e_{n,t}\}$ are energy sources assumed to be produced and supplied entirely domestically within the oil-consuming region. The associated production technology is linear in the final good; in particular, to produce $e_{k,t}$ units of energy source $k \in \{2, \ldots, n\}$, $p_{k,t}$ units of the final good is required. Thus, we allow for these marginal costs to change over time. Final goods not engaged in energy production are consumed or invested in a standard neoclassical way. In sum, the resource constraint for the final good reads

$$C_t + K_{t+1} = A_t L_t K_t^{\alpha} E_t^{\nu} - p_{1,t} e_{1,t} - \sum_{k=2}^{n} p_{k,t} e_{k,t} + (1-\delta) K_t.$$

We take the world market price of oil $p_{1,t}$ to be expressed in units of the global final good.

The oil-producing region, finally, produces oil without any resource cost. Its constraints are

$$\begin{aligned} R_{t+1} &= R_t - e_{1,t}, \qquad (3) \\ R_t &\geq 0 \forall t, \\ C_{o,t} &= p_{1,t} \left(R_t - R_{t+1}\right), \end{aligned}$$

where R_t is the remaining stock of oil in ground in the beginning of period t.

---

[2] This statement holds so long as the CES function has an elasticity parameter less than or equal to one, i.e., $\rho \leq 0$ (this is the empirically reasonable case for this application). For $\rho > 0$, the result is complete specialization: the production function becomes linear in one of the inputs.

2.2 The carbon cycle

The use of energy leads to carbon emission in the form of CO_2. Specifically, emissions in period t are given by

$$M_t = \sum_{k=1}^{n} g_k e_{k,t},$$

where g_k measures how "dirty" energy source k is. We measure fossil energy sources in terms of their carbon content, implying that for each of them $g_{k,t} = 1$. Conversely, purely green energy sources have $g_{k,t} = 0$. We could also, but do not currently, have intermediate cases.

We use the structure in Golosov et al. (2014) so we assume that the law of motion for the atmospheric stock of carbon S_t in excess of its preindustrial level is given by

$$S_t = \sum_{s=0}^{t} (1 - d_s) M_{t-s},$$

where

$$1 - d_s = \varphi_L + (1 - \varphi_L)\, \varphi_0\, (1 - \varphi)^s$$

captures how much carbon remains in the atmosphere s periods after it was emmited: the share of emissions that remains forever in the atmosphere is φ_L, the share that leaves the atmosphere within a period is $1 - \varphi_0$ and the remainder $(1 - \varphi_L)\, \varphi_0$ depreciates geometrically at rate φ.

2.3 The climate and the economic damages therefrom

The climate is affected by the atmospheric carbon concentration through the well-known greenhouse effect. Changes in the climate, in turn, have effects on the productivity of the economy. The effect of atmospheric carbon concentration on TFP can thus be thought of in two steps. In step one, there is a logarithmic effect of CO_2 on the Earth's energy budget and, hence, on global warming. This effect is known since long: see Arrhenius (1896). It can be expressed, using T_t, which denotes the global mean temperature (in excess of its preindustrial level), and the stock of carbon in the atmosphere as

$$T_t = \frac{\lambda}{\ln 2} \ln \left(\frac{S_t + \bar{S}}{\bar{S}} \right). \tag{4}$$

Here, λ represents the "climate sensitivity" and $\bar{S}$ the pre-industrial atmospheric carbon stock. We abstract from dynamics in the relation between S_t and T_t and assume that the long-run equilibrium temperature associated with a level of carbon concentration is achieved immediately. In this sense, we exaggerate the direct effect of emissions on temperature (it would be straightforward to include dynamics and we leave them out for convenience mostly).

Step two is the effect of changes in the global mean temperature on the economy. This mechanism appear in a variety of forms and is highly heterogeneous across geographic space. In contrast to step one, step two is typically modeled as convex – marginal global damages increase in temperature. Golosov et al. (2014) demonstrate that, at least relative to the literature, the combination of a concave step one and convex step two yields an overall effect of CO_2 concentration on productivity that is quite well captured by a simple log-linear specification. Specifically, they use a specification for TFP that reads

$$A_t = e^{z_t - \gamma_t S_{t-1}}, \tag{5}$$

where z_t is exogenous technical change and γ_t captures the possibly time-varying sensitivity to atmospheric CO_2 concentration.

2.4 Markets and equilibrium

All agents in our model are price takers. Consider the oil-producing region first. We thus assume that there are many oil producers operating under perfect competition, with the representative oil producer choosing how much oil to store for next period, R_{t+1}, taking the world market price of oil as given. Using the last part of (3) to substitute out $C_{o,t}$ in (1), and taking the first-order condition with respect to R_{t+1} then yields

$$\frac{1}{R_t - R_{t+1}} = E_t \frac{\beta}{R_{t+1} - R_{t+2}}.$$

This second-order difference equation, which really represents an Euler equation for consumption of the oil producer, is easily solved: it delivers $R_{t+1} = \beta R_t$ implying $C_{o,t} = p_{1,t}\left(1-\beta\right)R_t$. Note, in particular, that even if $p_{1,t}$ is stochastic, it has no effect on oil supply. The reason is simply that the income and substitution effects exactly cancel with logarithmic preferences. Conversely, note that our setup allows us to side-step the Hotelling price formula, by which the price of oil—in case its marginal production cost is zero and there is no monopoly power—would have to rise at the real rate of interest. The key behind this is that oil producers cannot invest their proceeds from an oil sale (say, in case of an oil-price hike) at a "global rate of interest", since they do not have access, by assumption, to the global capital market. This assumption is of course unrealistic in its extreme form but the notion that there are at least some restrictions on these kinds of trade should not be controversial. In any case, it has been very difficult to reconcile the Hotelling price formula with emperical observations, see e.g., Hart and Spiro (2011).

We may now write the behavior of energy service providers as the solution to the cost-minimization problem

$$\min_{e_{k,t}} \sum_{k=1}^{n} p_{k,t} e_{k,t} - \Lambda_t \left(\left(\sum_{k=1}^{n} \lambda_k \left(e_{k,t} \right)^{\rho} \right)^{\frac{1}{\rho}} - E_t \right). \tag{6}$$

Here we note that by construction the Lagrange multiplier $\Lambda_t = P_t$, the price index of energy services.

The first-order condition for $e_{k,t}$ yields, for $k \in \{2, n\}$,

$$e_{k,t} = E_t \left(\frac{P_t \lambda_k}{p_{k,t}} \right)^{\frac{1}{1-\rho}} \tag{7}$$

and similarly oil consumption satisfies

$$e_{1,t} = E_t \left(\frac{P_{t,} \lambda_1}{p_{1,t}} \right)^{\frac{1}{1-\rho}}. \tag{8}$$

Using this finding in the expenditure function, we arrive at

$$P_t = \left(\sum_{k=1}^{n} p_{k,t}^{\frac{\rho}{\rho-1}} \lambda_k^{\frac{1}{1-\rho}} \right)^{\frac{\rho-1}{\rho}}. \tag{9}$$

Producers of the final good maximize profits the oil price as given, so that

$$P_t = \nu \frac{A_t L_t^{1-\alpha-\nu} K_t^{\alpha} E_t^{\nu}}{E_t}.$$

This can be solved for energy-service demand:

$$E_t = \left(\nu \frac{A_t L_t^{1-\alpha-\nu} K_t^{\alpha}}{P_t} \right)^{\frac{1}{1-\nu}}.$$

Output net of energy expenses reads $(1-\nu)\,Y_t \equiv \hat{Y}_t$. Note, however, that the shares of spending on the different energy sources are not constant unless $\rho = 0$, i.e., unless the overall production function is Cobb-Douglas in all inputs.

Households in the oil-consuming economy supply labor inelastically; we will normalize its value to unity. The households thus maximize (1) subject to the budget constraint

$$C_t + K_{t+1} = w_t L_t + r_t K_t + (1-\delta)\,K_t.$$

Here $w_t = (1-\alpha-\nu)\,\frac{Y_t}{L_t}$ and $r_t = \frac{\alpha Y_t}{K_t}$, so that $w_t L_t + r_t K_t = \hat{Y}_t$.

We will take one time period to be long enough that we can make the assumption that $\delta = 1$. Define the savings rate out of net output to be $s_t = \frac{\hat{Y}_t - C_t}{\hat{Y}_t}$. We can then write the Euler equation for the households

$$\begin{aligned} \frac{C_{t+1}}{C_t} &= \beta \frac{\partial Y_{t+1}}{\partial K_{t+1}} \\ \frac{(1-s_{t+1})\,(1-\nu)Y_{t+1}}{(1-s_t)\,(1-\nu)Y_t} &= \beta \frac{\alpha Y_{t+1}}{s_t(1-\nu)Y_t}. \end{aligned}$$

By inspection we see that the savings rate must be constant over time at $s = \frac{\alpha\beta}{1-\nu}$.

Proposition 1 *In each period the allocation is determined by the state variables* K_t, R_t *and* S_{t-1} *such that i) the capital savings rate is constant at* $\frac{\alpha\beta}{1-\nu}$*, ii) oil supply is* $(1-\beta)R_t$*, iii) energy price is* $P_t = \left(\sum_{k=1}^{n} p_{k,t}^{\frac{\rho}{\rho-1}} \lambda_k^{\frac{1}{1-\rho}}\right)^{\frac{\rho-1}{\rho}}$*, iv) energy service demand is* $E_t = \left(\nu \frac{e^{(z_t - \gamma_t S_{t-1})} L_t^{1-\alpha-\nu} K_t^{\alpha}}{P_t}\right)^{\frac{1}{1-\nu}}$*, v) domestic fuel demand is* $e_{k,t} = E_t \left(\frac{P_t \lambda_k}{p_{k,t}}\right)^{\frac{1}{1-\rho}}$*, and vi) oil demand is* $e_{1,t} = E_t \left(\frac{P_t \lambda_1}{p_{1,t}}\right)^{\frac{1}{1-\rho}}$*. The price of oil is determined from equilibrium at the world oil market* $e_{1,t} = (1-\beta)\,R_t$*. The laws of motion for the state variables are* $K_t = \alpha\beta Y_t$*,* $R_{t+1} = \beta R_t$*, and* $S_t = \sum_{v=0}^{t}(1-d_{t-v})M_t$*.*

Two things are noteworthy here. First, the allocation is determined sequentially without any forward-looking terms; this is a result of the combination of functional forms that allow income and substitutions effects to cancel. Second, conditional on a world market price of oil, all equilibrium conditions have closed-form solutions. Finding the equilibrium in any period t is therefore only a matter of finding the equilibrium oil price, where supply is "predetermined" $(1-\beta)\,R_t$ (as a result of optimal oil extraction).

2.5 Taxation

A key goal of the present analysis is to analyze the consequences of taxing fossil fuel and, in particular, to assess the effectiveness of less than fully optimal taxation. With this aim, we allow the oil-consuming region to tax the users of fossil energy inputs. A carbon tax rate τ_t is thus imposed, implying that the total cost for the energy service provider of using energy type k becomes $(1 + \tau_t g_k)\, p_{k,t}$.

The immediate result of adding taxes is that the price of energy and the mix of fuels changes. These are straightforward to calculate. The prices $p_{1,t}$ and $p_{k,t}$ are simply replaced by tax-inclusive prices in (7), (8), and (9). The aggregate use of energy services is still given by

$$E_t = \left(\nu \frac{A_t L_t^{1-\alpha-\nu} K_t^{\alpha}}{P_t} \right)^{\frac{1}{1-\nu}}$$

but now using the tax-inclusive energy price.

The only complication resulting from taxes is that it matters for outcomes how the government revenues are handled. Due to the implied income effects, if the revenues are redistributed lump-sum to households, the savings rate will no longer be exactly $\alpha\beta/(1-\nu)$. However, our numerical analysis suggests that the quantitative effect of this effect is negligible, essentially because the income share of energy is small (ν is on the order of a few percent): energy taxes simply cannot generate much revenue measured as share of GDP. An alternative is to assume that the revenues from taxing fossil fuel are "wasted" or spent on goods whose consumption value do not interfere with how consumption is determined. However, if tax revenues are wasted, the calculation of optimal taxes will be biased. In order to maintain tractability we opt for the former assumption along with savings rules that remain at $\alpha\beta/(1-\nu)$, hence implying that consumers do not smooth consumption fully optimally over time (conditional on their revenues). This is unlikely to lead to a sizable bias compared to the one that would arise if the tax revenues were wasted. Given this approach, all the other features of proposition 1 remain intact.

3 Calibration

We first describe how we calibrate the benchmark model and then how the key uncertainty is captured.

3.1 Basic model parameters

We use a discount factor of 0.985^{10} with the understanding that a period is a decade. In the final-good production function, we set $\alpha = 0.3$ and the fuel income share ν to 0.055. We assume that labor input is constant and normalize it to 1.

The production of energy services is calibrated as follows. For the elasticity of substitution between the three sources of energy, we use a meta-study (Stern, 2012) of 47 studies of inter-fuel substitution. The unweighted mean of the oil-coal, oil-electricity, and coal-electricity elasticities is 0.95, i.e., slightly below unity. This elasticity implies $\rho = -0.058$, which we use as the main case. Note, in this context, that the meta-study is based on substitution elasticities for different time horizons. At the same time, our arguments in Hassler, Krusell, and Olovsson (2017) discussed above suggests that a close to Cobb-Douglas elasticity is likely a reasonable outcome from endogenous input-saving technology choice.

In order to calibrate the λ's we need prices and quantities of the three fuel types. Here we follow Golosov at al. (2014), who used a coal price of \$74/ton and a carbon content of 71.6%. The (pre-financial crises) oil price was \$70/barrel, corresponding to \$70·7.33 per ton and a carbon content of 84.6%. This implies a relative price between oil and coal in units of carbon of 5.87 (oil being worth more per carbon unit).

We then use the same source for the global ratio of oil to coal use in carbon units, namely 0.916. With the use of equations (7) and (8) we find that $\frac{\lambda_1}{\lambda_2} = 5.348$. For green energy we use data for the sum of nuclear, hydro, wind, waste, and other renewables, also from Golosov et al. (2014), and retain their assumption of a unitary relative price between oil and renewables. This delivers $\frac{\lambda_1}{\lambda_3} = 1.527$. Along with the normalization $1 = \lambda_1 + \lambda_2 + \lambda_3$, this implies that $\lambda_1 = 0.543$, $\lambda_2 = 0.102$, and $\lambda_3 = 0.356$. We also need a value for the initial stock of conventional oil. Again following Golosov at al. (2014), it is set to 300 GtC.

For the carbon cycle parameters, we also follow Golosov et al. (2014) and set $\varphi_L = 0.2$, $\varphi_0 = 0.393$, and $\varphi = 0.0228$. We take the year 2010 stock of excess atmospheric carbon (221 GtC) as an initial condition. Of that, 104 GtC is not depreciating but stays in the atmosphere indefinitely. The pre-industrial stock of carbon ($\bar{S}$ in equation (4)) is set to 581 GtC.

We assume that initial global GDP is 75 trillion US\$ per year and set initial productivity and capital so that the economy is on a balanced growth path. Productivity in final-goods production, e^{z_t}, is assumed to grow at 1.5% per year and we assume that the cost of producing coal and green fuel is constant in terms of the final good. This rate of productivity increase implies an annual GDP growth rate of about 2%.

3.2 Climate and damage uncertainty

As discussed in the introduction, the purpose of this paper is to explore the range of economic outcomes at the endpoints of a range of plausible estimates for (i) the sensitivity of the climate to the carbon concentration and (ii) the sensitivity of the economy to the climate. For the former, we use the range given in a 2013 IPCC report, where they state that the equilibrium climate sensitivity (λ) is "likely in the range 1.5 to 4.5°C".[3] Since we are interested in the end points of the ranges, denoted λ_H and λ_L, we set $\lambda_H = 4.5$ and $\lambda_L = 1.5$.

To provide a similar range for the sensitivity of the economy to global warming, we build on the recent paper by Nordhaus and Moffat (2017). There the authors provide a rather comprehensive survey of studies of global damages from climate change. They also argue that the different studies should not be given equal weight in trying to distill a representative estimate of the aggregate effects of global warning. One particularly convincing argument for the unequal weights is that some studies are derivatives of earlier studies. What they do is somewhat judgmental, but they operationalize their approach by assigning a weight between zero and one, representing in reliability/originality, to each of the studies. All in all, they find 36 "usable" estimates of damages, expressed as percentages of global GDP, for different temperatures and it is based on these 36 studies that they then construct their ranges.

In Figure 1, we show the estimates reported by Nordhaus and Moffat (2017). The x axis measures the increase in the average global temperature and the y axis represents the percentage loss in world GDP; the size of bubbles indicates the attached weight.

We use the Nordhaus-Moffat estimates to calibrate the likely range of economic sensitivity translated into our damage-function formulation. In our formulation, thus, we will need to derive a range for the parameter γ in (5). To accomplish this, we first observe that given a value of λ, the Arrhenius equation (4) can be inverted to yield S as a function of T:

$$S\left(T;\lambda\right) = \bar{S}\left(e^{\frac{T\ln 2}{\lambda}} - 1\right).$$

By assumption, the damage associated with a given amount S of excess atmospheric carbon concentration in our formulation is

$$1 - e^{-\gamma S}.$$

---

[3] (IPCC, 2013a, page 81 and IPCC, 2013b, Box 12.1). The report also makes explicit that "likely" should be taken to mean a probability of 66-100%.

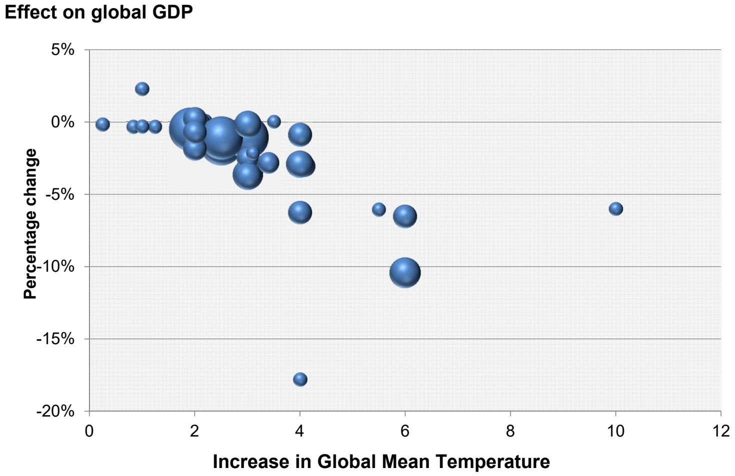

Figure 1: The Nordhaus-Moffat meta-study.

Thus, let $\hat{\Delta}_i(T_i)$ be a particular estimate of the effect on GDP at a temperature T_i. Then, for a given climate sensitivity λ, each one of the 36 estimates implies an estimate $\hat{\gamma}_i$ that satisfies

$$\hat{\gamma}_{i;\lambda} = -\frac{\ln\left(1 - \hat{\Delta}_i(T_i)\right)}{S(T_i;\lambda)}.$$

For each of the two climate sensitivities under consideration, λ_H and λ_L, we thus obtain a set of damage elasticities $\hat{\gamma}_{i;\lambda}$. Within each of the sets, we define two subsets, high and low damage elasticities, denoted $\Gamma_{H,\lambda}$ and $\Gamma_{L,\lambda}$. These are constructed as follows. Let π_i,$i \in \{1,\ldots,36\}$ denote the weight Nordhaus and Moffat (2017) assigned to the different studies on global climate damages. Then the sets of high-damage elasticities is defined as the smallest set of the highest $\hat{\gamma}_{i;\lambda}$ such that

$$\sum_{i\in\Gamma_{H,\lambda}} \pi_i \geq 0.2 \sum_{i=1}^{36} \pi_i.$$

The set of low-damage elasticities is defined by instead collecting the lowest damage elasticities. Finally, our endpoint elasticities are defined as the weighted average value in the respective sets. Our result is that for λ_L, the endpoints, denoted γ_{L,λ_L} and γ_{H,λ_L}, are 0.27 and 1.79. For λ_H, we obtain $\gamma_{L,\lambda_H} = 1.44$ and $\gamma_{H,\lambda_H} = 10.39$, all expressed as percent (of global GDP) per 1,000 excess atmospheric GtC.

4 Results

We now describe and discuss our results, beginning with optimal-tax calculations and then looking at outcomes (for the economy and the climate) under different scenarios.

4.1 Optimal taxes

The methodology starts with an optimal-tax calculation (or, equivalently, the calculation an optimal marginal damage externality, which will equal the optimal tax in a standard Pigou manner). Thus, given any value of γ, we can use the formula from Golosov et al. (2014) for an optimal tax—the setting here is a special case of that described there. This formula reads

$$\tau_t = \gamma Y_t \left(\frac{\varphi_L}{1-\beta} + \frac{(1-\varphi_L)\varphi_0}{1-(1-\varphi)\beta} \right), \tag{10}$$

where we note that all parameters are expressed for a period length of a decade. Note that the optimal tax is proportional to global GDP with only three kinds of parameters, representing discounting (β), carbon depreciation (the φs), and damages (γ).

We will maintain the carbon depreciation parameters throughout and mainly focus on damages, but we will also comment on, and do robustness with respect to, discounting. For the four values of γ, the associated optimal tax rates are given in Table 1. In addition to the tax per ton of carbon, we also express it in U.S. cents per gallon of gasoline using a carbon content of 2.4 kg/gallon.

Table 1	Base line	
γ	Tax US\$/ton C	Tax US cents/gallon gasoline
$\gamma_{L,\lambda_L} = 0.27$	6.9	1.6
$\gamma_{H,\lambda_L} = 1.79$	45.5	10.9
$\gamma_{L,\lambda_H} = 1.44$	36.6	8.8
$\gamma_{H,\lambda_H} = 10.39$	264.4	63.4

Less stern discounting We can also show the optimal tax rates assuming a lower subjective discount rate. Specifically, we select an alternative discount rate to be that suggested in the Stern Review (Stern, 2006), namely 0.1% per year. The optimal tax rates for this discount rate are presented in Table 2.

Table 2 Low discount rate

γ	Tax US$/ton C	Tax US cents/gallon gasoline
$\gamma_{L,\lambda_L} = 0.27$	60.3	14.5
$\gamma_{H,\lambda_L} = 1.79$	399.5	95.9
$\gamma_{L,\lambda_H} = 1.44$	321.4	77.1
$\gamma_{H,\lambda_H} = 10.39$	2319	556

Clearly, the tax values are much higher here. In the high-high sensitivity case, the tax per gallon of gas would exceed $5 and thus near ten times that with higher discounting.

Quasi-geometric discounting Iverson and Karp (2017) show that the if discounting is quasi-geometric, we can find a Markov-perfect Nash equilibrium in a tax-setting game using the current model setting. In particular, they can extend the closed-form solutions studied here to such cases. Applying their formula to a case when the discount rate is 1.5% per year during the first decade and thereafter 0.1%, we obtain optimal taxes as in Table 3.

Table 3 Non-geometric discounting

γ	Tax US$/ton C	Tax US cents/gallon gasoline
$\gamma_{L,\lambda_L} = 0.27$	55.8	13.4
$\gamma_{H,\lambda_L} = 1.79$	369.6	88.7
$\gamma_{L,\lambda_H} = 1.44$	297.4	71.4
$\gamma_{H,\lambda_H} = 10.39$	2146	515

We see that the implied numbers are similar to those coming from Stern-like discounting.

4.2 Scenarios

Let us now use the model to compare the different scenarios. We therefore solve the model for the four different combinations of parameters, representing the four combinations of high and climate sensitivity and high and low economic sensitivity. Moreover, for each of the four cases, we solve the model without taxes and with taxes. We set the tax to the optimal level in the first period and then let it increase by 2% per year (22% per decade) which is approximately equal to the balanced-growth path for GDP.[4] Throughout, we use the high discount rate, i.e., a level of 1.5% per year.

Note that the model's prediction for T_{2015} depends on the climate sensitivity and, to a less extent, on first period emissions (the two extreme values are 0.8 and 2.4 degrees Celsius). The current global mean temperature is approximately 1 degree above the average over the period 1951–1960. Using this as calibration target would yield a moderate climate sensitivity of around 2, interior to our range of uncertainty. There is no scientific consensus about whether the fairly low temperature increase is a sign of a low climate sensitivity or due to other temporary factors, such as inertia or dimming due to airborne particles.

In Figure 2, we show the path of global mean temperature. We graph increases in the temperature over the initial period, which varies between the scenarios as just discussed.

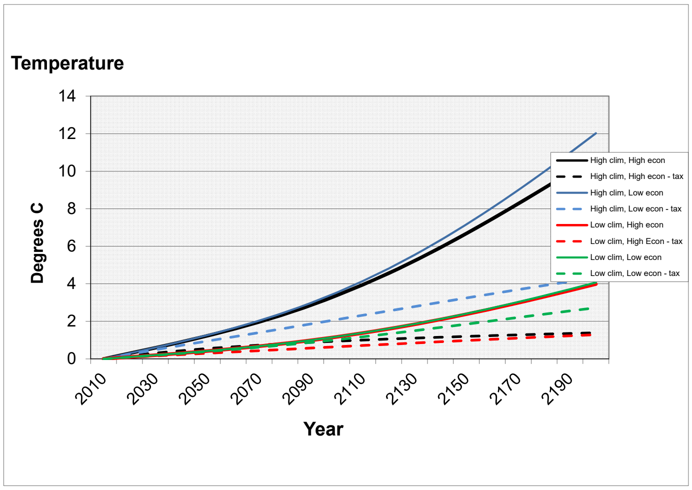

Figure 2: Climate outcomes in all scenarios

For all four combinations of parameters, solid curves represent the laissez-faire allocation. The figure shows that in laissez faire, the level of economic sensitivity is not important for the

---

[4] Recall that the optimal tax should be indexed to GDP, as shown in equation (10). Thus, solving for a fully optimal equilibrium path implemented by taxes involves a fixed-point problem: at all points in time, the tax level depends on optimal GDP but optimal GDP depends on the tax. The simplification we adopt here circumvents this fixed-point problem by having slightly suboptimal taxes.

climate. Instead, the speed of climate change is largely determined by the climate sensitivity. In the case of high climate sensitivity, the temperature increases very fast: it will have risen by 3.4 degrees Celsius by the end of the century and will continue to accelerate thereafter. In the opposite case, with low climate sensitivity, the increase in the global mean temperature relative to today is one degree Celsius by the end of the current century.

Figure 2 also shows that taxes are highly effective in bringing down global warming. When the climate sensitivity and the economic sensitivity both are high, the introduction of the optimal tax implies that global warming is slowed down sharply. Until 2100 the temperature increase over the current level is less than one degree Celsius and 100 years later it has increased by only an additional 0.4 degrees Celsius. This is substantially smaller than in the case of low climate sensitivity and no taxes.

Another important point shown in the figure is that with optimal taxes, there is a strong link between climate change and the economic sensitivity. In the case of a high climate sensitivity, climate change is, as just noted, almost halted. However, if the economic sensitivity is low, substantially more climate change should be allowed—2.1 degrees Celsius relative to the initial level by 2105 and 4.3 towards the end of the simulation period.

Finally, we see that if the climate sensitivity is low, climate change is obviously slower, but it is still affected rather substantially by the tax. This is particularly so in the case of high economic sensitivity, in which case no more than a 1.3 degrees Celsius increase should be allowed over the two-century horizon. In fact, this number is close to the corresponding number when the climate sensitivity is high. Thus, although the optimal tax rates are very different in the cases with low and high climate sensitivity, the targets for the temperature increase are similar when the economic sensitivity is high. Of course, the lower tax in the case of low climate sensitivity would imply more carbon emissions than in the high climate sensitivity case, but the resulting temperature increase would be almost the same.

Moving to economic effects, Figure 3 shows the damages caused by climate change. Reflecting the finding for climate change, we see that taxes are effective in mitigating climate damages in all cases, thus keeping them on a fairly flat trajectory. Of course, the damage estimates for very high levels of climate change are especially uncertain here, but the purpose in the present paper is not to speculate on costs beyond what is reported in the Nordhaus-Moffat meta-study.

Figure 4 shows global consumption, measured *relative* to the most benign scenario: that with low climate and economic sensitivities (with optimal taxes imposed). Consumption can be viewed as a flow measure of welfare.

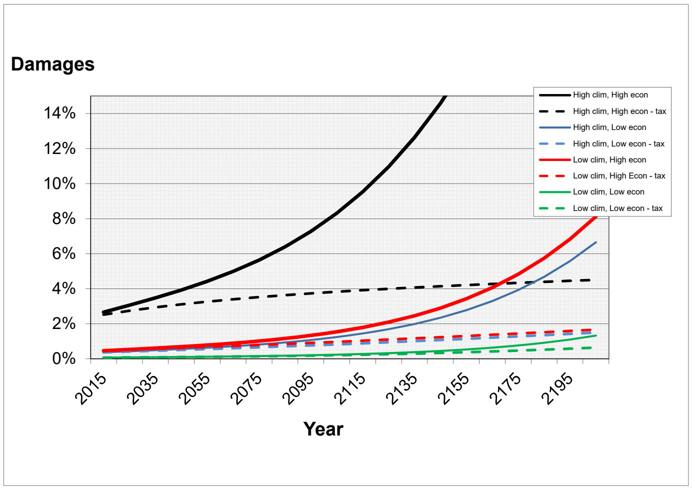

Figure 3: Economic externalities

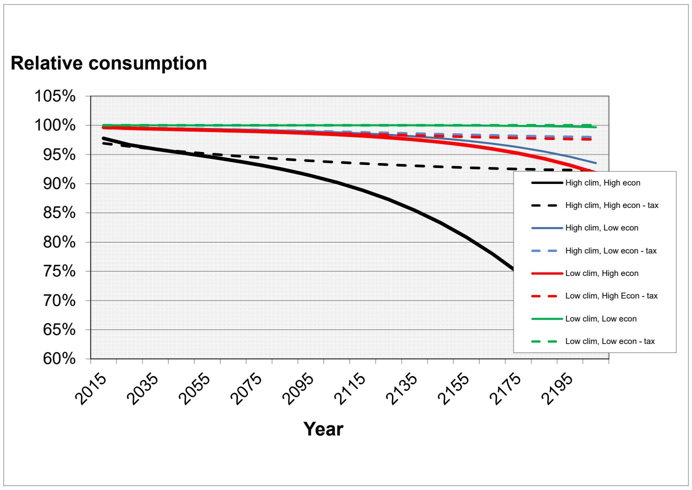

Figure 4: Consumption relative to case with low climate and low economic sensitivity with taxes

The figure reveals that the stakes are very high when climate and economic sensitivities are high. Without a climate policy, consumption is significantly lower. A climate policy cannot remove all negative consequences of climate change in this case, but it can remove a very significant part. In all the other scenarios, the stakes are substantially smaller.

Figure 5 depicts coal use.

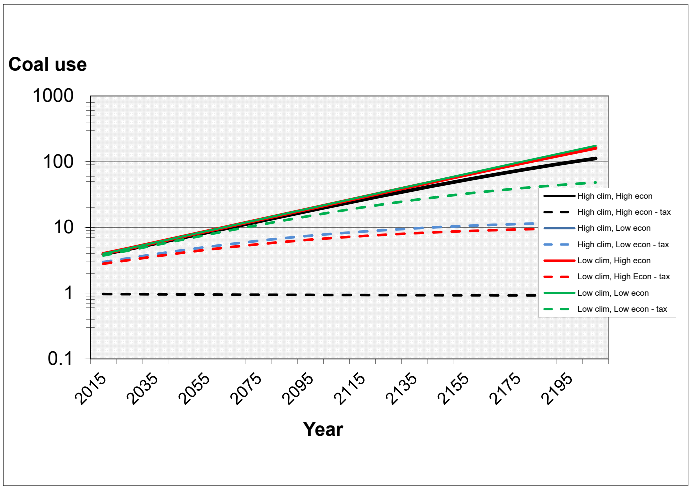

Figure 5: Coal use

We see that in all the scenarios without taxes, coal use grows approximately exponentially.[5] In the case of high climate and high economic sensitivities, coal use is approximately flat under the optimal tax while it does increase, albeit not exponentially, as long as either of the sensitivities is low.

Let us finally consider the consequences of policy mistakes. Specifically, suppose the true state of the world is that both the climate sensitivity and the economic sensitivity are high while a "overly passive climate policy" is pursued, as represented by a tax that is optimal in the state of low sensitivities. Conversely, also consider the situation where the true state

---

[5] Whether this implies that we will run out of coal within the simulation period is an unsettled issue. On the one hand, standard references like BP (2017) estimates global proved coal reserves to 816 Gt which would not allow a trajectory like the higher ones in figure 5. On the other hand, other estimates of the stock of all hydrocarbon sources that potentially could be used could actually allow such trajectories (Rogner, 1997).

of the world is benign, with both sensitivities at their low values, but where the highest tax (which is optimal in the high-sensitivities world) is adopted: “overly zealous climate policy”. The results in terms of global consumption of these two kinds of policy errors are presented in Figure 6. In both cases, we let the wrong tax be in place for all of the simulation period. Obviously, if we interpret this as only a mistake, such a persistent error is unlikely given that we would likely learn the true state and introduce the correspondingly appropriate tax. However, using a too low tax in the case when a high one is optimal could be due to a political failure not related to a lack of information but of international coordination. Thus, also such a scenario is of interest.

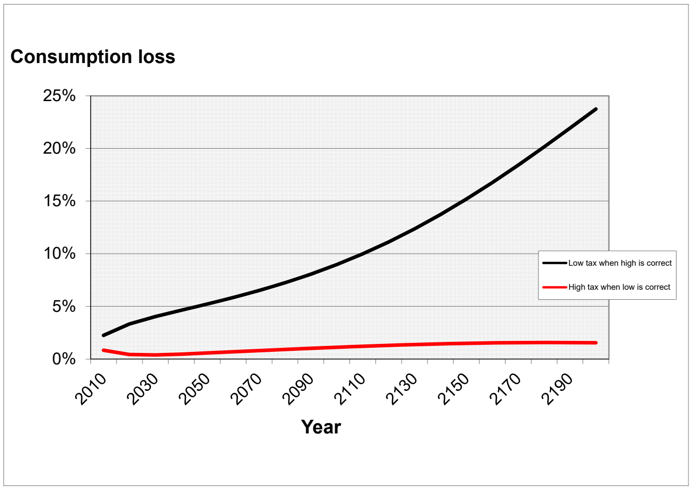

Figure 6: Overly passive and overly zealous policy

As we see from the graph, there is a stark difference between the two types of errors. Failing to introduce a high tax when it is necessary has dramatic consequences for consumption and welfare while unnecessarily imposing a (much) to high tax has very moderate consequences. The intuition for this result is that it is relatively cheap to replace coal-based energy production with greener sources. Thus, doing this in vain is not a great loss. On the other hand, not having replaced coal-based production with green energy if both the climate and economic sensitivities are high will inflict serious damage to welfare.

5 Concluding remarks

We have looked at two kinds of uncertainty here. There are others. For example, one could straightforwardly extend the present analysis to cover uncertainty about the carbon cycle. One could also consider uncertainty about mitigation costs, which could be accomplished by looking at a range of elasticities of substitution between green and fossil fuels in energy provision. One could also discuss uncertainty about the assumptions we have entertained here about technological change, both in its general form and in how technologies for energy production may develop. Yet another line of inquiry regards the possible irreversibilities involved by incorrectly scrapping fossil-based capital and infrastructure, thus influencing the discussion of the two kinds of policy errors. There are also basic model parameters that could be altered. We assume, for example, logarithmic utility curvature, which allows for greater tractability, but limits the range of welfare consequences somewhat. Similarly, more curvature could be introduced on the damage side. We leave all these extensions for future work.

6 References

Acemoglu D, Aghion P, Bursztyn L, Hémous D. 2012. The environment and directed technical change. *American Economic Review.* 102:131-66.

Acemoglu D, Aghion P, Hémous D. 2014. The environment and directed technical change in a north-south model. *Oxford Review of Economic Policy.* 30:513-30.

Aghion P, Dechezleprêtre A, Hémous D, Martin R, Van Reenen J. 2016. Carbon taxes, path dependency, and directed technical change: evidence from the auto industry. *Journal of Political Economy.* 124:1-51.

Arrhenius S. 1896. On the influence of carbonic acid in the air upon the temperature of the ground. *Philosophical Magazine and Journal of Science.* 41:237-76.

Bornstein G, Krusell P, Rebelo S. 2017. Lags, costs, and shocks: an equilibrium model of the oil industry". NBER WP 23423.

BP. 2017. BP Statistical Review of World Energy. http://bp.com/statisticalreview

Cai Y, Judd KL, Lontzek TS. 2013. The social cost of stochastic and irreversible climate change", NBER WP 18704.

Dasgupta P, Heal G. 1976. The optimal depletion of exhaustible resources. *The Review of Economic Studies.* 41:3-28.

EIA. 2012. Annual energy review 2011. U.S. Energy Information Administration.

Golosov M, Hassler J, Krusell P, Tsyvinski A. 2014. Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82:41-88.

Hart R, Spiro D. 2011. The elephant in Hotelling's room. Energy Policy 39:7834-38.

Hassler J, Krusell P. 2012. Economics and climate change: integrated assessment in a multi-region world", *Journal of the European Economic Association.* 10:974-1000.

Hassler J, Krusell P, Olovsson C. 2017. Directed technical change as a response to natural-resource scarcity. Working paper, IIES Stockholm, Univ.

Hassler J, Krusell P, Olovsson C, Reiter M. 2017. Integrated assessment in a multi-region world with multiple energy sources and endogenous technical change. Working paper, IIES Stockholm, Univ.

Hémous D. 2016. The dynamic impact of unilateral environmental policies. *Journal of International Economics.* 103:80-95.

Gollier, C. 2013, *Pricing the planet's future: the economics of discounting in an uncertain world.* Princeton University Press.

Hildebrand E, Hildebrand M. 2017. Optimal climate policies in a dynamic multi-country equilibrium model", Working Paper, Gutenberg School of Management & Economics, Mainz Univ.

Jensen S, Traeger CP. 2016. Optimal climate change mitigation under long-term growth uncertainty: stochastic integrated assessment and analytic findings. *European Economic Review.* 69:104-25.

Lemoine DM. 2010. Climate sensitivity distributions dependence on the possibility that models share biases. *Journal of Climate.* 23:4395–4415.

Nordhaus W. 1977. Economic growth and climate: the carbon dioxide problem. *American Economic Review.* 67:341–46.

Nordhaus W. 1994. *Managing the global commons: the economics of climate change*, Cambridge: MIT Press.

Nordhaus W. 2011. Integrated economic and climate Modeling. Cowles Foundation Discussion Paper 1839.

Nordhaus W, Boyer J. 2000. *Warming the world: economic modeling of global warming*, Cambridge: MIT Press..

Nordhaus W, Moffat A. 2017. A survey of global impacts if climate change: replications, survey methods and a statistical analysis. NBER Working Paper 23646.

McGlade C, Ekins P. 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature* 517:187-90

Pigou A. 1920. *The Economics of Welfare,* London: MacMillan.

Popp D. 2002. Induced innovation and energy prices. *American Economic Review.* 92:160-80.

Rogner H. 1997. An assessment of world hydrocarbon resources. *Annual Review of Energy and the Environment.* 22:217-2.

Romer P. 1986. Increasing returns and long-run growth. *Journal of Political Economy.* 9:1002-37.

Stern DI. 2012. Interfuel substitution: a meta-analysis. *Journal of Economic Surveys.* 26:307-31.

Sinn HW. 2017. Buffering volatility: a study on the limits of Germany's energy revolution. *European Economic Review.* 99:130-50.

Weitzman ML. 2011. Fat-tailed uncertainty in the economics of catastrophic climate change. *Review of Environmental Economics and Policy*, 5:275-92.

Earlier Working Papers:

For a complete list of Working Papers published by Sveriges Riksbank, see www.riksbank.se

Estimation of an Adaptive Stock Market Model with Heterogeneous Agents *by Henrik Amilon*	2005:177
Some Further Evidence on Interest-Rate Smoothing: The Role of Measurement Errors in the Output Gap *by Mikael Apel and Per Jansson*	2005:178
Bayesian Estimation of an Open Economy DSGE Model with Incomplete Pass-Through by Malin Adolfson, Stefan Laséen, Jesper Lindé and Mattias Villani	2005:179
Are Constant Interest Rate Forecasts Modest Interventions? Evidence from an Estimated Open Economy DSGE Model of the Euro Area *by Malin Adolfson, Stefan Laséen, Jesper Lindé and Mattias Villani*	2005:180
Inference in Vector Autoregressive Models with an Informative Prior on the Steady State *by Mattias Villani*	2005:181
Bank Mergers, Competition and Liquidity *by Elena Carletti, Philipp Hartmann and Giancarlo Spagnolo*	2005:182
Testing Near-Rationality using Detailed Survey Data *by Michael F. Bryan and Stefan Palmqvist*	2005:183
Exploring Interactions between Real Activity and the Financial Stance *by Tor Jacobson, Jesper Lindé and Kasper Roszbach*	2005:184
Two-Sided Network Effects, Bank Interchange Fees, and the Allocation of Fixed Costs *by Mats A. Bergman*	2005:185
Trade Deficits in the Baltic States: How Long Will the Party Last? *by Rudolfs Bems and Kristian Jönsson*	2005:186
Real Exchange Rate and Consumption Fluctuations follwing Trade Liberalization *by Kristian Jönsson*	2005:187
Modern Forecasting Models in Action: Improving Macroeconomic Analyses at Central Banks *by Malin Adolfson, Michael K. Andersson, Jesper Lindé, Mattias Villani and Anders Vredin*	2005:188
Bayesian Inference of General Linear Restrictions on the Cointegration Space *by Mattias Villani*	2005:189
Forecasting Performance of an Open Economy Dynamic Stochastic General Equilibrium Model *by Malin Adolfson, Stefan Laséen, Jesper Lindé and Mattias Villani*	2005:190
Forecast Combination and Model Averaging using Predictive Measures *by Jana Eklund and Sune Karlsson*	2005:191
Swedish Intervention and the Krona Float, 1993-2002 *by Owen F. Humpage and Javiera Ragnartz*	2006:192
A Simultaneous Model of the Swedish Krona, the US Dollar and the Euro *by Hans Lindblad and Peter Sellin*	2006:193
Testing Theories of Job Creation: Does Supply Create Its Own Demand? *by Mikael Carlsson, Stefan Eriksson and Nils Gottfries*	2006:194
Down or Out: Assessing The Welfare Costs of Household Investment Mistakes *by Laurent E. Calvet, John Y. Campbell and Paolo Sodini*	2006:195
Efficient Bayesian Inference for Multiple Change-Point and Mixture Innovation Models *by Paolo Giordani and Robert Kohn*	2006:196
Derivation and Estimation of a New Keynesian Phillips Curve in a Small Open Economy *by Karolina Holmberg*	2006:197
Technology Shocks and the Labour-Input Response: Evidence from Firm-Level Data *by Mikael Carlsson and Jon Smedsaas*	2006:198
Monetary Policy and Staggered Wage Bargaining when Prices are Sticky *by Mikael Carlsson and Andreas Westermark*	2006:199
The Swedish External Position and the Krona *by Philip R. Lane*	2006:200

Price Setting Transactions and the Role of Denominating Currency in FX Markets *by Richard Friberg and Fredrik Wilander*	2007:201
The geography of asset holdings: Evidence from Sweden *by Nicolas Coeurdacier and Philippe Martin*	2007:202
Evaluating An Estimated New Keynesian Small Open Economy Model *by Malin Adolfson, Stefan Laséen, Jesper Lindé and Mattias Villani*	2007:203
The Use of Cash and the Size of the Shadow Economy in Sweden *by Gabriela Guibourg and Björn Segendorf*	2007:204
Bank supervision Russian style: Evidence of conflicts between micro- and macro-prudential concerns *by Sophie Claeys and Koen Schoors*	2007:205
Optimal Monetary Policy under Downward Nominal Wage Rigidity *by Mikael Carlsson and Andreas Westermark*	2007:206
Financial Structure, Managerial Compensation and Monitoring *by Vittoria Cerasi and Sonja Daltung*	2007:207
Financial Frictions, Investment and Tobin's q *by Guido Lorenzoni and Karl Walentin*	2007:208
Sticky Information vs Sticky Prices: A Horse Race in a DSGE Framework *by Mathias Trabandt*	2007:209
Acquisition versus greenfield: The impact of the mode of foreign bank entry on information and bank lending rates *by Sophie Claeys and Christa Hainz*	2007:210
Nonparametric Regression Density Estimation Using Smoothly Varying Normal Mixtures *by Mattias Villani, Robert Kohn and Paolo Giordani*	2007:211
The Costs of Paying – Private and Social Costs of Cash and Card *by Mats Bergman, Gabriella Guibourg and Björn Segendorf*	2007:212
Using a New Open Economy Macroeconomics model to make real nominal exchange rate forecasts *by Peter Sellin*	2007:213
Introducing Financial Frictions and Unemployment into a Small Open Economy Model *by Lawrence J. Christiano, Mathias Trabandt and Karl Walentin*	2007:214
Earnings Inequality and the Equity Premium *by Karl Walentin*	2007:215
Bayesian forecast combination for VAR models *by Michael K. Andersson and Sune Karlsson*	2007:216
Do Central Banks React to House Prices? *by Daria Finocchiaro and Virginia Queijo von Heideken*	2007:217
The Riksbank's Forecasting Performance *by Michael K. Andersson, Gustav Karlsson and Josef Svensson*	2007:218
Macroeconomic Impact on Expected Default Freqency *by Per Åsberg and Hovick Shahnazarian*	2008:219
Monetary Policy Regimes and the Volatility of Long-Term Interest Rates *by Virginia Queijo von Heideken*	2008:220
Governing the Governors: A Clinical Study of Central Banks *by Lars Frisell, Kasper Roszbach and Giancarlo Spagnolo*	2008:221
The Monetary Policy Decision-Making Process and the Term Structure of Interest Rates *by Hans Dillén*	2008:222
How Important are Financial Frictions in the U S and the Euro Area *by Virginia Queijo von Heideken*	2008:223
Block Kalman filtering for large-scale DSGE models *by Ingvar Strid and Karl Walentin*	2008:224
Optimal Monetary Policy in an Operational Medium-Sized DSGE Model *by Malin Adolfson, Stefan Laséen, Jesper Lindé and Lars E. O. Svensson*	2008:225
Firm Default and Aggregate Fluctuations *by Tor Jacobson, Rikard Kindell, Jesper Lindé and Kasper Roszbach*	2008:226
Re-Evaluating Swedish Membership in EMU: Evidence from an Estimated Model *by Ulf Söderström*	2008:227

The Effect of Cash Flow on Investment: An Empirical Test of the Balance Sheet Channel *by Ola Melander*	2009:228
Expectation Driven Business Cycles with Limited Enforcement *by Karl Walentin*	2009:229
Effects of Organizational Change on Firm Productivity *by Christina Håkanson*	2009:230
Evaluating Microfoundations for Aggregate Price Rigidities: Evidence from Matched Firm-Level Data on Product Prices and Unit Labor Cost *by Mikael Carlsson and Oskar Nordström Skans*	2009:231
Monetary Policy Trade-Offs in an Estimated Open-Economy DSGE Model *by Malin Adolfson, Stefan Laséen, Jesper Lindé and Lars E. O. Svensson*	2009:232
Flexible Modeling of Conditional Distributions Using Smooth Mixtures of Asymmetric Student T Densities *by Feng Li, Mattias Villani and Robert Kohn*	2009:233
Forecasting Macroeconomic Time Series with Locally Adaptive Signal Extraction *by Paolo Giordani and Mattias Villani*	2009:234
Evaluating Monetary Policy *by Lars E. O. Svensson*	2009:235
Risk Premiums and Macroeconomic Dynamics in a Heterogeneous Agent Model *by Ferre De Graeve, Maarten Dossche, Marina Emiris, Henri Sneessens and Raf Wouters*	2010:236
Picking the Brains of MPC Members *by Mikael Apel, Carl Andreas Claussen and Petra Lennartsdotter*	2010:237
Involuntary Unemployment and the Business Cycle *by Lawrence J. Christiano, Mathias Trabandt and Karl Walentin*	2010:238
Housing collateral and the monetary transmission mechanism *by Karl Walentin and Peter Sellin*	2010:239
The Discursive Dilemma in Monetary Policy *by Carl Andreas Claussen and Øistein Røisland*	2010:240
Monetary Regime Change and Business Cycles *by Vasco Cúrdia and Daria Finocchiaro*	2010:241
Bayesian Inference in Structural Second-Price common Value Auctions *by Bertil Wegmann and Mattias Villani*	2010:242
Equilibrium asset prices and the wealth distribution with inattentive consumers *by Daria Finocchiaro*	2010:243
Identifying VARs through Heterogeneity: An Application to Bank Runs *by Ferre De Graeve and Alexei Karas*	2010:244
Modeling Conditional Densities Using Finite Smooth Mixtures *by Feng Li, Mattias Villani and Robert Kohn*	2010:245
The Output Gap, the Labor Wedge, and the Dynamic Behavior of Hours *by Luca Sala, Ulf Söderström and Antonella Trigari*	2010:246
Density-Conditional Forecasts in Dynamic Multivariate Models *by Michael K. Andersson, Stefan Palmqvist and Daniel F. Waggoner*	2010:247
Anticipated Alternative Policy-Rate Paths in Policy Simulations *by Stefan Laséen and Lars E. O. Svensson*	2010:248
MOSES: Model of Swedish Economic Studies *by Gunnar Bårdsen, Ard den Reijer, Patrik Jonasson and Ragnar Nymoen*	2011:249
The Effects of Endogenuos Firm Exit on Business Cycle Dynamics and Optimal Fiscal Policy *by Lauri Vilmi*	2011:250
Parameter Identification in a Estimated New Keynesian Open Economy Model *by Malin Adolfson and Jesper Lindé*	2011:251
Up for count? Central bank words and financial stress *by Marianna Blix Grimaldi*	2011:252
Wage Adjustment and Productivity Shocks *by Mikael Carlsson, Julián Messina and Oskar Nordström Skans*	2011:253

Stylized (Arte) Facts on Sectoral Inflation *by Ferre De Graeve and Karl Walentin*	2011:254
Hedging Labor Income Risk *by Sebastien Betermier, Thomas Jansson, Christine A. Parlour and Johan Walden*	2011:255
Taking the Twists into Account: Predicting Firm Bankruptcy Risk with Splines of Financial Ratios *by Paolo Giordani, Tor Jacobson, Erik von Schedvin and Mattias Villani*	2011:256
Collateralization, Bank Loan Rates and Monitoring: Evidence from a Natural Experiment *by Geraldo Cerqueiro, Steven Ongena and Kasper Roszbach*	2012:257
On the Non-Exclusivity of Loan Contracts: An Empirical Investigation *by Hans Degryse, Vasso Ioannidou and Erik von Schedvin*	2012:258
Labor-Market Frictions and Optimal Inflation *by Mikael Carlsson and Andreas Westermark*	2012:259
Output Gaps and Robust Monetary Policy Rules *by Roberto M. Billi*	2012:260
The Information Content of Central Bank Minutes *by Mikael Apel and Marianna Blix Grimaldi*	2012:261
The Cost of Consumer Payments in Sweden *by Björn Segendorf and Thomas Jansson*	2012:262
Trade Credit and the Propagation of Corporate Failure: An Empirical Analysis *by Tor Jacobson and Erik von Schedvin*	2012:263
Structural and Cyclical Forces in the Labor Market During the Great Recession: Cross-Country Evidence *by Luca Sala, Ulf Söderström and AntonellaTrigari*	2012:264
Pension Wealth and Household Savings in Europe: Evidence from SHARELIFE *by Rob Alessie, Viola Angelini and Peter van Santen*	2013:265
Long-Term Relationship Bargaining *by Andreas Westermark*	2013:266
Using Financial Markets To Estimate the Macro Effects of Monetary Policy: An Impact-Identified FAVAR* *by Stefan Pitschner*	2013:267
DYNAMIC MIXTURE-OF-EXPERTS MODELS FOR LONGITUDINAL AND DISCRETE-TIME SURVIVAL DATA *by Matias Quiroz and Mattias Villani*	2013:268
Conditional euro area sovereign default risk *by André Lucas, Bernd Schwaab and Xin Zhang*	2013:269
Nominal GDP Targeting and the Zero Lower Bound: Should We Abandon Inflation Targeting?* *by Roberto M. Billi*	2013:270
Un-truncating VARs* *by Ferre De Graeve and Andreas Westermark*	2013:271
Housing Choices and Labor Income Risk *by Thomas Jansson*	2013:272
Identifying Fiscal Inflation* *by Ferre De Graeve and Virginia Queijo von Heideken*	2013:273
On the Redistributive Effects of Inflation: an International Perspective* *by Paola Boel*	2013:274
Business Cycle Implications of Mortgage Spreads* *by Karl Walentin*	2013:275
Approximate dynamic programming with post-decision states as a solution method for dynamic economic models *by Isaiah Hull*	2013:276
A detrimental feedback loop: deleveraging and adverse selection *by Christoph Bertsch*	2013:277
Distortionary Fiscal Policy and Monetary Policy Goals *by Klaus Adam and Roberto M. Billi*	2013:278
Predicting the Spread of Financial Innovations: An Epidemiological Approach *by Isaiah Hull*	2013:279
Firm-Level Evidence of Shifts in the Supply of Credit *by Karolina Holmberg*	2013:280

Lines of Credit and Investment: Firm-Level Evidence of Real Effects of the Financial Crisis *by Karolina Holmberg*	2013:281
A wake-up call: information contagion and strategic uncertainty *by Toni Ahnert and Christoph Bertsch*	2013:282
Debt Dynamics and Monetary Policy: A Note *by Stefan Laséen and Ingvar Strid*	2013:283
Optimal taxation with home production *by Conny Olovsson*	2014:284
Incompatible European Partners? Cultural Predispositions and Household Financial Behavior *by Michael Haliassos, Thomas Jansson and Yigitcan Karabulut*	2014:285
How Subprime Borrowers and Mortgage Brokers Shared the Piecial Behavior *by Antje Berndt, Burton Hollifield and Patrik Sandås*	2014:286
The Macro-Financial Implications of House Price-Indexed Mortgage Contracts *by Isaiah Hull*	2014:287
Does Trading Anonymously Enhance Liquidity? *by Patrick J. Dennis and Patrik Sandås*	2014:288
Systematic bailout guarantees and tacit coordination *by Christoph Bertsch, Claudio Calcagno and Mark Le Quement*	2014:289
Selection Effects in Producer-Price Setting *by Mikael Carlsson*	2014:290
Dynamic Demand Adjustment and Exchange Rate Volatility *by Vesna Corbo*	2014:291
Forward Guidance and Long Term Interest Rates: Inspecting the Mechanism *by Ferre De Graeve, Pelin Ilbas & Raf Wouters*	2014:292
Firm-Level Shocks and Labor Adjustments *by Mikael Carlsson, Julián Messina and Oskar Nordström Skans*	2014:293
A wake-up call theory of contagion *by Toni Ahnert and Christoph Bertsch*	2015:294
Risks in macroeconomic fundamentals and excess bond returns predictability *by Rafael B. De Rezende*	2015:295
The Importance of Reallocation for Productivity Growth: Evidence from European and US Banking *by Jaap W.B. Bos and Peter C. van Santen*	2015:296
SPEEDING UP MCMC BY EFFICIENT DATA SUBSAMPLING *by Matias Quiroz, Mattias Villani and Robert Kohn*	2015:297
Amortization Requirements and Household Indebtedness: An Application to Swedish-Style Mortgages *by Isaiah Hull*	2015:298
Fuel for Economic Growth? *by Johan Gars and Conny Olovsson*	2015:299
Searching for Information *by Jungsuk Han and Francesco Sangiorgi*	2015:300
What Broke First? Characterizing Sources of Structural Change Prior to the Great Recession *by Isaiah Hull*	2015:301
Price Level Targeting and Risk Management *by Roberto Billi*	2015:302
Central bank policy paths and market forward rates: A simple model *by Ferre De Graeve and Jens Iversen*	2015:303
Jump-Starting the Euro Area Recovery: Would a Rise in Core Fiscal Spending Help the Periphery? *by Olivier Blanchard, Christopher J. Erceg and Jesper Lindé*	2015:304
Bringing Financial Stability into Monetary Policy* *by Eric M. Leeper and James M. Nason*	2015:305
SCALABLE MCMC FOR LARGE DATA PROBLEMS USING DATA SUBSAMPLING AND THE DIFFERENCE ESTIMATOR *by MATIAS QUIROZ, MATTIAS VILLANI AND ROBERT KOHN*	2015:306

SPEEDING UP MCMC BY DELAYED ACCEPTANCE AND DATA SUBSAMPLING *by MATIAS QUIROZ*	2015:307
Modeling financial sector joint tail risk in the euro area *by André Lucas, Bernd Schwaab and Xin Zhang*	2015:308
Score Driven Exponentially Weighted Moving Averages and Value-at-Risk Forecasting *by André Lucas and Xin Zhang*	2015:309
On the Theoretical Efficacy of Quantitative Easing at the Zero Lower Bound *by Paola Boel and Christopher J. Waller*	2015:310
Optimal Inflation with Corporate Taxation and Financial Constraints *by Daria Finocchiaro, Giovanni Lombardo, Caterina Mendicino and Philippe Weil*	2015:311
Fire Sale Bank Recapitalizations *by Christoph Bertsch and Mike Mariathasan*	2015:312
Since you're so rich, you must be really smart: Talent and the Finance Wage Premium *by Michael Böhm, Daniel Metzger and Per Strömberg*	2015:313
Debt, equity and the equity price puzzle *by Daria Finocchiaro and Caterina Mendicino*	2015:314
Trade Credit: Contract-Level Evidence Contradicts Current Theories *by Tore Ellingsen, Tor Jacobson and Erik von Schedvin*	2016:315
Double Liability in a Branch Banking System: Historical Evidence from Canada *by Anna Grodecka and Antonis Kotidis*	2016:316
Subprime Borrowers, Securitization and the Transmission of Business Cycles *by Anna Grodecka*	2016:317
Real-Time Forecasting for Monetary Policy Analysis: The Case of Sveriges Riksbank *by Jens Iversen, Stefan Laséen, Henrik Lundvall and Ulf Söderström*	2016:318
Fed Liftoff and Subprime Loan Interest Rates: Evidence from the Peer-to-Peer Lending *by Christoph Bertsch, Isaiah Hull and Xin Zhang*	2016:319
Curbing Shocks to Corporate Liquidity: The Role of Trade Credit *by Niklas Amberg, Tor Jacobson, Erik von Schedvin and Robert Townsend*	2016:320
Firms' Strategic Choice of Loan Delinquencies *by Paola Morales-Acevedo*	2016:321
Fiscal Consolidation Under Imperfect Credibility *by Matthieu Lemoine and Jesper Lindé*	2016:322
Challenges for Central Banks' Macro Models *by Jesper Lindé, Frank Smets and Rafael Wouters*	2016:323
The interest rate effects of government bond purchases away from the lower bound *by Rafael B. De Rezende*	2016:324
COVENANT-LIGHT CONTRACTS AND CREDITOR COORDINATION *by Bo Becker and Victoria Ivashina*	2016:325
Endogenous Separations, Wage Rigidities and Employment Volatility *by Mikael Carlsson and Andreas Westermark*	2016:326
Renovatio Monetae: Gesell Taxes in Practice *by Roger Svensson and Andreas Westermark*	2016:327
Adjusting for Information Content when Comparing Forecast Performance *by Michael K. Andersson, Ted Aranki and André Reslow*	2016:328
Economic Scarcity and Consumers' Credit Choice *by Marieke Bos, Chloé Le Coq and Peter van Santen*	2016:329
Uncertain pension income and household saving *by Peter van Santen*	2016:330
Money, Credit and Banking and the Cost of Financial Activity *by Paola Boel and Gabriele Camera*	2016:331
Oil prices in a real-business-cycle model with precautionary demand for oil *by Conny Olovsson*	2016:332
Financial Literacy Externalities *by Michael Haliasso, Thomas Jansson and Yigitcan Karabulut*	2016:333

The timing of uncertainty shocks in a small open economy *by Hanna Armelius, Isaiah Hull and Hanna Stenbacka Köhler*	2016:334
Quantitative easing and the price-liquidity trade-off *by Marien Ferdinandusse, Maximilian Freier and Annukka Ristiniemi*	2017:335
What Broker Charges Reveal about Mortgage Credit Risk *by Antje Berndt, Burton Hollifield and Patrik Sandåsi*	2017:336
Asymmetric Macro-Financial Spillovers *by Kristina Bluwstein*	2017:337
Latency Arbitrage When Markets Become Faster *by Burton Hollifield, Patrik Sandås and Andrew Todd*	2017:338
How big is the toolbox of a central banker? Managing expectations with policy-rate forecasts: Evidence from Sweden *by Magnus Åhl*	2017:339
International business cycles: quantifying the effects of a world market for oil *by Johan Gars and Conny Olovsson l*	2017:340
Systemic Risk: A New Trade-Off for Monetary Policy? *by Stefan Laséen, Andrea Pescatori and Jarkko Turunen*	2017:341
Household Debt and Monetary Policy: Revealing the Cash-Flow Channel *by Martin Flodén, Matilda Kilström, Jósef Sigurdsson and Roine Vestman*	2017:342
House Prices, Home Equity, and Personal Debt Composition *by Jieying Li and Xin Zhang*	2017:343
Identification and Estimation issues in Exponential Smooth Transition Autoregressive Models *by Daniel Buncic*	2017:344
Domestic and External Sovereign Debt *by Paola Di Casola and Spyridon Sichlimiris*	2017:345
The Role of Trust in Online Lending *by Christoph Bertsch, Isaiah Hull, Yingjie Qi and Xin Zhang*	2017:346
On the effectiveness of loan-to-value regulation in a multiconstraint framework *by Anna Grodecka*	2017:347
Shock Propagation and Banking Structure *by Mariassunta Giannetti and Farzad Saidi*	2017:348
The Granular Origins of House Price Volatility *by Isaiah Hull, Conny Olovsson, Karl Walentin and Andreas Westermark*	2017:349
Should We Use Linearized Models To Calculate Fiscal Multipliers? *by Jesper Lindé and Mathias Trabandt*	2017:350
The impact of monetary policy on household borrowing – a high-frequency IV identification *by Maria Sandström*	2018:351
Conditional exchange rate pass-through: evidence from Sweden *by Vesna Corbo and Paola Di Casola*	2018:352
Learning on the Job and the Cost of Business Cycles *by Karl Walentin and Andreas Westermark*	2018:353
Trade Credit and Pricing: An Empirical Evaluation *by Niklas Amberg, Tor Jacobson and Erik von Schedvin*	2018:354
A shadow rate without a lower bound constraint *by Rafael B. De Rezende and Annukka Ristiniemi*	2018:355
Reduced "Border Effects", FTAs and International Trade *by Sebastian Franco and Erik Frohm*	2018:356
Spread the Word: International Spillovers from Central Bank Communication *by Hanna Armelius, Christoph Bertsch, Isaiah Hull and Xin Zhang*	2018:357
Predictors of Bank Distress: The 1907 Crisis in Sweden *by Anna Grodecka, Seán Kenny and Anders Ögren*	2018:358

Diversification Advantages During the Global Financial Crisis *by Mats Levander*	2018:359
Towards Technology-News-Driven Business Cycles *by Paola Di Casola and Spyridon Sichlimiris*	2018:360
The Housing Wealth Effect: Quasi-Experimental Evidence *by Dany Kessel, Björn Tyrefors and Roine*	2018:361
Identification Versus Misspecification in New Keynesian Monetary Policy Models *by Malin Adolfson, Stefan Laseén, Jesper Lindé and Marco Ratto*	2018:362
The Macroeconomic Effects of Trade Tariffs: Revisiting the Lerner Symmetry Result *by Jesper Lindé and Andrea Pescatori*	2019:363
Biased Forecasts to Affect Voting Decisions? The Brexit Case *by Davide Cipullo and André Reslow*	2019:364
The Interaction Between Fiscal and Monetary Policies: Evidence from Sweden *by Sebastian Ankargren and Hovick Shahnazarian*	2019:365
Designing a Simple Loss Function for Central Banks: Does a Dual Mandate Make Sense? *by Davide Debortoli, Jinill Kim and Jesper Lindé*	2019:366
Gains from Wage Flexibility and the Zero Lower Bound *by Roberto M. Billi and Jordi Galí*	2019:367
Fixed Wage Contracts and Monetary Non-Neutrality *by Maria Björklund, Mikael Carlsson and Oskar Nordström Skans*	2019:368

Sveriges Riksbank
Visiting address: Brunkebergs torg 11
Mail address: se-103 37 Stockholm

Website: www.riksbank.se
Telephone: +46 8 787 00 00, Fax: +46 8 21 05 31
E-mail: registratorn@riksbank.se