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# Evolutionary macroeconomic assessment of employment and innovation impacts of climate policy packages

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Climate policy has been mainly studied with economic models that assume representative, rational agents. Such policy aims, though, at changing carbon-intensive consumption and production patterns driven by bounded rationality and other-regarding preferences, such as status and imitation. To examine climate policy under such alternative behavioral assumptions, we develop a model tool by adapting an existing general-purpose macroeconomic multi-agent model. The resulting tool allows testing various climate policies in terms of combined climate and economic performance. The model is particularly suitable to address the distributional impacts of climate policies, not only because populations of many agents are included, but also as these are composed of different classes of households. The approach accounts for two types of innovations, which improve either the carbon or labor intensity of production. We simulate policy scenarios with distinct combinations of carbon taxation, a reduction of labor taxes, subsidies for green innovation, a price subsidy to consumers for less carbon-intensive products, and green government procurement. The results show pronounced differences with those obtained by rational-agent model studies. It turns out that a supply-oriented subsidy for green innovation, funded by the revenues of a carbon tax, results in a significant reduction of carbon emissions without causing negative effects on employment. On the contrary, demand-oriented subsidies for adopting greener technologies, funded in the same manner, result in either none or considerably less reduction of carbon emissions and may even lead to higher unemployment. Our study also contributes insight on a potential double dividend of shifting taxes from labor to carbon.



## 1. Introduction

The study and testing of climate policies is predominantly undertaken using models that assume representative, rational economic agents. It is nevertheless widely accepted now that this does not represent an accurate approximation of a reality characterized by heterogeneous agents with bounded rationality and socially mediated preferences, such as imitation, status

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or snob effects. Recognizing such boundedly rational behavior is relevant for the study of climate policies, as they aim to stimulate people to drastically change their decisions and even life styles (Gowdy, 2008; Brekke and Johansson-Stenman, 2008; Gsottbauer and van den Bergh, 2010). This raises questions about behavioral barriers and opportunities, and to what extent we can expect major societal changes and systems transitions (Grin et al., 2010). Existing climate-economy models are not well equipped in a behavioral sense to answer such questions.

Here we offer an original study of climate policy using an evolutionary macroeconomic model. It uses agent-based methodology to describe an artificial one-country economy, accounting for different types of boundedly rational and socially mediated preferences of agents. It is the result of adapting and extending a general-purpose evolutionary macroeconomic model developed by Rengs and Scholz-Wäckerle (2014, 2017, 2019). This model belongs to a growing set of agent-based models (ABMs) in macroeconomics and political economy, which respond to a call in economics to give more attention to behavior, heterogeneity and complexity in financial- and macroeconomics (LeBaron and Tesfatsion, 2008; Farmer and Foley, 2009; Delli Gatti et al., 2010; Kirman, 2011; Stiglitz and Gallegati, 2011). It further connects to earlier climate policy studies such as Gerst et al. (2013) – which rely on an aggregated household sector and do not feature a banking sector – and an emerging literature on evolutionary-economic analysis of energy transitions (Safarzynska et al., 2012). In contrast, the evolutionary macroeconomic model presented here features heterogeneous firms and households, a banking sector with credit relations and private debt, and distinctive ownership of firms by capitalists. Thus it provides a solid basis for investigating the economic and environmental effects of climate policy packages.

The proposed model describes households who consume goods that serve aspirations for needs and wants, respectively. The first type of consumption is necessary, while the social mediation of preferences, such as through status and imitation, motivates people's consumption of the second type. In the present model setting, status and snob effects make firm and bank owners switch the consumption of wants and search for new firms, thus forming an important factor of economic innovation. Firms innovate on the basis of how well they performed in the last period. The model includes two types of innovation: in emission reduction technology, increasing the productivity of carbon in the economy (thus reducing the need for carbon or fossil fuels), which may be subsidized by governments; and innovation in labor productivity.[1] The incorporation of the two innovation types is relevant as it allows comparing and balancing innovations that affect the environment and employment, and also other economic variables such as income and wealth, in distinct ways. The environmental extension of the general evolutionary macroeconomic model further involves the specification of $CO_2$ emissions by firms. The carbon intensity (emissions per unit of (monetary) output) of a firm can be reduced through enhancing its carbon productivity, i.e., green innovation. Firms ask for loans at commercial banks in order to invest into new machinery and R&D, while the government decides about a policy package that comprises various types of taxes, including possibly a carbon tax, subsidies that lower consumer prices of low-carbon alternatives, and subsidies on technological innovation or adoption, or investment in green procurement. These climate policy packages are the only mechanisms assumed in the model that could enable a systemic change towards a low-carbon economy in the simulation experiments. It is crucial to stress that we do not assume any further agent-specific behavioral mechanisms that could additionally enable the mitigation of emissions (e.g., a particular aspiration for less carbon-intensive goods).

We use the resulting evolutionary macroeconomic model and its environmental extension to test different climate policies in terms of their impacts on a range of relevant environmental and economic indicators as well as on the distribution of wealth. Except for a first climate policy package (CPP), which transfers the collected tax revenues to the regular government budget, we study CPPs which put these revenues in a "carbon fund" which then financially supports additional policies. This gives rise to five additional CPPs. The second CPP subsidizes green innovation. A third one considers a tax shift from labor to carbon, which essentially means using the carbon fund to reduce labor taxes. A fourth examines the effects of a direct consumer subsidy by the carbon fund to stimulate diffusion of green products. As a fifth CPP, we consider a carbon tax with revenues spent on green procurement. A final CPP undertakes all these policies simultaneously. The selection of these CPPs is motivated by recent discussions about effective climate policies and recycling of carbon tax revenues (Carl and Fedor, 2016; Baranzini et al., 2017; Cramton et al., 2017; Meckling et al., 2017; Stiglitz et al., 2017), which have however not yet been systematically tested using agent-based models. We will investigate the policy packages in terms of environmental and economic performance. Environmental performance will focus on the time patterns of carbon intensity of production, and cumulative $CO_2$ emissions as a measure of global warming. Economic indicators include GDP, unemployment and wealth distribution. This issue is of crucial importance, as carbon pricing is not part of the Paris Climate Agreement, which likely means it will be rather ineffective in reducing emissions. In fact, it is widely accepted now that the agreement cannot guarantee emissions to stay within or even near a carbon budget consistent with its high target of 2 °C warming. According to a study by Raftery et al. (2017) the expected median temperature rise under the Paris Agreement is 3.2 °C while the likely range of warming is up to 4.9 °C. In other words, there is an urgent need for robust analysis of climate policies using realistic assumptions of economic behavior and complexity, as captured by evolutionary macroeconomic models.

As part of the analysis, we will test the effect of an environmental tax on (un)employment, and address in a new, innovative way the well-known "double dividend", i.e. achieving environment and employment goals, of environmental tax revision (e.g., Fullerton and Metcalf, 1997; de Mooij, 1999; Bosello et al., 2001; Freire-González and Ho, 2018). This debate

[1] Labor productivity is equivalent to total factor productivity in this model since we work with a Leontief-type production function, as explained later. We use the term labor productivity throughout the article in relation to technological change that advances the performance of physical capital of firms (i.e., machinery and equipment), thereby reducing the demand for labor.

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has been largely waged over general equilibrium effects under rationality assumptions without explicitly taking into account innovation impacts, endogenous consumer dynamics and wealth distributions. Here we re-examine its main conclusion that a double dividend is unlikely. Apart from testing it for bounded rationality and social interactions, our approach will take into account the dual effect of a tax shift from labor to carbon: (i) providing incentives to firms to innovate in improvements in carbon rather than in labor productivity; and (ii) stimulating a shift in household consumption to less carbon-intensive products and services. The central question is how different the findings of our approach are compared with those of traditional economic model studies.

Our study contributes to the debate on green growth, which so far has not devoted much attention to climate constraints, and certainly not from the angle of evolutionary macroeconomic analysis (Antal and van den Bergh, 2016). In this context, the productivity trap is relevant: higher labor productivity due to innovation results in more unemployment which is compensated by more demand due to higher wages; but higher wages stimulate further labor productivity rises (Jackson and Victor, 2011). We can well study this issue in relation to the policy involving a shift of taxes from labor to carbon, accounting for two types of innovation, namely affecting carbon and labor productivities. The question is whether this results in a double dividend, that is, a reduction in emissions along with an increase in employment. According to a recent survey by Freire-González (2018) the evidence on this is rather divided. Hence, it is worthwhile to also study this topic using agent-based modeling, as done here.

The remainder of this article is organized as follows. Section 2 explains the general structure of the agent-based model used and clarifies unique features in comparison with similar model approaches. In Section 3 we discuss the environmental-climate extension of this model, define the policy scenarios and select performance indicators. Section 4 presents the simulation results and provides interpretations of these. Section 5 concludes.

## 2. The basic evolutionary macroeconomic model

The basic model we later extend encompasses a full macro-economy that evolves from bottom-up according to agent-based methodology (Tesfatsion and Judd, 2006; Gilbert, 2007), building upon the framework presented in Rengs and Scholz-Wäckerle (2014, 2017, 2019). It includes the following sectors: households, firms producing consumption and capital goods, banks, central bank and government. All sectors are disaggregated, except central bank and government, in the sense that they are composed of a multitude of agents and their interactive dynamic relations. Our model is close in spirit to recent evolutionary macroeconomic models by Dosi et al. (2010), Ciarli et al. (2010), Cincotti et al. (2010), Delli Gatti et al. (2011), Seppecher (2012), Lengnick (2013), Riccetti et al. (2013), Chen et al. (2014), Dawid et al. (2014), Lorentz et al. (2016), Caiani et al. (2016) and Safarzynska and van den Bergh (2016). The model is able to generate emergence of specialization patterns of firms in terms of needs and wants aspirations of consumers, as shown in Rengs and Scholz-Wäckerle (2019). To illustrate, a firm produces goods that may initially serve just basic needs, and over time shift endogenously to serving the want aspirations of heterogeneous households. This avoids the more common approach of starting with a fixed classification of firms or sectors with particular goods that permanently retain their character.

The social mediation of preferences – via signaling-by-consuming as empirically validated by Heffetz (2011) – steers consumer demand in this macroeconomic agent-based model, taking the form of imitation (bandwagon effects) or status seeking behavior, depending on the particular consumer class. In the case of status-seeking behavior, we consider Veblen effects (conspicuous consumption) and snob effects; both imply a focus on luxury goods, but while the first is about expensive, the second is related to rare goods (Leibenstein 1950). Because of the population structure consisting of different agent groups, including for consumers and firms, the model can generate co-evolutionary changes in behaviors and institutions (van den Bergh and Stagl, 2003; Hodgson, 2006; Dopfer and Potts, 2008; Wäckerle, 2014).

A detailed analytical description of the base model is contained in Rengs and Scholz-Wäckerle (2019). In what follows, we introduce first an overview of the different types of agents, namely households, firms, the banking system (commercial banks and a central bank), and the government.

### *2.1. Households*

Households do not optimize their consumption behavior but are instead assumed to be rather loyal in their choice of vendors, while also being open to new opportunities that arise. Their decisions (namely, which firms' products to buy) are linked to two differently motivational aspirations, one for needs and the other for wants. The tendency to buy from a specific firm then is contingent on the respective aspiration, the current product's relative price and firm reputation, in turn depending on the firm's market shares. The latter two are based on well-documented consumer behaviors: bandwagon, Veblen and snob effects (Leibenstein 1950). The consumption decision differs with respect to social class and income group as empirically observed and documented by Veblen (1899), validated by Bourdieu (1984) , recently tested by Heffetz (2011) and extensively discussed by Trigg (2001) and Wright (2015). In our model, we differentiate between capitalist households, wealthy workers and (other) workers (see Rengs and Scholz-Wäckerle, 2019). Capitalist households and wealthy workers have a higher saving rate than workers who spend a larger share of their budget on satisfying needs aspiration, following Engel's law (Chai and Moneta 2010; Heffetz 2011). Changes of social class are possible and endogenous: capitalists may go bankrupt, wealthy workers may found a firm, etc. Eventually, workers, wealthy workers and capitalists are characterized by distinct preferences and behaviors.

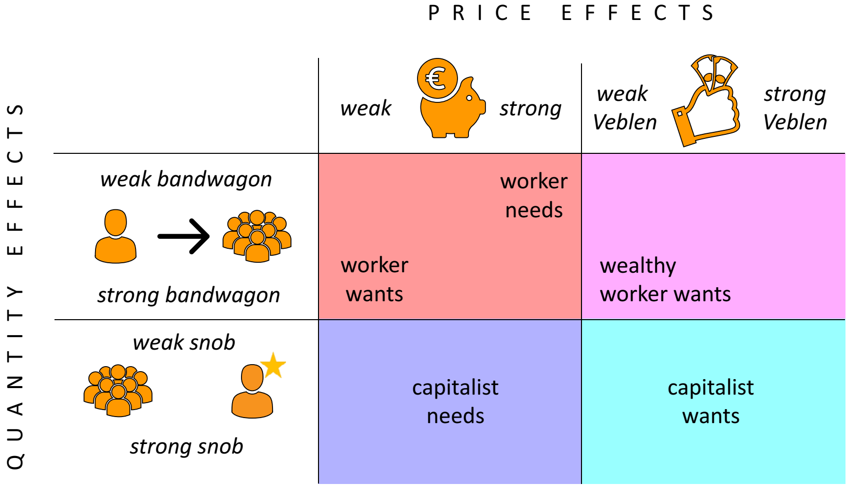


**Fig. 1.** Social interactions and associated signaling-by-consuming effects dependent on social class.

We model Veblenian consumer dynamics in a similar manner as Kapeller and Schütz (2015) but with substantially more details about differences in quantity and price effects as well as about the underlying social dynamics. Additionally, we employ a snob effect that roughly represents Bourdieu's (1984) model of trickle-around (Trigg 2001). Snob consumption is modeled as pure distinction, that is, the opposite of the bandwagon effect. This distinction is crucial for our setting, because it avoids potential lock-in due to market dynamics. As a result of this approach, even already established firms may crash after many years, giving rise to a market restructuring of the economy.

According to Leibenstein (1950: 205), there are four possible combinations of consumption behavior, dependent on price (normal price and Veblen effect) and firm reputation (bandwagon and snob effect). We extend his framework by including needs and wants aspirations as well as social class. This results in connecting aspiration (wants and needs) to social class (workers, wealthy workers, capitalists), as illustrated graphically in Fig. 1. Workers' consumption for satisfying the needs aspirations has a high normal price effect (indicating a strong preference for the cheap over the expensive) and a low bandwagon effect. Workers imitate the behavior of all consumers with a needs aspiration. Workers' wants aspirations have a low normal price effect (indicating a weak preference for the cheap over the expensive) and a high bandwagon effect; see Heffetz (2011) for an empirical test of income elasticity vs. visibility across different income groups. In particular, they imitate capitalists' wants aspirations. Whereas wealthy workers follow the same bandwagon, they further show a weak Veblen effect in consumption, i.e., weakly preferring the expensive over the cheap. Finally, needs of capitalists, including firms and bank owners, are triggered partially by a snob effect (i.e., searching for rare goods – inverted imitation) and partially by a normal price effect. Capitalists' wants work similarly, with the same partial snob effect but additionally with a Veblen effect, as they prefer the expensive over the cheap. In view of this, consumption takes the form of a co-evolving process between behaviors of consumers and social structure.

Households choose their seller in a boundedly rational way, by having a short list of preferred "vendors" at any given time (Lengnick, 2013). They try to buy equal amounts from each firm on their list, as firms' stock and household budgets permit. Households actually employ two lists, one for needs and one for wants. Initially, each of these lists consists of $n$ randomly chosen firms. During the simulation, households change the composition of these lists based on their preferences, slowly improving them in each round. As preferences are assumed to be different for needs and wants, these two lists will tend to comprise different firms. In the case of needs aspirations, households replace a firm that did not deliver – because of insufficient production or inventory – by another, randomly chosen one. In the case of wants consumption, households do not immediately replace a firm that could not deliver, as it indicates a highly sought after good. Instead, they wait up to three months before randomly choosing a new one.

If a seller (firm) is considered for potential replacement and is perceived to be better (by some small but noticeable degree) in terms of price and firm reputation (implying a utility premium for a household consuming its good) than the one selected for potential elimination from the list, the replacement is effectuated. These lists are updated every period by considering a random firm that is not yet part of the shortlist. Next, the utilities are compared of purchasing from this specific firm with that of purchasing from a random firm on the shortlist. This difference depends on the households' social class and consumption aspiration as previously described (for more details, see Rengs and Scholz-Wäckerle 2019).

An individual can changes its social class: e.g., capitalists may go bankrupt with their firm, or wealthy workers may found a firm. As such class changes tend not to be recognized immediately by society, they happen in the model with a time lag (set at three months).

Workers, wealthy workers and capitalists have different preferences and behaviors, as highlighted in Fig. 1. Worker consumption has a high normal price effect (indicating a strong preference for the cheap over the expensive) and a low

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bandwagon effect. Workers imitate the behavior of all needs consumers. Worker want aspirations have a low normal price effect (indicating a weak preference for the cheap over the expensive) and a high bandwagon effect (they imitate the capitalist wants aspirations), while wealthy workers follow the same bandwagon and consume showing a weak Veblen effect (i.e., they weakly prefer the expensive over the cheap).

Finally, capitalist (firm and bank owners') needs are triggered partially by a snob effect (searching for rare goods – inverted imitation) and partially by a normal price effect. Capitalist wants work with the same partial snob effect but additionally with a Veblen effect (they prefer the expensive over the cheap). Consumption behavior is thus not static but a co-evolving process between behaviors of consumers and the social structure.

As indicated before, our model households employ shortlists of preferred firms for each consumption case. These lists are updated every period by considering a random firm, not yet part of the shortlist, and comparing the utility of purchasing from this specific firm with that of purchasing from a random firm on the shortlist. This evaluation follows the behavioral modes (as described above and sketched in Fig. 1) and thus differs for the household social class and consumption aspiration. The following equations show how utility is derived for the worker needs in period $t$:

$$b_{1,i,t} = \left( \frac{p_{max,t} - p_{i,t}}{p_{max,t} - p_{min,t}} \right) \tag{1}$$

$$b_{2,j,t} = \left( \frac{m_{max,t} - m_{j,t}}{m_{max,\,t} - m_{min,t}} \right) \tag{2}$$

$$b_{3,i,t} = \left( \frac{v_{i,t} - v_{min,t}}{v_{max,t} - v_{min,t}} \right) \tag{3}$$

$$U_{i,j,t} = b_{1,i,t} b_{2,j,t} \xi \; + b_{3,i,t} (1 - \xi) \tag{4}$$

Here $i$ denotes a firm, $j$ denotes the household and $t$ the time period. The symbol $b_{1,\,i,\,t}$ represents the firm's normalized relative price in comparison to the prices of all other firms and $b_{2,\,j,\,t}$ denotes the household's normalized relative wealth in relation to all other households. Furthermore, $b_{3,\,i,\,t}$ stands for the firm's normalized reputation, while $v$ is calculated from firms' past sales; in this illustrative case of needs aspirations of workers, it directly corresponds to firms' market shares to reflect the bandwagon effect. Finally utility $U_{i,\,j,\,t}$ is composed of the price component $b_{1,\,i,\,t}$ weighted with the relative wealth $b_{1,\,j,\,t}$ and the weight parameter $\xi$, plus the firm's reputation weighted by $(1 - \xi)$. Thereby parameter $\xi$ controls for the price effect. The remaining three cases of wants aspirations of worker classes, and needs as well as wants aspirations of capitalists are defined similarly, as discussed in Appendix 3.

In this respect we follow on the one hand Veblen's general suggestion of trickle-down effects in social structure (Trigg, 2001) due to working class consumers imitating capitalist class consumers. On the other hand, we are inspired by Leibenstein (1950), who specified consumption dynamics as resembling a bandwagon effect (imitation of other consumers) and contrasted it to the status-seeking Veblen effect (luxury consumption) and snob effect (consumption striving for rare goods – "exclusiveness"). Consumption behavior is thus a dynamic interplay between individual aspirations (needs/wants), status-seeking behavior, wealth and imitation, dependent on emergent social structure driven by interactive evolution of populations of different classes of consumers.

### *2.2. Firms*

A second group of agents are firms, which produce final goods using inputs of capital and labor. They employ a firm-specific production technology, with respect to either labor or carbon productivity (the latter causing a reduction of emissions per output unit), being heterogeneous among firms. Firms start with a number of differently scheduled credits (each with their own duration) emulating the reinvestment necessary to uphold the constant capital level to counter depreciation. They can apply for loans at banks operating in a credit market to increase or maintain production capacity. Goods-producing firms acquire capital from a single firm that produces capital goods. Physical capital is complementary to the production factor of labor. Profits made by the capital goods firm are distributed to households in relative proportion to their accumulated wealth. However, technology, i.e. the means of production, remains in the hands of the capitalists and the wealthiest workers. Every month, a full production cycle up to delivery to final demand is achieved as one period (time step) in the simulation.

The initial firm population starts with randomly (using a uniform probability distribution) assigned workers, resulting in slightly heterogeneous firms in terms of numbers of workers. These are then assigned a matching physical capital stock, in accordance with labor productivity and start with homogenous production technology. Every round each firm adjusts its production by monitoring the level of goods left in the inventory after sales. If sales exceed expectations, i.e., the inventory contains less than the targeted reserve stock (Godley and Lavoie, 2012), the firm decides to increase its output. The reserve stock is calculated by multiplying the firm's sales in the previous period by the production reserve stock rate. Unsold stock depreciates over time since "old" goods are more difficult to sell over time. Prices are adjusted analogously to production, i.e., in relation to the level of under- or overestimation of sales. They are changed by small amounts and never fall below the estimated marginal cost per unit of output plus some mark-up. If the planned production requires more physical capital than available, the firm tries to get a loan to buy the additional machinery. Moreover, innovation takes the form of upgrades of machinery which are supplied by the capital goods firm. The analytical apparatus of those mechanisms is described in Eqs. (6) and (11) in detail.

Otherwise the firm maintains its current capital stock, since it cannot reduce it actively in this model, as opposed to the input of labor, which can be adjusted by hiring or firing workers, although with some delay ($\eta_1$). An interpretation of this could be protection by labor laws, conform Seppecher (2012), who offers an agent-based macro implementation of this mechanism where wages have to be paid two more months as a protection against dismissal, thus decreasing the effective production capacity. Otherwise, physical capital depreciates annually so that the firm will need to reinvest if it desires to maintain the current level of physical capital. The profits of the firm accumulate in its current account over a whole fiscal year (12 months). At the end of the year funds are set aside for research and development (R&D) investments and corporate taxes are applied to the remaining amount. The rest is transferred to the firm owners. Also at the end of each year, firms with positive profits increase wages based on the increase of consumer prices, whereas firms without or with negative profits keep wages constant. In other words, wages are downward rigid.

Firms make their investment decision based on their estimated profit rate, defined as the ratio between profit and physical capital. The estimated profit of the firm is given by expected revenues minus current wages, interest payments, fixed credit repayments and expected additional credit costs.[2] If their estimated profit rate exceeds the interest rate of their bank, the bank will guarantee a loan with a fixed duration and a fixed interest rate. Moreover, banks only grant additional credit if the sum of unrepaid credit of that firm is smaller than the firm's production capital. If the profit rate is too low or the debt-to-equity ratio is too high, the specific firm has to reduce its production output as much as possible. Obviously, if the profits become too low the firm needs to fire workers and reduce capital inputs, which together will lead to lower production output. In the process, firms may go bankrupt, in which case capitalist households owning the firm become unemployed.

Every period one new firm can be founded, with a low probability, by the wealthiest worker household, who then changes it social class from working to capitalist class once the firm is operative. On founding, the owner of the new firm endows the firm with an operating budget for the first quarter and invests in initial machinery. The former is fully financed out of the households budget, while the latter is equally financed out of own budget and firm credits. If the household does not have enough savings to finance its part of the investment, the bank grants it a form of private credit (overdraft on its account). This is used as a proxy for risky private investment, and results in private debt which the owner cannot transfer to the firm. Newly founded firms start with production and emission reduction technologies that represent the average technology of the current firm population.

### 2.3. Banking system

Next we consider commercial banks and the central bank, which serve various roles in the model. Banks keep current accounts for firms, the capital goods firm and households (allowing for deficits) and savings accounts for households. In addition, they grant firm loans. They pay and charge interest for these different financial services applying distinct rates, limited by central bank interest rates, which are hold constant over the whole course of the simulation. Banks have to refinance themselves, by monitoring assets (loans) and liabilities (savings). If banks lack liquidity they request loans at the central bank.

The central bank keeps current accounts for the government (including overdraft functionality) and banks, as well as deposit facilities for banks, involving the paying or charging of interest. Furthermore it acts as a lender of last resort, but for the presented simulation experiments it does not accommodate any monetary policies.

### 2.4. Government

The government serves various roles in the model. It makes social transfers to unemployed and retired households. A constant share of the agent population is set to retired, receiving a fixed pension every month. These agents generally represent the largest group of households who are out of the labor force, but depend for their survival on social transfers. Note that we do' not assume any demographic processes that make young people become pensioners; instead, as most other agent-based model studies, we just assume the pre-existence of the two groups. Furthermore, the government collects taxes on labor, income and capital gains, on corporate profits made by banks and firms and the capital good firm, and on the value-added of sales (taxes are fixed over the whole course of the simulation). The government budget in the model is never perfectly in balance because of uncertainty about both tax revenues and government expenditures – as is the case in reality. As unemployment benefits and pensions are downward rigid, the government has no means to cut costs and has to deficit spend if necessary. If indebted, it pays interest to banks and households (in relation to their wealth) as a proxy for government bonds.

[2] See Rengs and Scholz-Wäckerle (2019 – Section 3.1.) for more detailed description of how production is modeled. Note that the chosen notation of the variables, symbols, indexations and equations here follows the notation choices in that publication.

## 3. Extension of the model for climate policy analysis

The environmental or more precisely climate extension of the previously described agent-based model involves a number of elements:

- describing $CO_2$ emissions during the processes that firms employ to produce goods,
- describing environmental innovations and its effects on carbon intensity, emissions and employment.
- policies to curb emissions through behavioral changes by all agents, environmental innovation or a mixture of these channels. These include carbon taxation, environmental tax revision (shifting taxes from labor to carbon), producer and consumer subsidies, green procurement, and a combination of these.

The general structure of this extended model is provided in Fig. 2.

Each firm ($i$) emits $CO_2$ over the course of the production process every round ($t$) depending on the employed emission reduction technology ($a^z_{i,t}$), where $z_{i,\,t}$ represents the actual carbon dioxide emissions dependent on produced commodities $q_{i,\,t}$.

$$z_{i,t} = q_{i,t} a^z_{i,t} \tag{5}$$

Initially, only half of the firm population possesses emission reduction technology. The emissions per output (carbon intensity as a measure of pollution) can alter over time through innovation in carbon productivity ("green innovation"). Investment in R&D leading to innovation is assumed to have an immediate effect either on carbon or on labor productivity of the respective firm's output. In other words, innovation is an individual process with a small role given to spillovers, a side effect of R&D. Since there are two different technology branches (carbon vs. labor productivity), both may benefit from spillovers. The extent of spillover is proportional to the total amount of R&D, while the highest spillover effect will occur if all firms perform research on the same technology branch, and achieving a much higher improvement in technology than without spillovers. The existence of spillover indicates that knowledge creation regarding energy efficiency is relatively easily transferred between sectors.

Our model does not account for climate change and its feedback to the economy, causing economic costs in terms of lost production (e.g., in agriculture), damage to infrastructure and buildings due to extreme climate events, increased resource scarcity (water), health effects, etc. This is the focus of long-term climate-economy models like DICE, FUND and PAGE. Our approach remains close to climate policy assessment models, which often use a general equilibrium format (Jorgenson et al., 2008; Söderholm, 2007).

Climate policies generally will raise prices for both more and less carbon-intensive goods and services. While these are subject to normal demand responses (less demand for higher price), higher prices of goods produced by processes with a lower carbon intensity ("greener goods") may in the short run attract conspicuous consumers. These then act in accordance with the Veblen (wealthy consumers looking for expensive goods that provide status) or snob effect (capitalists that look for rare goods; some small firms may innovate and offer a small amount of "green goods"). All other consumer classes will slowly, in the medium run, imitate these richer classes (bandwagon effect).

### 3.1. Emission reduction and adoption of low-carbon technologies by firms

As indicated, firms can improve either through labor productivity (labor input per unit of output) or carbon productivity (carbon emissions per unit of output), the latter depends on the current level of the firm's emission reduction technology. The former is part of the simple Leontief-type production function of the base model ($q_{i,\,t}$), and is endogenously adjusted by the firm ($a_{i,\,t}$), thus increasing output for given capital ($x^c_{i,t}$) and labor input ($x^l_{i,t}$) measured in number of workers, times the *labor productivity parameter* ($\alpha_7$):

$$q_{i,t} = a_{i,t} min\left(x^c_{i,t},\ x^l_{i,t}\alpha_7\right) \tag{6}$$

These two options are exclusive, with the firm decision about which type of R&D to invest in depending on past performance (profits). Basically this decision heuristic relies on a simple profit comparison among a chosen subset of firms. Firms consider a small number of their competitors (randomly chosen each year) ($k$) and compare the annual profit-rate of these firms at the end of a fiscal year ($r^a_{i,t}$), which corresponds to the profit accrued ($\pi_{i,\,t}$) in relation to the average current value of the production capital ($x^c_{i,t}$) over the last 12 periods.

$$r^a_{i,t} = \frac{\sum_{n=t-11}^{t} \pi_{i,n}}{\frac{1}{12}\sum_{n=t-11}^{t} x^c_{i,n}} \tag{7}$$

Every firm $i$ then evaluates which innovation strategy each of these ($k$) firms employed and whether they were more or less successful in terms of profit-rate than firm $i$ itself. If one of the innovation strategies proved more successful than the other, then this strategy is adopted by the observing firm in the next year, independent of the previous strategy. If the situation is indecisive, then the firm sticks to its former strategy. As all firms observe the technology chosen by their competitors in the past year, firms can also imitate a strategy that the observed firms themselves no longer follow. Generally, firms engage in research and development only if the costs of R&D ($RC_{i,\,t}$) are lower than the annual profit ($\pi^a_{i,t} = \sum_{n=t-11}^{t} \pi_{i,n}$)

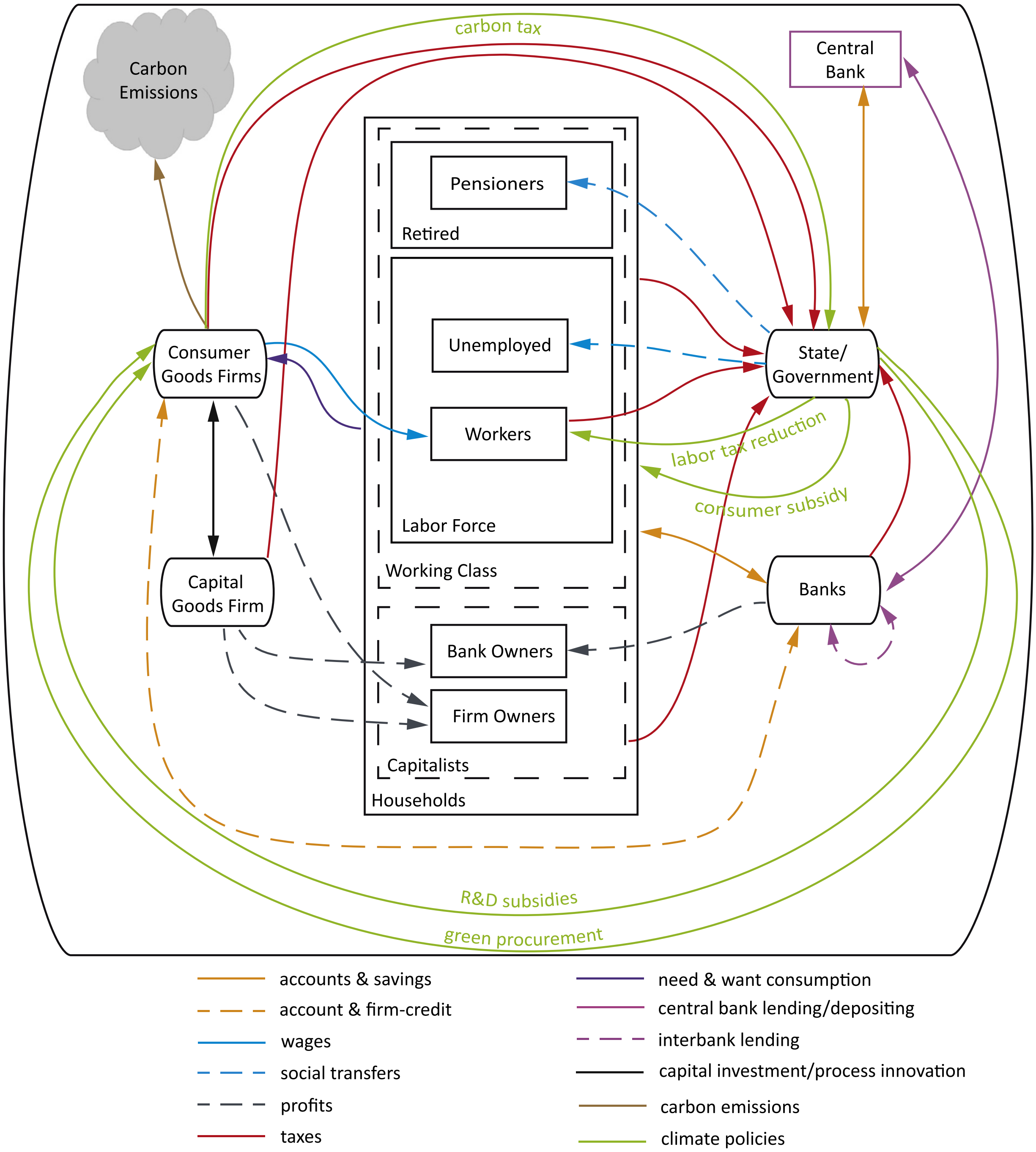


**Fig. 2.** General structure of the modeled artificial economy.

retained after paying corporate taxes $\tau_1$) and the dividend emitted to the owner. To keep the firm operational, these retained profits either cover a number of periods (equal to the length of the protection against dismissal) of total costs ($\eta_1 TC_{i,\,t}$) as a crude measure to absorb unexpected market disruptions, or the firm's profit net of taxes if it was lower, thus:

$$RC_{i,t} \leq min\Big(\, \eta_1 TC_{i,t}, \pi^a_{i,t}(1-\tau_1)\Big) \tag{8}$$

If the retained profits are lower than the R&D costs, the firm has to apply for a loan that is conditional on the usual lending constraints (see Eqs. (19–21) in Rengs and Scholz-Wäckerle 2019). The costs of R&D are the same for both strategies (general and green innovation), defined as a fixed fraction of the firm's current production capital. The costs can be financed partly by retained profits and partly by loans, should profits not suffice to cover the costs. This reflects the reality that some (notably large, established or successful) firms finance their innovation completely out of profits, while others (notably starters) fully depend for this on loans, while a third category will combine the two funding sources.

Innovation takes the form of upgrades of machinery, which is bought at the end of the year and is effective immediately at the beginning of the new fiscal year (bought from the capital goods firm). The cost of technological innovation is based on the firm's capital stock ($x^c_{i,t}$) and a fraction ($\kappa$) of the capital firm's current price for new capital/machinery ($c^c_t$):

$$RC_{i,t} = x^c_{i,t} c^c_t \kappa \tag{9}$$

We assume that investing in R&D can lead either to an increase in the labor productivity coefficient, or to a decrease in the carbon productivity coefficient, by a factor $\zeta_1$. The carbon productivity depends on the firm's current coefficient of emission reduction technology, starting with 1 for the whole firm population. Improvements in carbon productivity lower the emission reduction coefficient in the direction of a (technically non-reachable) minimum of 0. To simulate the increasing technical difficulties and costs of reducing emissions per output unit, we assume that consecutive reduction of emissions gets less effective in a non-linear way. That is, the more effective the emission reduction technology that a firm currently employs already is, the smaller the next improvement from its R&D efforts will be. This is in line with the widely accepted assumption in economic analysis of environmental policy that marginal abatement costs are rising with the level of abatement. Arguably, this derives from cost-minimizing ranking of abatement options. Furthermore all R&D efforts are subject to an early mover advantage for both R&D branches, which is formalized as a late mover disadvantage. R&D success gets discounted over time by a parameter $\zeta_3$, as given in Eqs. (10) and (11). The longer the firm waits to invest in R&D, the lower will be the productivity gain. Thus, if firm $i$ invests in emission reduction R&D in a given year, it would change its coefficient representing emission reduction through technology ($a^z_{i,t}$) to:

$$a^z_{i,t} = a^z_{i,t-1}\left(1 - \zeta_1\left(1 + \frac{\zeta_2 N^f_{z,t}}{N^f_t}\right)\right)(1-\zeta_3)^{\frac{t}{12}} \tag{10}$$

With $\zeta_2$ representing the maximum spillover effect, if all firms ($N^f_t$) would engage in this R&D branch in $t$ (with $N^f_{z,t}$ representing the number of firms engaged in emission reduction). Likewise, if a firm invests in R&D on labor productivity, its production technology would improve in terms of output generated per unit of labor input:

$$a_{i,t} = a_{i,t-1} + \left(1 - \zeta_1\left(1 + \frac{\zeta_2 N^f_{a,t}}{N^f_t}\right)\right)(1-\zeta_3)^{\frac{t}{12}} \tag{11}$$

In this context it is assumed that firms are indifferent towards improving their carbon footprint without additional incentives.

### 3.2. Climate policies: carbon taxation, environmental tax revision, producer and consumer subsidies, and green procurement

To stimulate reduction of emissions by firms, the government can implement a price incentive via carbon taxes. The total revenues of these ($T^z_t$) are the product of emitted units of carbon ($z_{i,\,n}$) times the per unit carbon tax ($\tau_2$). These revenues accumulate in a "carbon fund" during the fiscal year – Eq. (12) shows the sum of the last ($t-11$) periods till period $t$ therefore –, which is used to fund a number of policy instruments that are carried out in the following fiscal year, described in a later section.

$$T^z_t = \sum_{n=t-11}^{t} \sum_{i=1}^{N^f_n} z_{i,n}\tau_2 \tag{12}$$

The above mentioned carbon tax revenues are dedicated to finance the other climate policy instruments. In other words, the government budget is neutral and thus not a relevant criteria for comparing distinct climate policy packages.

Additional policy instruments involve the government offering subsidies to households or firms if they undertake specific actions. As the government has to announce the amount of subsidies granted before households and firms take decisions (as they will base their decision on the extent of the subsidy), it does not know how many subsidies will actually be requested every month. Therefore it needs to estimate the amount to be paid per subsidy on a monthly basis. To do so it bases the estimate for this period's (a month) number of requested subsidies on the number of subsidies paid in the previous period. This may cause a cyclical movement of budget deficits and surpluses (i.e., under/overshooting the carbon tax fund) on a monthly basis but leads to a nearly balanced carbon tax fund budget on a yearly basis.

The government can thus employ various policy instruments to either reinforce or complement the effect of the primary climate policy (carbon taxes), such as: direct support (subsidies) of green innovation, reducing labor taxes (to encourage employment creation), product subsidies to consumers to stimulating diffusion of low carbon products, green procurement or combining these instruments. Since the carbon taxes are collected in the first year of simulation for the first time, the additional policy instruments are not applied until the second year.

Governments can use the subsidy instrument as part of environmental policy. This takes the form of stimulating green innovations or adoptions (i.e., diffusion of market applications) of environmental technologies, such as renewable energy or more energy-efficient technologies. Innovation subsidies are widely regarded as an instrument of technology policy that is complementary to carbon taxes, in the sense that they serve largely complementary roles in fostering a transition to a low-carbon economy. The reason is that carbon taxes alone will select the most cost-effective current technology (e.g., wind instead of solar PV, or a particular type of PV over another), even if it is uncertain whether this is the best technology in the long run. To keep a potentially attractive technological trajectory (e.g., solar PV) open, i.e., avoiding early lock-in of a competing technology that is currently cheaper, one can subsidize R&D into the first technology. Private companies typically underinvest in such R&D as returns on investment are too (s)low or uncertain, implying the need for public support. Formulating a policy package with carbon taxes and innovation subsidies allows us to test to what degree these are complements or substitutes in an evolutionary multi-agent context.

Basically the government has two different options to foster a certain technological trajectory or even changing a technological paradigm, namely "supply-push" and "demand-pull" (Dosi, 1982). The former strategy in our case aims to change technologies in a more sustainable direction by subsidizing "environmental innovation". Firms then "push" the technological trajectory in a certain innovation direction, and demand is hoped to follow. The second option relates to the idea that technological change is largely driven (or "pulled" in a certain direction) by the demand side. This takes the form of the government providing product subsidies to lower consumer prices so as to stimulate the diffusion of less carbon-intensive products. Since in reality both supply-push and demand-pull mechanisms are continuously at work, in our model we include both mechanisms and associated policy instruments as well.

## 4. Simulation scenarios, settings and results

The first step is to run the model without any policy setting in business-as-usual (Scenario 1 *BAU*), which serves as a reference scenario for assessing the impacts of the following six policy scenarios.

1. *Carbon taxation*, i.e., a constant tax per unit of $CO_2$ emissions (Scenario 2 *T*): as the government has no means to reduce or increase its general spending (unemployment subsidies and pensions) willingly, eventual budget surpluses due to revenues from the tax are redistributed to all households. As discussed in Section 1, carbon pricing has received much attention in recent discussions about effective climate policies. This includes attention for use of carbon tax revenues, as under the following scenarios.
2. *Subsidizing research and development* (Scenario 3 *R*): this can take the form of subsidies for more energy-efficient technologies. The total amount of R&D subsidies provided by the government will be approximately equal to the revenue of the carbon tax. Individual firms receive subsidies in relation to their R&D costs, weighted by the effectiveness of the improvement. Thus, if two firms have equal R&D costs (i.e., who have the same production capital), the firm achieving a higher emission reduction due to R&D receives a higher subsidy.
3. *Labor tax reduction* (Scenario 4 *L*): this is the much discussed idea of a shift from labor taxes to carbon ($CO_2$) taxes. It is intended to alter the incentives for innovation from stimulating improvements in labor to carbon productivity, with potentially beneficial effects for both the environment and the labor market (less unemployment).
4. *Consumer product adoption subsidy* (Scenario 5 *C*): a subsidy to lower consumer prices to encourage adoption of less carbon-intensive products, aimed at stimulating their rapid diffusion.
5. *Green procurement* (Scenario 6 *P*): the government buys (green) goods with a relatively low carbon intensity. This is operationalized by letting the government search randomly half of the population of firms producing relatively clean products, and sorting them according to carbon intensity. The lower the distance to the cleanest firm, the more the government purchases (so that it buys the most from the cleanest product).
6. A combination of all of the above mentioned instruments of climate policy (Scenario 7 *ALL*): in particular, we consider the case of carbon tax revenues being divided in equal parts among the other climate policy instruments.

All simulations start in a comparable initial situation in $t = 0$ (before regular simulation) and are then subject to a shock through the introduction of the policies in the first simulated month.

### 4.1. Simulation settings

The following section presents results of a simulation experiment implementing the described macroeconomic multi-agent model. Simulations were run with 5000 households, five banks, one government, a central bank and initially started with 250 firms. The experiment was set up to simulate all combinations of the seven policy scenarios described above with multiple levels of a carbon tax. To investigate the effectivity and repercussions of policies we choose three different equidistantly spaced tax levels, which we refer to as low, medium and high (2.5%, 6.25% and 10% of the initial mean price, respectively). Each of the 19 resulting combinations (i.e., one *BAU* and six policies with three tax levels) was simulated 100 times with different seeds to account for variations in random factors and render the obtained results more robust. Re-runs of identical policy/tax combinations generally varied only slightly – due to stochasticity – underpinning high robustness of the results. Each of these 1900 runs was simulated for 360 time steps, representing months, resulting in a simulated time horizon of 30 years.[3]

[3] See Table A.1 in Appendix 1 for a list showing the timing of monthly and annual simulation events.

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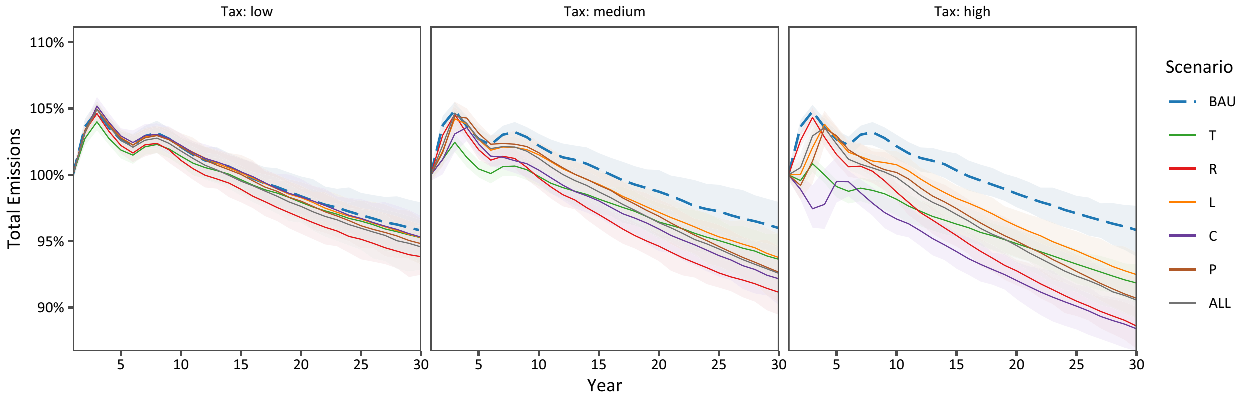


**Fig. 3.** Total emissions under each policy scenario and tax level.

Appendix 2 provides an overview of the main common simulation parameters used in the experiment, which were held constant for all simulations. As one might expect, changes in the value of the maximum firm's debt-to-equity ratio parameter have a large influence on the economic system. In the presented simulations this parameter value was chosen so that banks would only grant a loan if the sum of open loans would not exceed half of the firm's production capital after granting the potential loan. Thus, banks follow a conservative policy in granting loans. As a consequence, newly founded firms can only grow slowly. We decided to keep this parameter constant at the given level, resulting into a stable financial economic setting that does not distort our central simulation experiment on climate policy.

### *4.2. Simulation results*

Simulation results are presented below in a format that allows direct comparison of the six policy scenarios described in the previous section. The figures with results show annual aggregates for a number of central macroeconomic measures of the artificial economies. Each line in the following graphs represents the mean of all simulations for a specific policy/tax combination, with the *BAU* scenario shown as a dot-dashed line. Subfigures represent the effects of applying the specific policy with different tax levels.

As can be seen in all the figures, the first 5–10 years of a simulation run involves an adaption process. The reason is that the initial preferred vendor lists of households contain random firms and so does not yet reflect households' preferences. Hence, households change their preferred firms, thus influencing the attractiveness of the firm for other households, causing a lagged cycle of adaptions, decreasing in intensity after some years, though never reaching an equilibrium state. The introduction of climate policies creates a disequilibrating effect, the strength of which depends on the tax level. This causes adaptions of the market during some transition period. As this affects environment and welfare, it is necessary to show and assess this adaption phase.

In the following we first take a look at the effectiveness of each policy scenario in reducing emissions, and subsequently assess the economic effects that these policies have. Introduction of the discussed policy packages has rather strong effects on our artificial economy, with those policies that directly or indirectly influence households' purchasing power (namely, *L*, *C* and *ALL*) having the strongest impacts. The latter effectively lead to an increase of household budgets, thus increasing the aspiration for wants. This effect negatively compensates for the positive environmental effect of the introduction of the carbon tax, causing the net beneficial effect to be smaller.

Fig. 3 shows the total $CO_2$ emissions of the initial economy.[4] For low tax levels only the *R* scenario reduces total emissions significantly after 10 years. However, in the long run all policies lead to slight improvements compared to the base scenario, with *C*, *T* and *L* scenarios being almost at par with the base scenario at the end of the simulation. For higher tax levels all scenarios quickly fare better than the base scenario, with the *L* scenario having the smallest and the *R* scenario having the largest effects. Overall the *R* scenario performs very well at reducing emissions, even though for high taxes the *C* scenario reduces emissions to a similar degree.

Low levels of emissions under scenario *C* result from a fall in GDP and come at a high cost of increasing unemployment as can be seen in later figures. Fig. 4 shows the annual development of carbon intensity, corrected for consumer price inflation, i.e., emissions/real GDP. The *R* scenario is the only climate policy package effectively lowering carbon intensity below the *BAU* level throughout the whole simulation time, at all the three tested carbon tax levels. All other scenarios result into higher levels of carbon intensity compared to *BAU*. Furthermore, the simulation experiments show that higher

[4] The shaded areas around the timelines in Fig. 3 (and the following figures) indicate the 0.05 and 0.95 percentiles, respectively, of all simulation results rather than indicating standard deviations, as simulation results are not necessarily normally distributed. As expected, these narrow bands slightly increase as the simulation progresses, as individual simulation runs take slightly different paths.

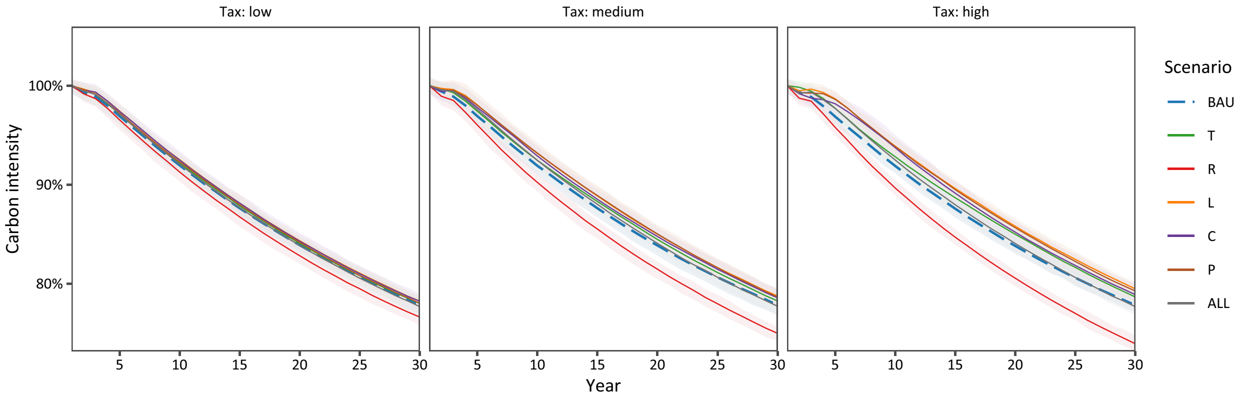


**Fig. 4.** Carbon intensity under each policy scenario and tax level.

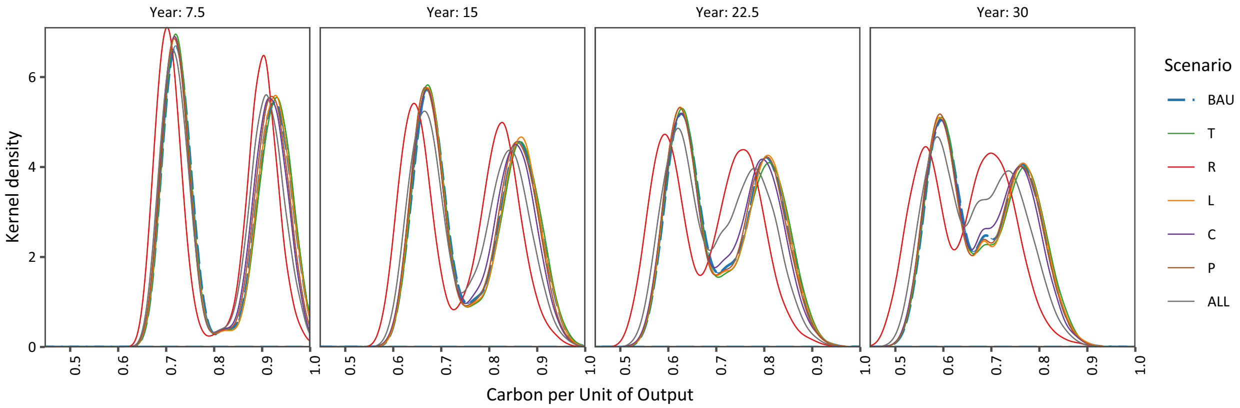


**Fig. 5.** Kernel density estimates of the distribution of emission reduction technology under each policy scenario for the high tax level.

tax levels do not necessarily lead to lower carbon intensities, except in the *R* scenario. These counterintuitive findings are explained through a higher costs for firms, especially under medium and high carbon taxes. In the *R* scenario these costs are compensated through R&D subsidies provided to firms.

The bad performance of scenarios *T, L, C* and *P* in carbon intensity results from investment problems at the medium and high tax level. Once firms invest in R&D on carbon productivity, excess demand for green products is likely to result, initially from capitalists due to the snob effect and subsequently from working class consumers due to the bandwagon effect. However, this demand cannot be satisfied in scenarios *T, L, C* and *P*, as green firms cannot grow quickly enough, due to a risk-averse banking sector (see parameter $\phi_1$ in Appendix 2, Table A.2). As households try to satisfy their needs and wants aspirations, they consume carbon-intense products instead. This leads to sharp increases in prices, which takes time, though, as firms do not alter prices quickly. Furthermore, these adaptions are imperfect due to the lack in investment activities which move the economy onto a different path with increasing purchases of carbon-intensive products instead. Eventually, carbon as well as labor productivity are hold back for medium and high tax levels, unless environmental innovation gets sufficiently subsidized as is the case in scenario *R*, where we see carbon intensity decreasing compared to BAU.

Fig. 5 shows the evolution of carbon emitted per unit of output (or the emission reduction technology) by firms over time for the high tax level only (but all tax levels produce similar patterns). The sub-figures show kernel density estimations of emission technology at equidistant points in simulation time, namely 7.5, 15, 22.5 and 30 years. While the firm population was initialized with a starkly pronounced bimodal distribution of the effectiveness of reduction technology (to create minimum diversity, capturing the essence of rich real-world diversity in such technologies), the peaks of the density distribution slowly drop and move to the left. Most scenarios lead to a very similar distribution (for the same tax level), with a high number of firms possessing better reduction technology. The reason is that most climate policy packages do not lead to higher profit for firms, whereas we assumed that firms imitate those with high profits with regard to the innovation strategy. The exception is the *R* scenario, in which most firms choose to invest in R&D on carbon productivity as this policy results in higher profits of firms. In contrast, in the *ALL* scenario a larger number of firms have medium effective reduction technologies, which is more pronounced for higher tax levels. The reason is that the other policy components cause demand

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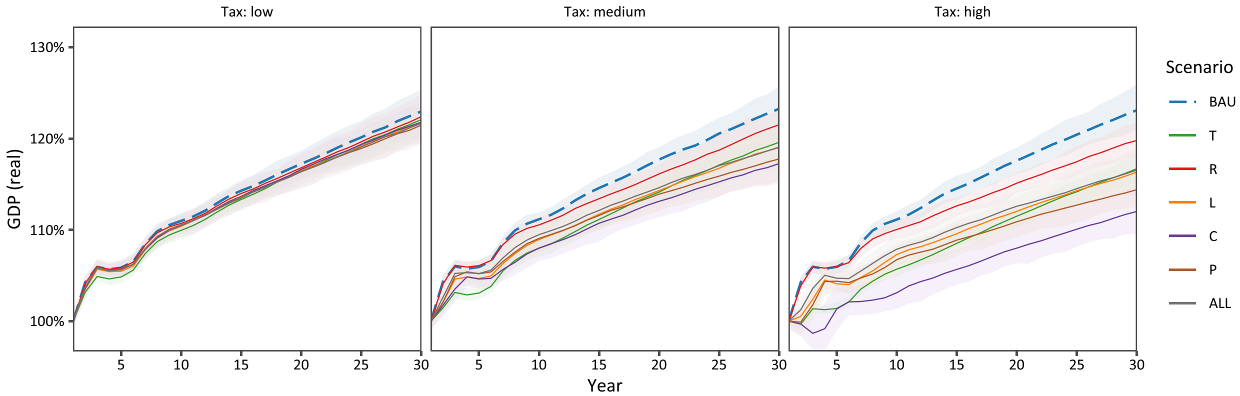


**Fig. 6.** Real GDP under each policy scenario and tax level.

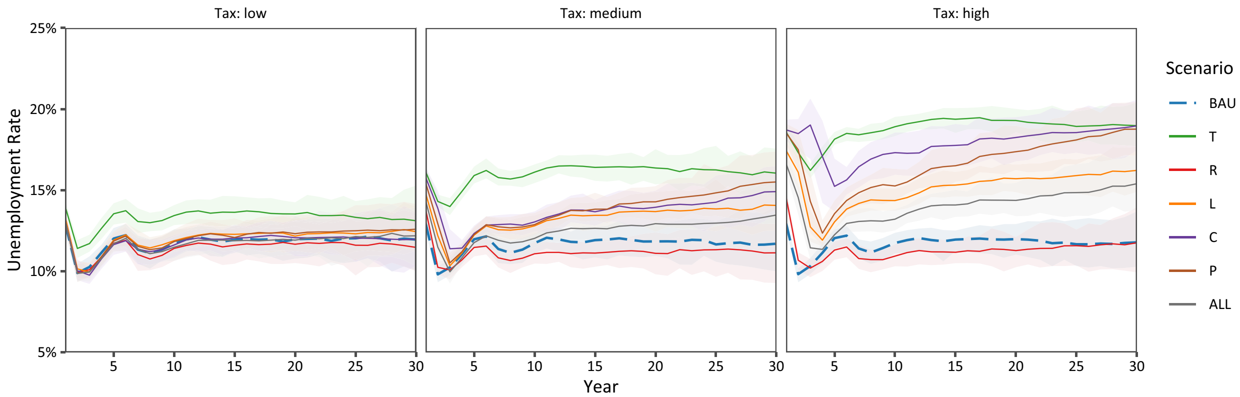


**Fig. 7.** Unemployment rate under each policy scenario and tax level.

and profit increasing effects from which even firms producing carbon-intense goods profit, thus reducing the effect of the R&D subsidies.

Fig. 6 shows the patterns of real GDP over time. It is measured as the aggregated final demand by households and the government, adjusted by the consumer price index (weighted mean price). Compared to the base scenario, the introduction of a carbon tax dampens GDP over the entire simulated period for all tax levels. However, for low tax levels, the collected revenues from this carbon tax can bring back GDP almost to the level of the base scenario, if they are used to finance R&D subsidies (*R*). All other policy scenarios perform worse in terms of real GDP than the *R* scenario. Whereas the difference between *R* and the other scenarios is not that large with a low carbon tax, it increases significantly at a medium or high level. We find that for a medium and higher tax level the economy gets severely shocked at the moment the tax is introduced (see scenario *T*). However, real GDP falls even more once the carbon tax is combined with a consumer subsidy for less carbon intensive products, or with a reduction in labor taxes or with procurement. These results are surprising and could not be anticipated from merely observing the assumptions of the model.

Fig. 7 shows that the unemployment level for the base scenario lies around 10–12% of the labor force, staying steady at this level over time. The *T* scenario has the highest unemployment for the whole simulation time, as the carbon tax revenues are not re-invested by the state (but merely redistributed), thus reducing demand due to missing multiplier effects. The *P*, *C* and *L* scenarios cause higher unemployment for medium and high tax levels. In the latter scenarios unemployment even increases over time, reaching levels of 15% for a medium carbon tax and levels of 17% for a high carbon tax. The main reason for the former effect is excess demand that results from the huge shock over demand on the market, due to the largely increased governmental (*P*) and household (*C*) budgets, which increase demand in total. The *L* and *ALL* scenarios perform slightly better than *P* and *C* with regard to unemployment. However, the *R* scenario performs very well in terms of employment resulting into lower levels than BAU, as investments in R&D on carbon productivity go at the cost of investments in R&D on labor productivity, given that each firm has to choose between the two each year. This stimulates labor demand, thus increasing consumption above the *BAU* level.

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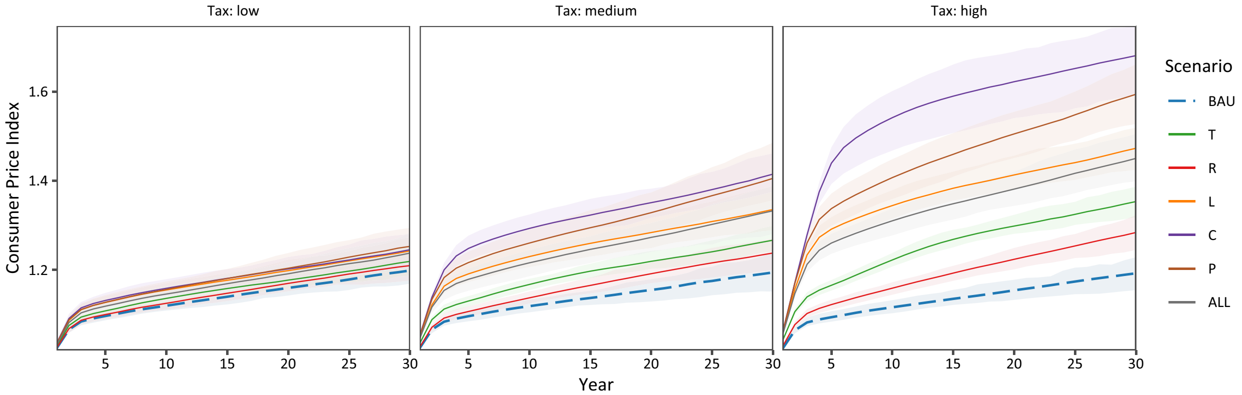


**Fig. 8.** Weighted consumer price level under each policy scenario and tax level.

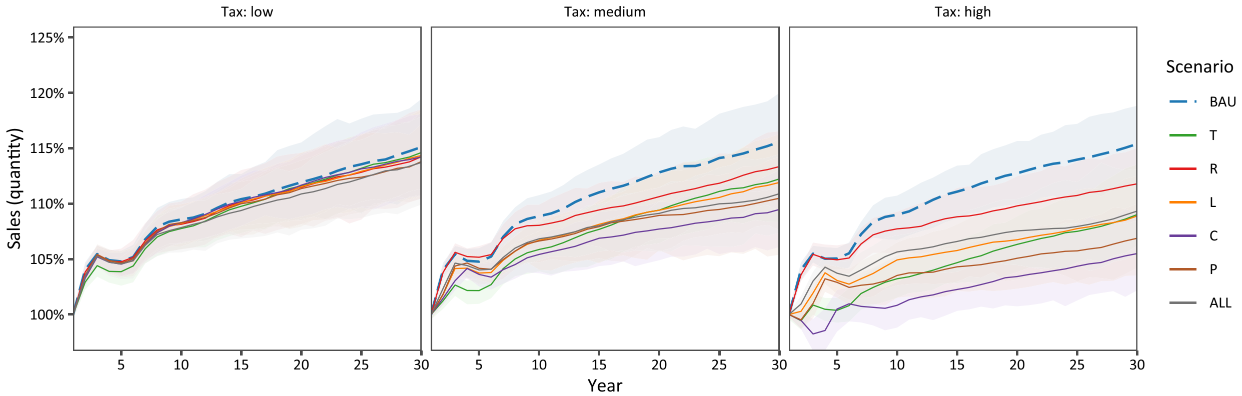


**Fig. 9.** Quantity of consumption good sales under each policy scenario and tax combination.

Fig. 8 shows consumer price inflation, i.e., the composite weighted average price for all goods and services. As can be immediately seen, all policy scenarios cause at least a somewhat higher price inflation than the base case due to the implicit market interventions. Nevertheless, for *R* and *T* scenarios, this effect is very small for all tax levels. The *L* scenario positively affects worker households' budgets, thus boosting demand, but much less than the *C* scenario. The reason is that the former increases also savings, whereas the latter scenario exclusively increases the household budget set aside for consumption. Even though scenario *P* shows a higher long term increase of price levels than all others, all prices stabilize once the artificial economy has adapted to the shock induced by the respective climate policy packages.

Fig. 9 substantiates the aforementioned results by taking a closer look at market dynamics. It shows the development of the quantity of consumption good sales. Basically, in our model this measure serves as a proxy for purchasing power. The higher the relative income/wealth the higher the sales of want goods. As we have already shown, this significantly affects carbon dioxide emissions, especially under scenarios *L* and *C*. The reason is that the adaptation process of firms does not come about automatically, possibly resulting in the production of fewer carbon-intensive products. For low tax levels, most scenarios lead to a higher purchasing power of more households, with the exception of the *T* scenario. Higher tax levels lead to lower purchasing power for most scenarios compared to the *BAU* scenario, with the exception of the *L* scenario, under which it is higher for the medium tax level.

As the distribution of wealth in our model is mainly shaped by the sharp distinction between the capitalist and worker class, with the capitalists starting the simulation with much more wealth than workers, the cumulative share in wealth per wealth group (Lorenz curve for wealth) is very similar for all scenarios. Fig. 10 illustrates this by showing the evolution of average capitalists' wealth in real terms over time. It is found to decrease in comparison with *BAU* under all scenarios, due to a redistribution of wealth from the capitalist to the working class. Furthermore the economic situation in all scenarios at high tax levels is worse than under *BAU* (compare Fig. 6), which leads to lower firm profits and higher unemployment, resulting in an additional redistribution effect. Finally, although scenario *R* outperforms almost all scenarios, it involves the least redistribution of income from capitalist to working class among all scenarios (though economic inequality is still lower in *R* than in *BAU*).

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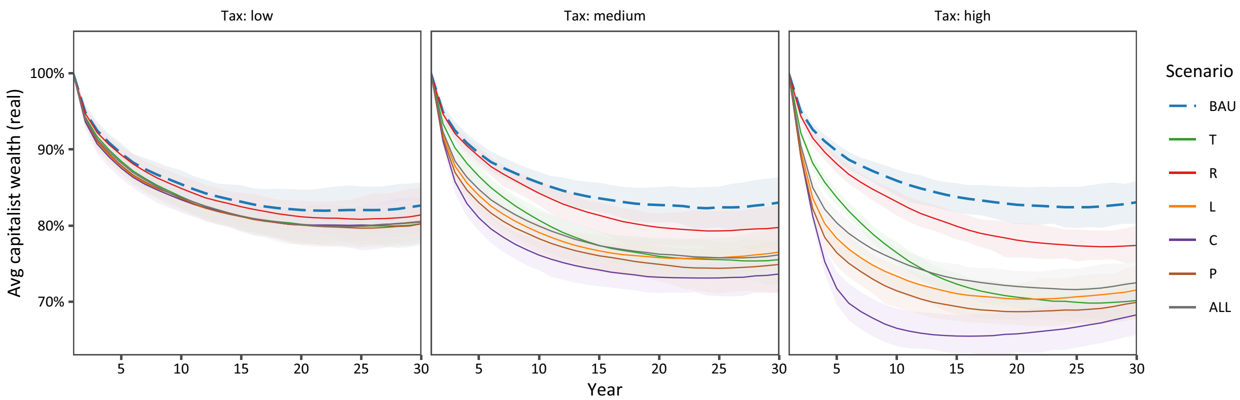


**Fig. 10.** Real wealth of capitalists (relative to BAU) under each policy scenario and tax combination.

**Table 1**
An overview of the simulation results.

| Indicator | Tax level | Policy scenario | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | BAU | *T* | *R* | *L* | *C* | *P* | *ALL* |
| Total emissions relative to $BAU_{t=360}$ after 30 years | Low | 100% | 99.3% | **97.9%** | 99.3% | 99.3% | 98.9% | 98.7% |
| | Medium | | 97.6% | **94.9%** | 97.7% | 96.0% | 96.5% | 96.4% |
| | High | | 95.8% | **92.4%** | 96.5% | 92.2% | 94.6% | 94.6% |
| Carbon intensity (emissions/real GDP) relative to $BAU_{t=360}$ after 30 years | Low | 100% | 100.3% | **98.2%** | 100.0% | 100.5% | 100.4% | 99.6% |
| | Medium | | 99.9% | **95.8%** | 99.8% | 99.6% | 99.7% | 99.0% |
| | High | | 100.6% | **94.7%** | 100.4% | 99.5% | 100.2% | 98.5% |
| Real GDP relative to $BAU_{t=360}$ after 30 years | Low | 100% | 99.1% | **99.5%** | 98.8% | 98.8% | 98.7% | 98.9% |
| | Medium | | 97.0% | **98.6%** | 96.6% | 95.1% | 95.5% | 96.6% |
| | High | | 94.8% | **97.3%** | 94.5% | 90.9% | 92.9% | 94.8% |
| Relative change in unemployment over the simulated period | Low | 11.8% | 13.2% | **11.6%** | 12.4% | 12.1% | 12.6% | 12.2% |
| | Medium | | 16.0% | **11.0%** | 14.0% | 14.9% | 15.5% | 13.5% |
| | High | | 19.0% | **11.9%** | 16.3% | 19.1% | 18.7% | 15.3% |
| Relative change in consumer prices over the simulated period | Low | 119.5% | 122.0% | **121.0%** | 124.5% | 124.8% | 125.1% | 123.8% |
| | Medium | | 126.8% | **123.7%** | 133.4% | 141.2% | 140.4% | 133.2% |
| | High | | 135.5% | **128.5%** | 147.5% | 168.8% | 159.1% | 144.6% |

*Notes:* (1) the scenario names represent: *T* – carbon tax, *R* – R&D subsidy, *L* – reducing labor taxes, *C* – subsidy for consumers to adopt low-carbon option, and *P* – green procurement, and *ALL* – a combination of all previous instruments. (2) Bold faced percentages indicate the best performances.

Table 1 shows significant differences in the performance of economic and environmental factors for most of the scenarios and tax levels. The table summarizes simulation results for the end time, i.e., at 30 years or $t = 360$, for total emissions, carbon intensity and real GDP in relative differences to the *BAU* scenario, in the first three rows. Moreover, Table 1 shows relative changes in unemployment and consumer prices over the whole course of the simulation (i.e., between $t = 0$ and $t = 360$) in the last two rows. The overall striking result is given by the performance of the *R* scenario which is able to outperform every other scenario at all tax levels for the economic and environmental measures in focus.

Overall, these results are generally in line with climate policy experiments performed in Gerst et al. (2013) where subsidizing research and development in emission reduction technology is also highlighted as a perfect complementary policy funded by the revenues of a carbon tax. However – as previously shown – the presented evolutionary macroeconomic model allows a unique computational analysis since it can address implications of economic heterogeneity and diversity along micro, meso and macro levels (compare Rengs and Scholz-Wäckerle 2019) for all the investigated climate policy packages. We have looked particularly into the effects of these packages on firm adaptation patterns and on heterogeneous household behavior governed by the social mediation of preferences. Thus we have been able to investigate also the political economy effects on the distribution of wealth dependent on different climate policy packages.

## 5. Conclusions

An evolutionary macroeconomic model of a one-country closed economy was developed to study climate policy packages. The model accounts for a variety of observed behavioral features of consumers, such as imitation, status and snob effects. The model describes interactions between populations of heterogeneous households, firms and commercial banks, as well as a capital goods firm, a central bank and a central government. The innovative part of the model is that it addresses changes in carbon intensity of the economy resulting from innovation and diffusion of associated less carbon-intensive ("greener") products, but without assuming – exogenously – specific household inclinations for greener products. In addition, the model includes a rich set of behavioral patterns for the social mediation of preferences. The consumer markets feature heterogeneous agents on both the supply and demand sides. In that way firms adapt their output, size and technological trajectory in co-evolutionary dependence on the heterogeneous social evolution of household preferences, in particular for needs and wants aspirations. The model accounts furthermore for firms financing emission reduction technology via ownership wealth and corporate loans with mutual credit relations to individual banks.

Six policy scenarios were studied. A basic policy scenario *T* examined different levels of a fixed carbon tax. The tax revenues are used to create a "carbon fund" that is used to finance additional instruments of a climate policy package, leading to four additional scenarios: subsidizing green innovation *R*, a shift from labor to carbon taxes *L*, a direct consumer subsidy for greener (less carbon-intensive) products *C*, and green procurement *P* (governmental spending on green products). In addition, we consider a policy package comprising all the mentioned policy instruments *ALL*.

The artificial agent-based economy was simulated for 30 years. We chose parameter values following empirical evidence from the literature (see Appendix 2) plus calibrated the parameters via an extensive sensitivity analysis (see online Appendix 4) for the baseline case, scenario BAU. The resulting artificial economy develops on a stable disequilibrium path with an average unemployment rate around 1/8th of the labor force and an average annual consumer price inflation of 2% over the whole simulation run. In addition to that, we targeted for a left-skewed wealth distribution with this parameter setting as well as a rather risk-averse banking sector. The simulation results show that in all scenarios low levels of a carbon tax cause a monotonous decrease in carbon intensity. However, a decrease in total emissions for all scenarios can be observed after 10 years. Under all scenarios, real GDP increases while unemployment stays at almost the same level for scenario *T* and *R* (the latter even with lower unemployment than *BAU*), but increases for the other scenarios. Furthermore, a close analysis suggests that scenario *R* significantly outperforms all other scenarios across different levels of the carbon tax in economic as well as environmental terms. This result is striking, but we need to highlight that scenario *R* also has the lowest level of wealth redistribution, although in this respect it performs better than the baseline case. Furthermore, we find that our model study does not indicate a double dividend in terms of emissions reduction and employment increase due to shifting taxes from labor to carbon (i.e., scenario *L*). A win–win outcome for the economy and the environment results though with scenario *R*, i.e., requires a combination of carbon taxes and innovation subsidies for R&D on carbon productivity. Scenarios *C, P* and *ALL* perform very well in emission reduction but face significant adverse economic side-effects, such as a considerably higher unemployment or a lower GDP, thus achieving a reduction in total emissions partly through economic decline.

The given analysis allows a dynamic comparison of economic and environmental performances of CPPs. If the government spends the collected carbon tax sums for discounting greener products or for lowering the income tax, the co-evolutionary dynamics of heterogeneous firm and household behavior faces significant inertia in increasing the share of greener products. As a result, our simulation experiments show that households may even demand more carbon-intensive products in such cases, because those firms intending to change their technological trajectory cannot grow quickly enough to satisfy the increasing demand stemming from the recycled carbon tax sums. That is why subsidizing research and development with the revenues from the carbon tax outperforms all the other CPPs.

As this analysis depends on the heterogeneity of firms as well as households, the result can only be shown via a disaggregated complex adaptive system such as the presented evolutionary macroeconomic model. One of the main features of the model presented here is that the disaggregated economy is structured through evolving local interaction networks and individual preferences. As a result, the artificial economy develops via nonlinear and cumulative causation. An aggregated – e.g., computable general equilibrium – or partly aggregated system – e.g., ABM with aggregated firm and/or household sectors – would allow for immediate adaptation of all capacities to the new technological trajectory and would thereby overlook such deeper problems of inertia emerging through a risk-averse banking sector and the co-evolutionary dynamics of the complex adaptive system.

## Acknowledgments

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## Appendix 1. Timing of events

**Table A.1.1**
Simulation phases.

| |
|---|
| *Monthly simulation phases* |
| *Founding phase* |
| Households evaluate and initiate firm founding |
| *Production phase* |
| Firms demand estimation and pricing |
| Firms credit adjustment and production |
| Firms adapt prices |
| *Sales and consumption phase* |
| Conditional (scenario P): Government purchases products with low carbon intensity |
| Conditional (scenario C): Government calculates consumption subsidy base pre consumption |
| Households check financial status |
| Households decide consumption budget |
| Households buy need goods |
| Households (capitalists) buy want goods |
| Households (workers) buy want goods |
| Households update need vendor lists |
| Households update want vendor lists |
| Households balance accounts with savings if indebted or declare bankruptcy |
| *Wages payment phase* |
| Firms pay wages |
| Government pays pensions |
| Government pays unemployment subsidies |
| *Saving phase* |
| Households transfer money to savings accounts |
| *Interest and consolidation phase* |
| Banks collect credit interest |
| Banks collect credit repayments |
| Banks calculate accounts interest |
| Banks calculate savings interest |
| Banks pay central bank loans interest |
| Banks pay central bank loans repayments |
| Firms' monthly accounting |
| Banks verify firms' solvency |
| Banks monthly accounting |
| Banks calculate refinancing demands |
| Banks refinance at central bank |
| Banks transfer funds to facilities at central bank |
| Central banks pay reserve interest |
| Central banks pay deposit facilities interest |
| *Government refinancing phase* |
| *Update macro indicators* |
| Banks monthly accounting |
| Central banks monthly accounting |
| Government monthly accounting |
| Country updates macro indicators |
| *Annual simulation phases* |
| *Annual accounting phase* |
| Banks collect and pay accounts interest |
| Banks pay savings interest |
| Firms calculate profits and pay taxes |
| Banks calculate profits and pay taxes |
| Firms distribute profits |
| Banks distribute profits |
| Capital goods firms distribute profits |
| Government calculates annual emission tax redistribution funds |
| Firms evaluate R&D activities |
| Government update annual statistics (annual taxes) |
| Country compile annual report |
| Government check minimum wage increase |
| Government increases unemployment subsidies if minimum wage increased |
| Government evaluates pension increase based on CPI |
| Firms evaluate wage increases based on CPI |
| Capital goods firm adapts prices based on CPI |
| *Firms depreciate production capital* |
| *Firms engage in R&D activities* |

## Appendix 2. Technical details of the computational simulation

Computational simulations of the model were performed with Netlogo (Wilensky 1999), version 5.3.1. We used Netlogo's built-in BehaviorSpace experiment management engine to repeat each scenario and tax level combination 100 times, every time using a different random seed to test the effect of random factors in the model. Aggregate time series data was generated directly by BehaviorSpace for each period, whereas micro data was only saved for selected periods. Data analysis and visualization was realized using the R language (using the ggplot2 package).

The experiments were run with 5000 households including worker, pensioner and capitalist households, and started with an initial firm population of 250 firms. Additionally the experiment included five banks, a rudimentary capital goods firm, a government and a central bank. Other relevant simulation parameters are shown in Table A.2.1.

The baseline simulation (i.e., the business as usual scenario, *BAU*) was calibrated using the results of sensitivity analyses (see Appendix 4) so that the artificial economy follows a steady path of economic development with an average unemployment rate around 1/8th of the labor force, an average annual price inflation of 2% over the whole simulation run and a left-skewed wealth distribution.

The choice of simulation parameters was made in accordance with existing agent-based macroeconomic models from the literature and wherever possible we have listed references to empirical support of choices made.

*Household parameters*

Gaffeo et al. (2008) characterize agents "by loyalty" to trading partners of former periods. Lengnick (2013: 105) takes up this behavioral motive and develops a network approach for trading partners. We took the opportunity to follow this

**Table A.2.1**
Simulation parameters.

| *Households* | |
|---|---|
| Number of vendors on preferred lists ($\gamma_2$) | 7 |
| Number of regular replacement checks (monthly) | 1 |
| Reserves of needs | 1 period |
| Intended consumption rate, worker households ($\beta_1$) | 0.1 |
| Intended consumption rate, wealthy worker households ($\beta_2$) | 0.15 |
| Intended consumption rate, capitalist households ($\beta_3$) | 0.2 |
| Rate of consumption with respect to savings (monthly) ($\gamma_1$) | 0.05/12 |
| Initial savings endowment of worker households | $X_2$*$annual\,wage_h$; $X_2 \sim U(1, 2)$ |
| Initial savings endowment of capitalist households | 10*($initial\,minimum\,wage$) |
| *Firms* | |
| Initial ratio capital (individual firm level) to wages (annual) | 2 |
| Production reserve stock rate ($\alpha_1$) | 0.1 |
| Unsold stock depreciation rate (per period) ($\delta_1$) | 0.5 |
| Capital depreciation rate (annual) | 0.1 |
| Firm founding probability (monthly) | 0.05 |
| Price adjustment rate ($\alpha_2$) | 0.01 |
| Maximum price adjustment ($\alpha_3$) | 0.1 |
| Stock adjustment indifference rate ($\alpha_4$) | 0.25 |
| Common fixed production technology coefficient ($\alpha_5$) | 1 |
| Labor productivity parameter ($\alpha_7$) | 3750 |
| New price adoption probability ($\theta_1$) | 0.3 |
| R&D base success ($\zeta_1$) | 0.02 |
| R&D maximum spillover ($\zeta_2$) | 0.5 |
| R&D early mover advantage ($\zeta_3$) | 0.02 |
| *Banks* | |
| Credit term | 5 years |
| Credit interest rate (annual) | 0.04 |
| Account interest rate (annual) | 0.01 |
| Account overdraft rate (private credit, annual) | 0.05 |
| Savings interest rate (annual) | 0.015 |
| Firm credit risk parameter ($\phi_1$) | 0.5 |
| Central bank deposit interest rate (annual) | 0.01 |
| Central bank loans interest rate (annual) | 0.02 |
| *Governments* | |
| Initial minimum wage | 1000 |
| Initial unemployment subsidy | 1000 |
| Minimum wage increase minimal interval | 5 years |
| Duration of the protection against dismissal ($\eta_1$) | 2 months |
| Value added tax rate | 0.1 |
| Income tax rate (flat for all capitalist households) | 0.15 |
| Corporate tax rate (banks, firms, capital goods firm) ($\tau_1$) | 0.15 |
| Carbon tax rate ($\tau_2$) | 0.025, 0.0625, 0.1 |
| Labor tax rate (flat for all worker households) | 0.15 |
| Capital gains tax rate | 0.15 |

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approach with adaptations as given in Section 2.1. The value for a preferred list of trading partners is parameterized as a list of 7 vendors per household, with the same configuration as in Lengnick (2013: 105).

In line with the same source (p. 108), wealthier households are inclined to consume less of their disposable income. Parameter $\beta_3$ indicates the capitalist household's intended consumption, set as 20%. Elsewhere we have outlined (Rengs and Scholz-Wäckerle 2019: Eq. (17)) that such a rate results into intended consumption as 80% of disposable income plus a small additional reserve from savings (dependent on $\gamma_1$, ibid. equation 18). For worker households ($\beta_1 = 0.1$), the intended consumption uses up 90% of disposable income. This parameterization follows comparably similar works in the agent-based macroeconomic literature, e.g., the propensity to consume from current income as set to 80% in Russo et al. (2016: 36) or 63% in Caiani et al. (2016: 406). Furthermore, we assume that households with positive savings of all classes set aside a very small share of their savings for additional consumption, dependent on $\gamma_1 = \frac{0.05}{12}$. This wealth-dependent consumption component is followed also Gaffeo et al. (2008) or by Lengnick (2013: 108) who refers to empirical evidence by Souleles (1999) as well as Carroll and Kimball (1996).

*Firm parameters*

Following similar agent-based macroeconomic models, we set the production reserve stock rate ($\alpha_1$) to 10%, meaning in particular that 10% of produced output are kept as inventories, in order to be prepared for situations of short-term excess demand. Our approach is similar to Ciarli et al. (2010: 243) with a desired ratio of inventories of 10% (who tested between 11% and 25%) and Dosi et al. (2010: 1755) with desired inventories of 10%. In addition, we employ a price adjustment rate for firms in our model – not to be misunderstood as a markup rate. We restrained from implementing a markup rule eventually, because it led to rather unrealistic and drastic movements in prices, since firms usually do' not pass on increases in costs to their customers immediately, otherwise they would experience consequential losses in the number of customers. That is why in our model we opted for firms adjusting the price simply in correspondence to relative changes in demand as well as to changes in their own inventories. We thereby employ a possible spectrum of price adjustment from a minimum value of $\alpha_2 = 1\%$ to a maximum value of $\alpha_3 = 10\%$, for every firm. All firms start with a fixed technological coefficient of 1, implying that firms are not innovating from the start. The capital intensity parameter $\alpha_6$ is set to 20%, comparable to Ciarli et al. (2010: 243), with an intensity of 40%, by referring empirically to King and Levine (1994). Capital depreciates annually in our model and follows thereby a different approach as other models of this kind. We use a simple accounting rule that depreciates capital with 10% per year. Others such as Dawid et al. (2018: Table 8) depreciate capital with 1% per month or Ciarli et al. (2010: 243) test for ranges between 3 and 14% per month. The initial endowment of a firm is parameterized as twice the sum of the wages and is a qualitative approximation for small and medium sized enterprises.

Following Qi (2019: 47–48) innovation spillover is "in reality more likely to be partial…where the spillover factor is $\phi = 0.5$. With partial innovation spillover, the entrants are less advantageous over the incumbents compared to the full spillover case." In our parameter setting we choose $\zeta_2 = 0.5$, having the maximum spillover factor given by 50%.

*Bank parameters*

Credit terms are set to 5 years following Caiani et al. (2016: 385), whereby the interest rate on loans is set to 4%, representing an average value between 1% chosen by Dosi et al. (2010: 1755) and the 0.75% per month by Caiani et al. (2016: 406). The interest rate on deposits is set to 1% and on savings 1.5%, therefore a little bit lower than the 0.25% per month in Caiani et al. (2016: 406) and same as the generic rate given in Dosi et al. (2010: 1755). The central bank rate for loans is set to 2% whereas Caiani et al. (2016: 406) choose a monthly rate of 0.5%.

*Government parameters*

We set the income tax rate as well as the profit tax to 15% which is in line with the benchmark agent-based macroeconomic model by Caiani et al. (2016: 406) who set those two parameters to 18%.

## Appendix 3. Utility specifications for worker and capitalist classes

Here is more background information on how utility is specified for each social class.

*Needs aspirations of workers*

The needs aspirations of workers were already specified in Eqs. (1)–(4) in Section 2. Parameterization of the price effect involves setting $\xi = 0.75$.

*Wants aspirations of workers*

Signaling-by-consuming is defined here in accordance with Eqs. (1)–(4), by setting $\xi = 0.25$. In this case we put a much stronger weight for the bandwagon effect than for the price effect.

*Wants aspirations of wealthy workers* are described by

$$b^{\nu}_{1,i,t} = \left( \frac{p_{i,t} - p_{min,t}}{p_{max,t} - p_{min,t}} \right) \tag{A5}$$

$$U_{i,j,t} = b^{\nu}_{1,i,t} b_{2,j,t} \xi \; + b_{3,i,t}(1 - \xi) \tag{A6}$$

Signaling-by-consuming is defined here in accordance with Eqs. (5), (2), (3) and (6), by setting $\xi = 0.25$, assigning a much stronger weight for the bandwagon effect than for the price effect. The price effect ($b^{\nu}_1$) is now a Veblen effect and thus reversed.

*Needs aspirations of capitalists*

$$b^s_{3,i,t} = \left( \frac{v_{max,t} - v_{i,t}}{v_{max,t} - v_{min,t}} \right) \tag{A7}$$

$$U_{i,j,t} = b_{1,i,t} b_{2,j,t} \xi \ + b^s_{3,i,t}(1 - \xi) \tag{A8}$$

Signaling-by-consuming is defined here in accordance with Eqs. (1), (2), (7) and (8), by setting $\xi = 0.5$, thus putting equal weights for the bandwagon and price effects. The price effect ($b_1$) is again a regular price effect (though less strong because of the different $\xi$ parameterization). Furthermore, $b^s_3$ now represents a snob effect.

*Wants aspirations of capitalists*

$$U_{i,j,t} = b^v_{1,i,t} b_{2,j,t} \xi \ + b^s_{3,i,t}(1 - \xi) \tag{A9}$$

Signaling-by-consuming is defined here in accordance with Eqs. (5), (2), (7) and (9), by setting $\xi = 0.5$, thus setting again equal weights for the bandwagon and price effects. The price effect (now $b^v_1$) is a Veblen effect as in the case of needs aspirations of capitalists while $b^s_3$ again represents a snob effect.

## Appendix 4. Sensitivity analysis

Here we present the results of sensitivity analyses of the main parameters in the model (listed in Appendix 2), in order to prove the robustness of presented simulation results as well as motivate certain parameter values adopted. In each experiment, a parameter or combination of parameters is simulated 100 times for different random seeds to account for the influences of the model's stochastic elements. The following sensitivity experiments were performed with the same scale as the simulations presented above. Univariate sensitivity experiments (1–15) have been performed for "sensitive" parameters that have been identified through extensive testing of the model system, which cause significant changes in simulation results once altered, as is common in the agent-based macroeconomic literature. Table A.4.1 lists these parameters.

In addition, we provide results for three multivariate experiments, to address the sensitivity of the climate extension of the model, which combine the carbon tax (three levels) with the R&D base success rate ($\zeta_1$) (experiment 16); R&D maximum spillover effect ($\zeta_2$) (experiment 17); and the R&D early mover advantage ($\zeta_3$) (experiment 17).

For every presented simulation experiment, we show the trajectories of the most important economic indicators over simulation runs of 30 years (360 months/periods). In each graph below, the dashed line represents the results for the parameter value chosen in the baseline (*BAU*) case. The shaded areas around the timelines indicate 0.05 and 0.95 percentiles, respectively, of the annual average of all simulation results.

***Sensitivity Experiment 1****:* Variation of $\gamma_2$ (number of vendors on preferred lists)

In the first experiment, as presented in Fig. A.4.1, the parameter $\gamma_2$, representing the length of households' shortlist for buying on the consumer market, i.e., the number of vendors that a household will prefer to buy from, was varied over a technically meaningful range of [1,10].

The parameter has a strong economic influence only for extreme cases of $\gamma_3 \leq 2$. There prices increase steadily due to the stable individual firm's demands, which distorts the market and eventually leads to drops in sales paralleled by a strong increase in inequality. Furthermore an extended shortlist of $\gamma_3 \geq 8$ initially has a rather strong impact on the initial adaption process of the price level during the first years due to the increasing firm's individual demand and other calibrated model behavior. Such extended shortlists lead to a broader distribution of the consumer price.

***Sensitivity Experiment 2***: Variation of the number of regular replacement checks (monthly)

In this experiment, as presented in Fig. A.4.2, we explore the sensitivity of voluntary changes of (some form of) household vendor/brand loyalty on the consumer market. Settings range from slowly adapting habits [1] up to effectively having no vendor/brand loyalty at all [7], where all entries on a household's shortlist are evaluated and adapted every period/month.

High values of this parameter represent more rational agents, who very quickly adapt their actions to their preferences. For very frequent (>3) voluntary changes in demand, adaptations are so frequent that it results in long term economic fluctuation. We can see quickly increasing prices that lead to high (excess) investments (resulting in low capacity utilization) and low unemployment. After prices adjust to the individual demand, production and sales grow very strongly, with

**Table A.4.1**
Parameters tested in univariate sensitivity experiments 1–15.

| Household parameters | Firm, bank and government parameters | Climate extension |
|---|---|---|
| Number of vendors on preferred lists ($\gamma_2$) | Production reserve stock rate ($\alpha_1$) | R&D base success ($\zeta_1$) |
| Number of regular replacement checks | Probability of households for founding a new firm | R&D maximum spillover ($\zeta_2$) |
| Intended consumption rate of worker households ($\beta_1$) | Price adjustment rate ($\alpha_2$) | R&D early mover advantage ($\zeta_3$) |
| Intended consumption rate of wealthy worker households ($\beta_2$) | Labor productivity parameter ($\alpha_7$) | |
| Intended consumption rate of capitalist households ($\beta_3$) | Firm credit risk parameter ($\phi_1$) | |
| Rate of consumption with respect to savings ($\gamma_1$) | Duration of the protection against dismissal ($\eta_1$) | |

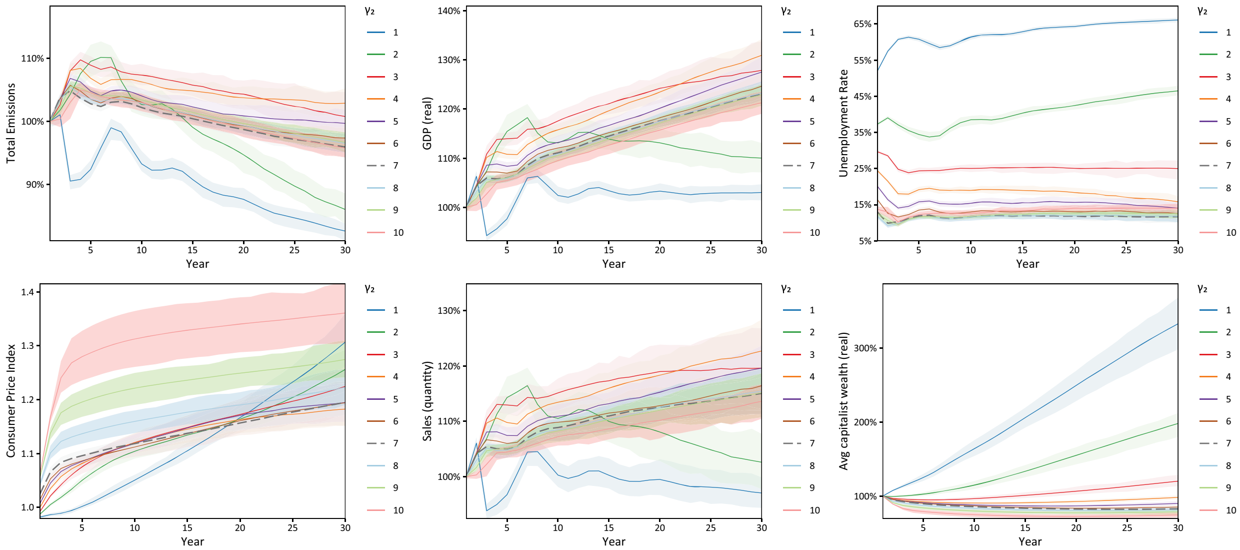


**Fig. A.4.1.** Simulation results for sensitivity Experiment 1: variation of $\gamma_2$ (number of vendors on preferred lists).

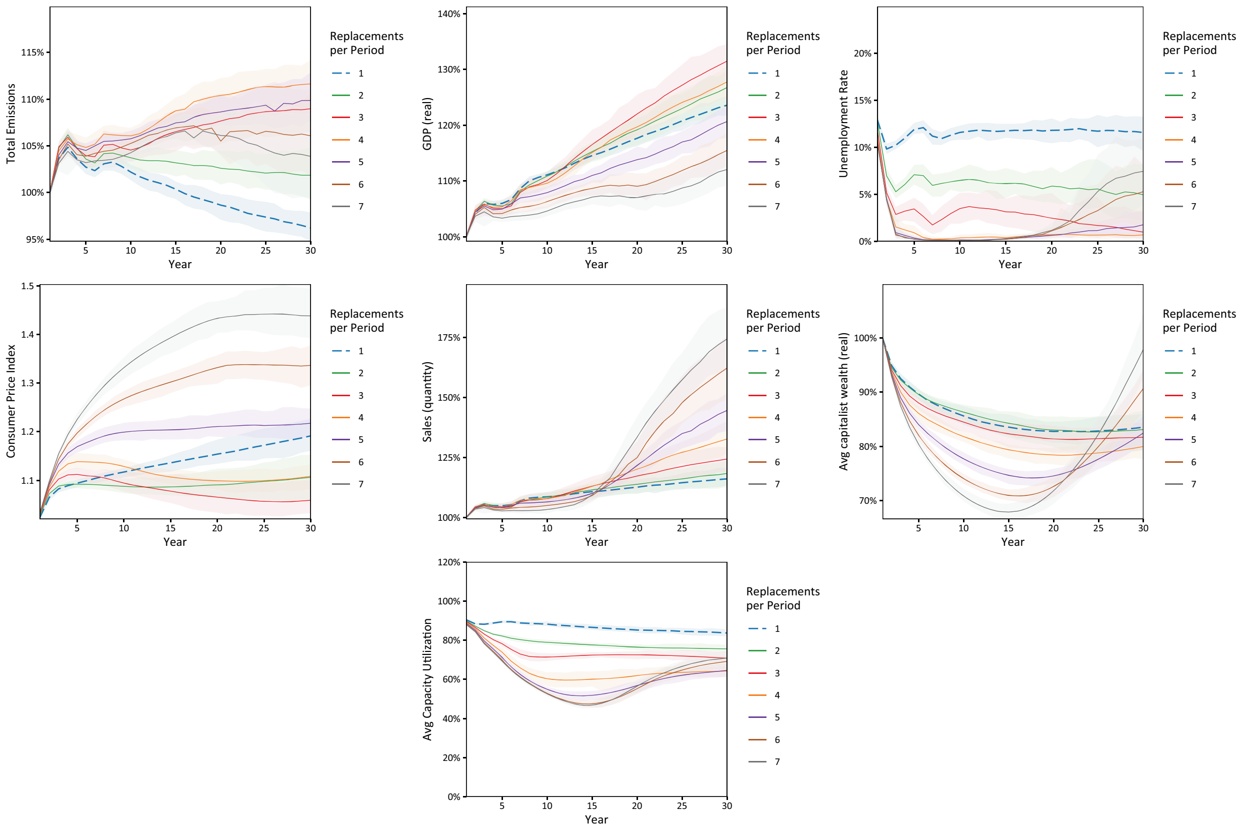


**Fig. A.4.2.** Simulation results for Sensitivity Experiment 2: variation of the number of regular replacement checks (monthly).

capitalists average wealth increasing strongly, even though real GDP is lower than in the baseline case. Medium settings of this parameter initially lead to somewhat stronger initial price increases than in the baseline case, but without maxing out the capacities of the labor market. Therefore, the parameter for replacements per period is set to a value of 1.

***Sensitivity Experiment 3***: Variation of $\beta_1$ (Intended consumption rate of worker households)

In this experiment, as presented in Fig A.4.3, we explore parameter configurations for the intended consumption rate (thus indirectly the savings rate) of the worker households (including unemployed and pensioner households). We vary it

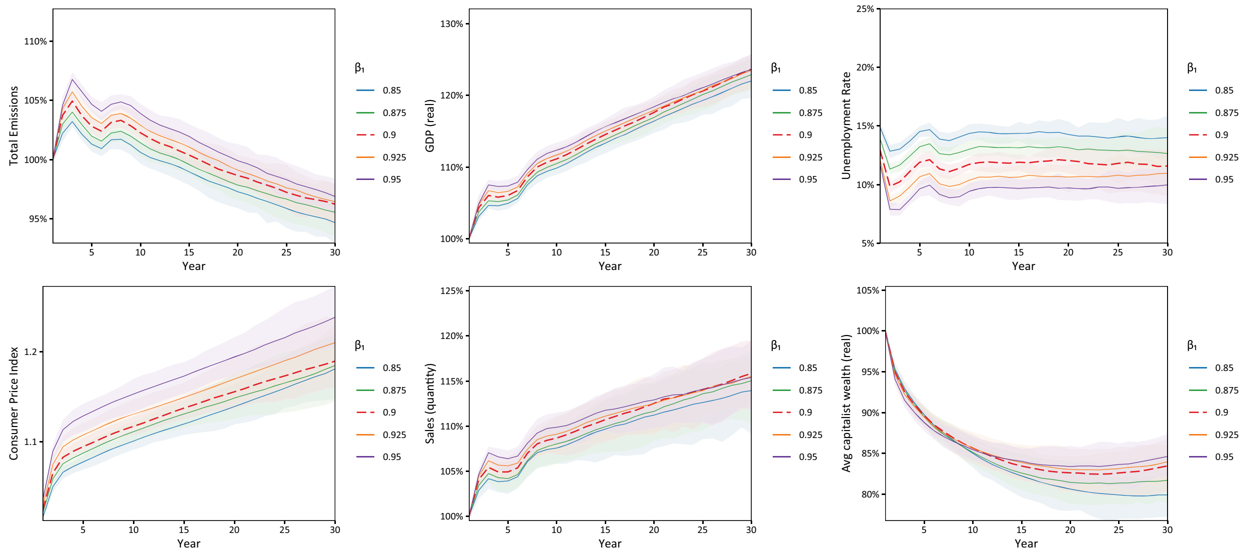


**Fig. A.4.3.** Simulation results for Sensitivity Experiment 3: variation of $\beta_1$ (intended consumption rate of worker households).

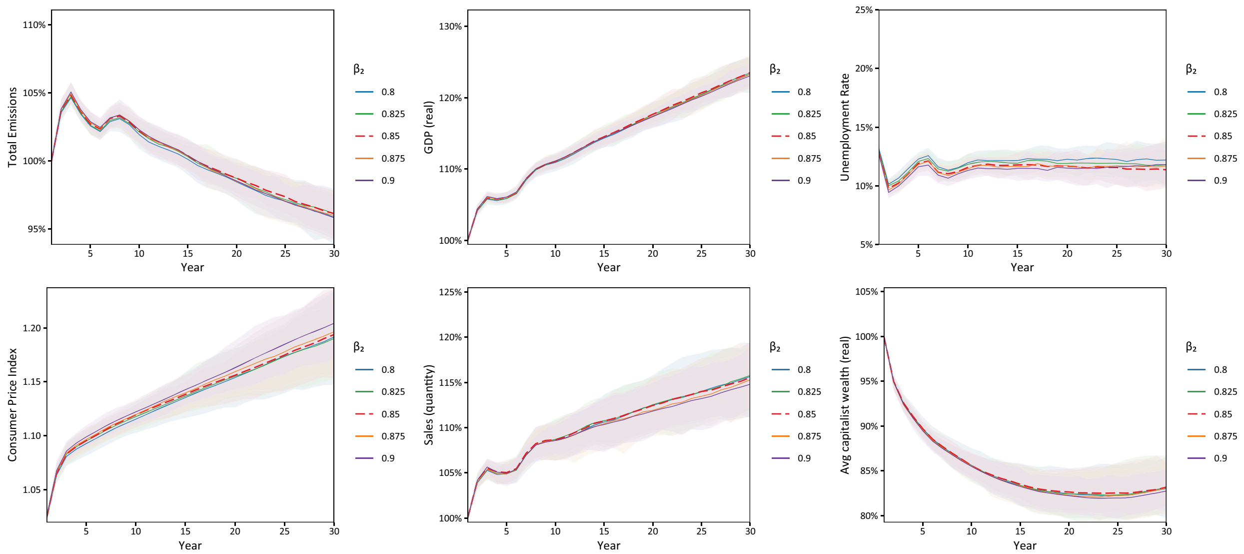


**Fig. A.4.4.** Simulation results for Sensitivity Experiment 4: variation of $\beta_2$ (intended consumption rate of wealthy worker households).

within a range of 85%–95% of their income, i.e., a rate which is always at least as high as the intended consumption rate of the wealthy worker class in the baseline case. The rate is called an intended rate as households rely on the availability of consumer goods to fulfill their needs and wants, which is not guaranteed in cases of excess demand.

The results show that an intended consumption rate of 0.9 guarantees an average and stable economic development path for the chosen macroeconomic aggregates. Lowering the rate will lead to slightly higher unemployment rates due to eventual drops in aggregate demand (see total sales) translating into smaller firms. A higher intended consumption rate will lead to higher total emissions and price inflation. The distribution of wealth becomes more equal with a smaller $\beta_1$ since worker households save more from their monthly budget. Since the working class makes up the largest part of the population, changes in its intended consumption rate leads to a more volatile distribution of results than changes in $\beta_2$ and $\beta_3$ (compare the next two experiments).

***Sensitivity Experiment 4***: Variation of $\beta_2$ (Intended consumption rate of wealthy worker households)

In this experiment, as presented in Fig. A.4.4, we explore the effect of variating the intended consumption rate (thus indirectly the savings rate) of the wealthy worker households, who form a rather small share of the simulated population. We variate it within a range of 80%–90% of their income, i.e., a rate which is always at least as high as the intended consumption rate of the capitalist class and always at most as high as the one of the worker class in the baseline case.

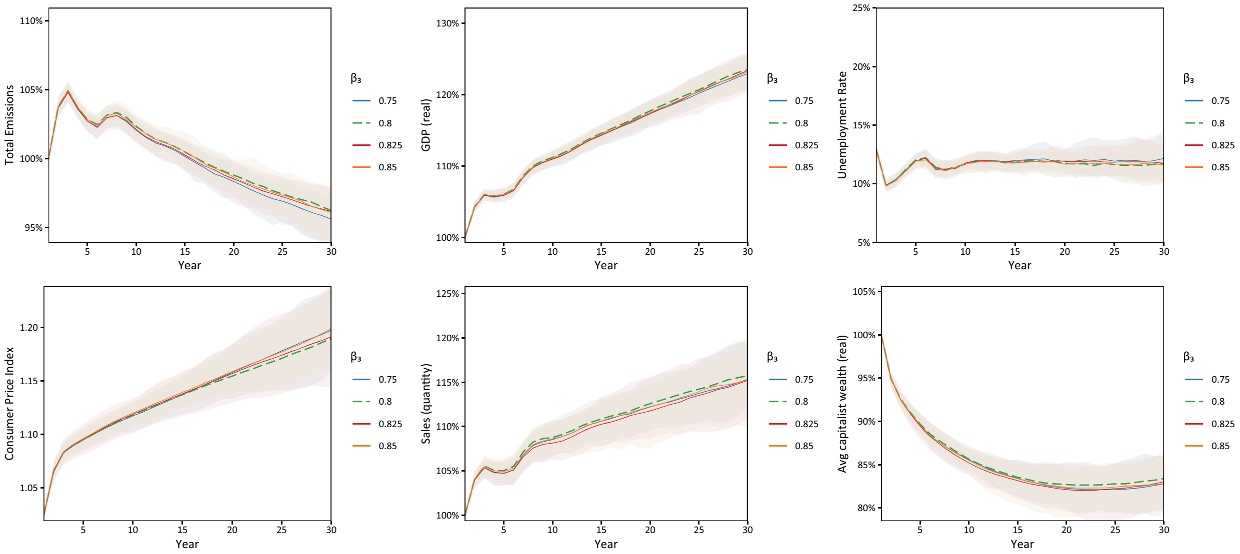


**Fig. A.4.5.** Simulation results for Sensitivity Experiment 5: variation of $\beta_3$ (intended consumption rate of capitalist households).

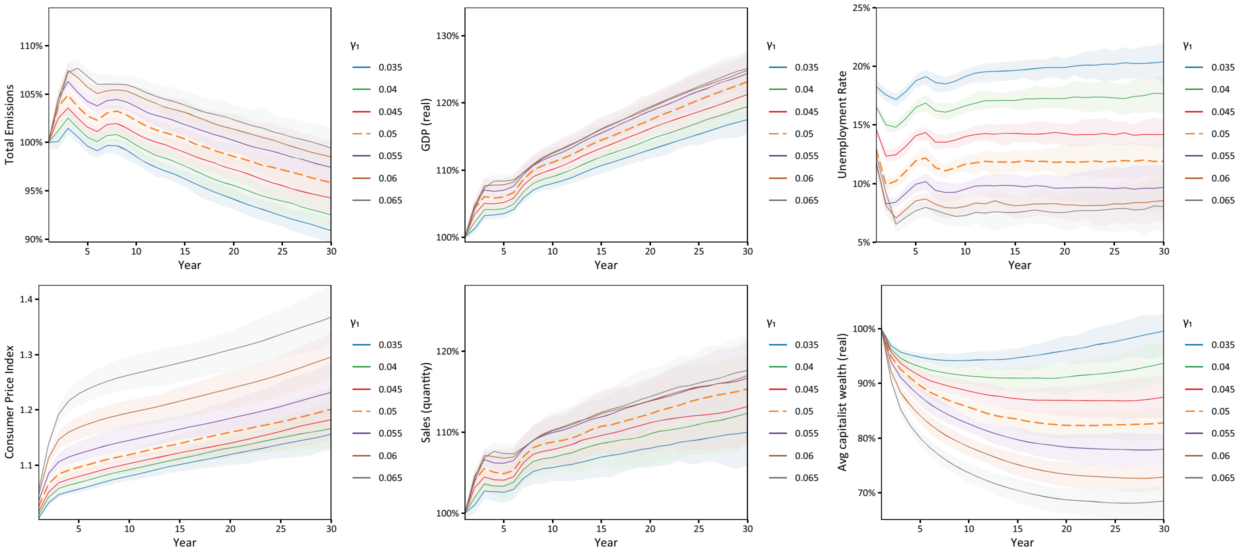


**Fig. A.4.6.** Simulation results for Sensitivity Experiment 6: variation of $\gamma_1$ (rate of consumption with respect to savings).

***Sensitivity Experiment 5***: Variation of $\beta_3$ (Intended consumption rate of capitalist households)

In this experiment, as presented in Fig. A.4.5, we explore the effect of variating the intended consumption rate (thus indirectly the savings rate) of the capitalist households, who form the smallest class of the simulated population. We variate it within a range of 75%–85% of their income, i.e., a rate which is always at most as high as the one of the wealthy worker class in the baseline case.

Capitalists consume the smallest share of their income compared to the other two classes, but changes in that share (at the given interval) do not lead to significant differences on aggregate.

***Sensitivity Experiment 6***: Variation of $\gamma_1$ (Rate of consumption with respect to savings)

In this sensitivity experiment, as presented in Fig. A.4.6, we explore the effect of varying $\gamma_1$, where all households consume additional goods financed not by income, but by withdrawing some funds from their savings. The rate is variated between withdrawing 3.5%–6.5% of each individuals' savings per year – distributed over each month.

There is a rather strong initial effect for higher shares – of withdrawing from savings for consumption – in the first period of the simulation. After these price adaptions have taken place, the economies settle for a very similar macro behavior, albeit a very different levels (price, output, GDP, unemployment, etc.). The more savings are additionally used for household consumption the better will be the final sales of firms. This increase in demand leads to less unemployment, more equality

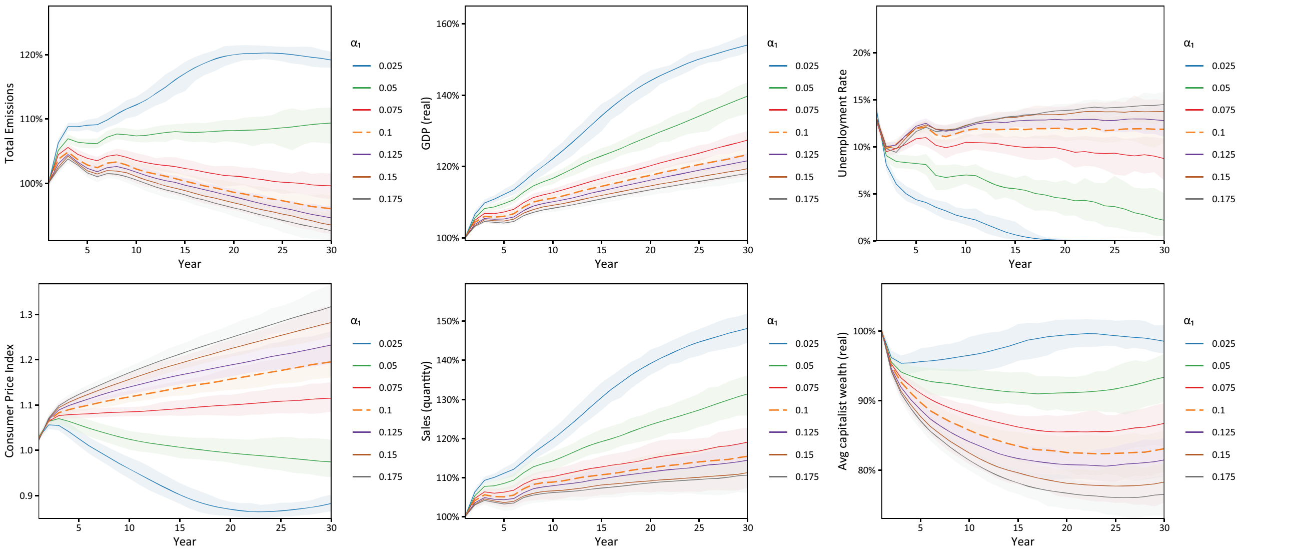


**Fig. A.4.7.** Simulation results for Sensitivity Experiment 7: variation of $\alpha_1$ (production reserve stock rate).

with regard to wealth across social classes, but higher prices and higher total emissions. The opposite is true for lower shares of withdrawing from savings for household consumption. Eventually, the chosen setting for this parameter – in the main simulation of the article – is exactly in-between those more extreme cases, $\gamma_1$ is set to 0.5.

***Sensitivity Experiment 7***: Variation of $\alpha_1$ (Production reserve stock rate)

In this experiment, as presented in Fig. A.4.7, we explore the effect of changes in $\alpha_1$, i.e., how much more goods firms will produce than they expect for their estimated individual demand in the next period. This reserve stock is then monitored by firms and used as a proxy for the individual demand of their goods.

In this sensitivity experiment a special situation occurs with very low values of $\alpha_1$. There are two main effects: First, firms use the reserve stock as a buffer to meet previously unexpected demand. When they have less reserve stock, they will lose customers more quickly, due to unmet excess demand for their goods. Thus, the households will more often buy at other firms to fulfill their need consumption. Smaller reserve stocks will then lead to empty reserve stocks much quicker and firms will increase production capacities much faster. These dynamics lead secondly (in the short and medium run) to a fall in prices, because firms produce too much due to the previous capacity expansion and need to get rid of their supplies now, that's why they start lowering their prices rapidly at this point in simulation time. Further, the fall in prices can eventually attract more demand in the medium run and final sales increase tremendously in this case. These somehow special circumstances (deflationary dynamics) in this case – given by the very low reserve stock rate – lead to full employment after 20 years, although with a very high inequality in wealth and moreover with a steeply increasing and very high output of total emissions. The calibration of $\alpha_1 = 1$ makes a very reasonable parameter setting, where the production reserve stock rate represents just a high enough buffer to dodge short-run excess in demand and prevent deflationary dynamics. Higher values of $\alpha_1$ lead otherwise to inflationary dynamics that need to get avoided as well.

***Sensitivity Experiment 8***: Variation of the probability of households founding a new firm

The firm founding probability affects foremost final sales and thereby real GDP. Every month there is a chance between 0% and 15% that one of the wealthy worker households founds a new firm of startup size. The sensitivity experiment, as presented in Fig. A.4.8, indicates that higher values of this probability decrease total sales and thereby GDP.

Basically, a higher chance of founding new firms comes together with higher prices with less produced and sold goods, because there are more heterogeneous firms. This effect leads nevertheless to a more equal distribution of wealth across social classes. Finally, we refer to a firm founding probability of 5% for the parameter in the main simulation of the article. For this value, sales are still improving over time and we find an average rate of unemployment, compared to the other potential values.

***Sensitivity Experiment 9***: Variation of $\alpha_2$ (Price adjustment rate)

The actual price variation will be a fraction of this value, see Eq. (8) in Rengs and Scholz-Wäckerle, 2019: 239). In the given sensitivity experiment, as presented in Fig. A.4.9, we have varied this value between 0.25% and 1.75% of the average base price of the simulation run.

A higher rate of price adjustment makes price dynamics more volatile, whereas a very low adjustment rate leads to price stagnation as well as lower levels of unemployment. However, these employment gains depend on a steeper increase in total sales, which translates also into much higher levels of emissions and a more unequal distribution of wealth. Otherwise higher levels of the adjustment rate lead just to a parallelization between the scenarios at higher macro outcomes. Therefore,

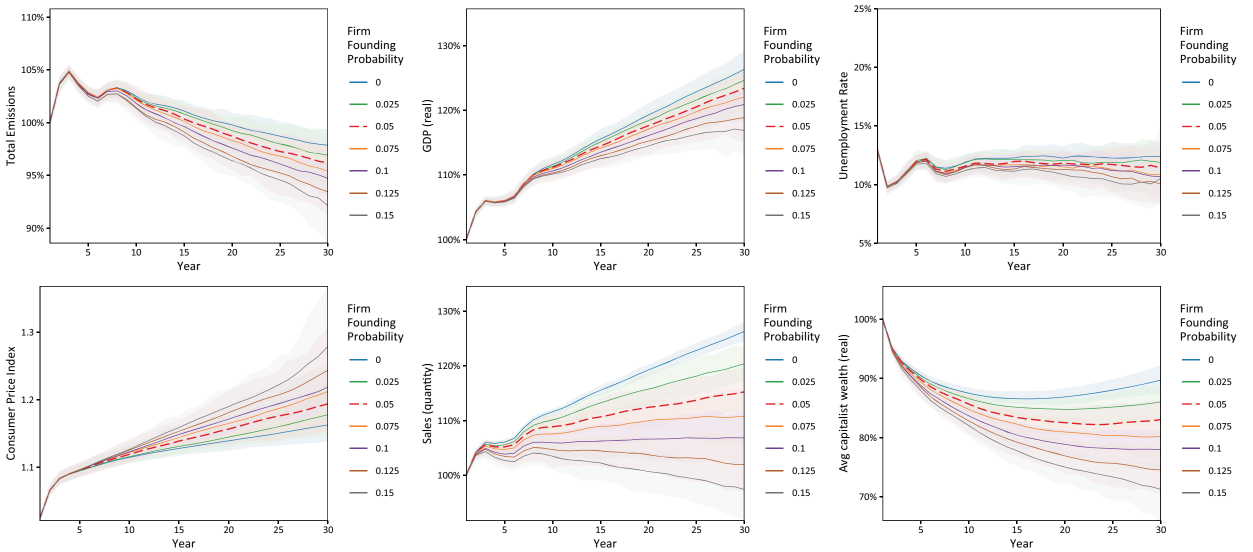


**Fig. A.4.8.** Simulation results for Sensitivity Experiment 8: variation of the probability of households founding a new firm.

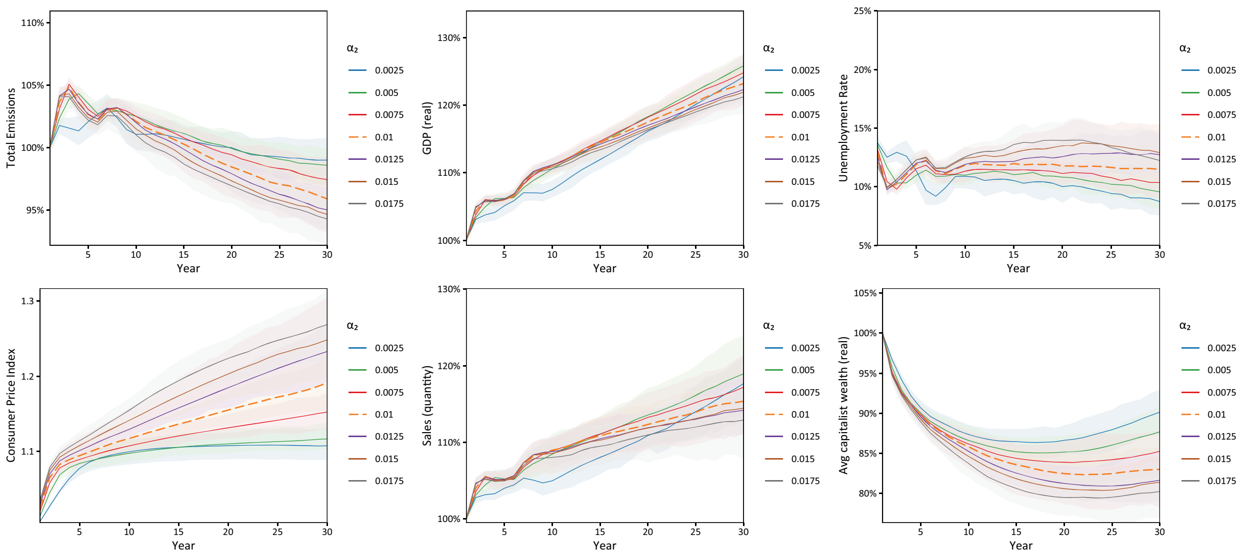


**Fig. A.4.9.** Simulation results for Sensitivity Experiment 9: variation of $\alpha_2$ (price adjustment rate).

the parameter was calibrated at 1%, indicating an average developmental path of macroeconomic aggregates, within the spectrum of the parameter interval.

***Sensitivity Experiment 10***: Variation of $\alpha_7$ (Labor productivity parameter)

The labor productivity parameter determines the firm's production technology, i.e., how many goods (units) can a worker produce per month, at given technology. We have tested variations for $\alpha_7$ between 1500 units and 6750 units per month (stepwise increased with 750 units), as presented in Fig. A.4.10. Settings where labor productivity is above 4000 units per month translate (obviously) into higher unemployment. Nevertheless, firms can yield slightly higher final sales than on average at such productivity levels that increases real GDP as well but also total emissions. A higher productivity leads otherwise to a more unequal distribution of wealth.

Moreover, the parameter plays a central role in the initialization process of the main simulation in the article because it can be used to directly regulate unemployment in the economy. If productivity is high, but the demand for goods remains the same, then unemployment increases. If productivity is very low, then at some point the worker households with lower income can only finance their need consumption and prices increase rapidly (see productivity of e.g., 1500 or 2250 units per month), as overall demand cannot be satisfied. Where employment is very high in the short run (almost hitting full employment), it falls tremendously in the medium run where we observe an unusually steeply increasing rate of unemployment

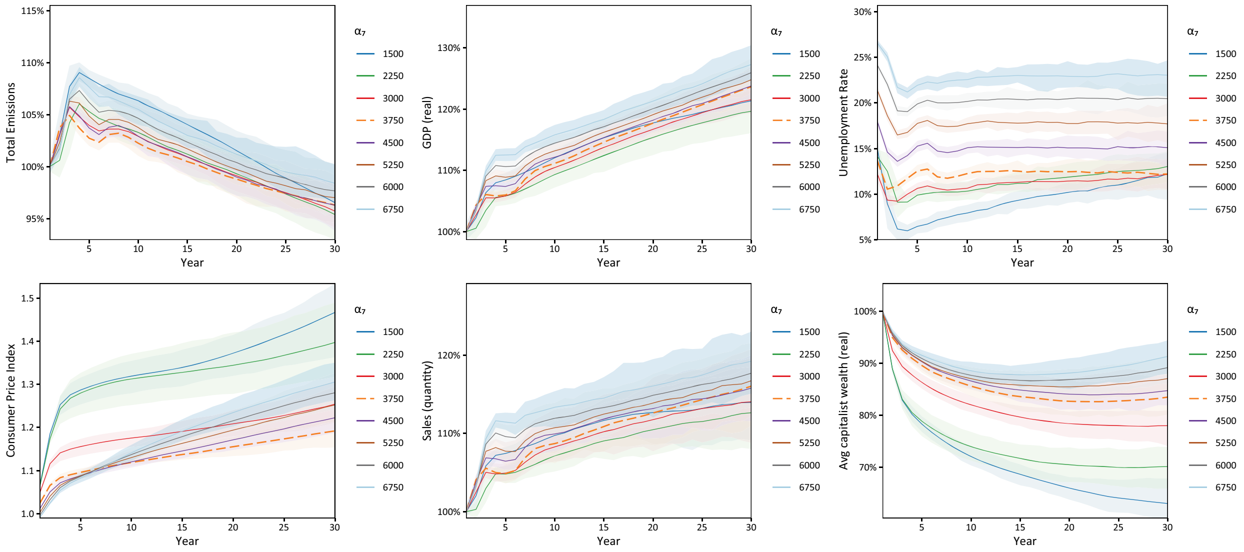


**Fig. A.4.10.** Simulation results for Sensitivity Experiment 10: variation of $\alpha_7$ (labor productivity parameter).

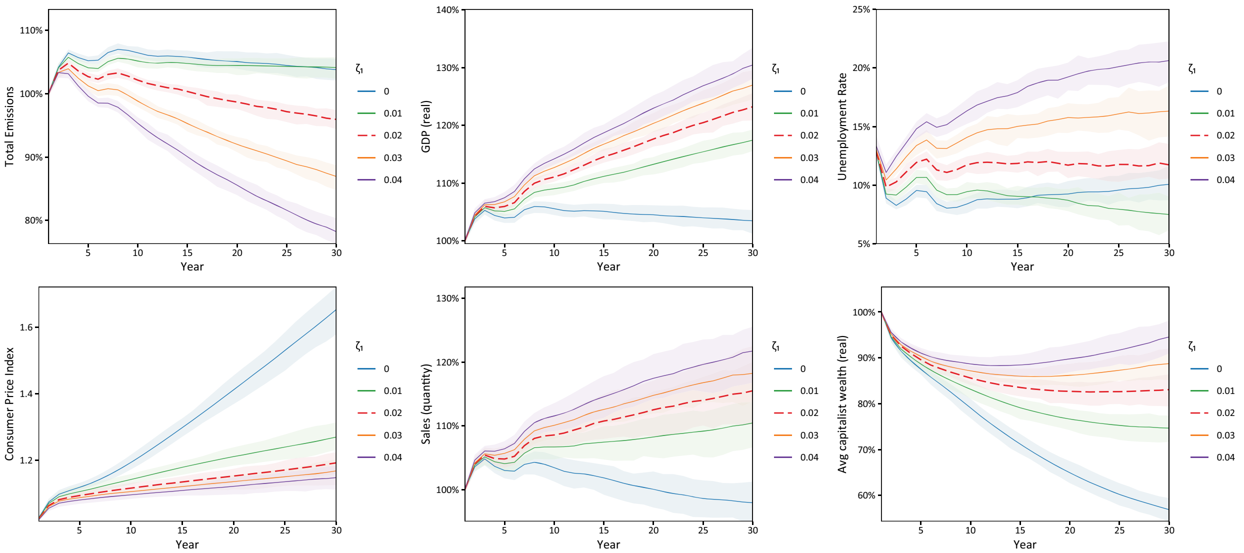


**Fig. A.4.11.** Simulation results for Sensitivity Experiment 11: variation of $\zeta_1$ (R&D base success).

(at a productivity of 1500 units/month). These experiments with lower productivity lead also to a more equal distribution of wealth. Given this sensitivity of the parameter, $\alpha_7$ is set to 3750 units/month.

***Sensitivity Experiment 11***: Variation of $\zeta_1$ (R&D base success)

The R&D base success rate ($\zeta_1$) sets the percentage of productivity gains for allocation of investment in R&D between carbon and labor productivity improvements. Setting $\zeta_1 = 0$ leads to the rather hypothetical case where firms make their R&D investments but do' not get any returns with regard to process innovation. Consequently, this special case just increases the cost burden of firms. Furthermore, R&D for carbon and labor productivity are both subject to spillover effects and an early mover advantage.

This sensitivity experiment shows that both types of R&D improve more if $\zeta_1$ is assumed higher, as presented in Fig. A.4.11. Further, the experiment demonstrates that a higher initially assumed success rate (e.g., 4%) leads to very high unemployment rates and a stark decrease in total emissions and consequently carbon intensity (combined with an increase in real GDP). This comes with a socioeconomic burden, namely a higher unemployment and a more unequal distribution of wealth. On the contrary, $\zeta_1 = 1$ leads to unstable inflationary dynamics with lower unemployment, total sales and real GDP). Eventually $\zeta_1 = 0.02$ makes a meaningful setting parameter setting for the base success rate of R&D.

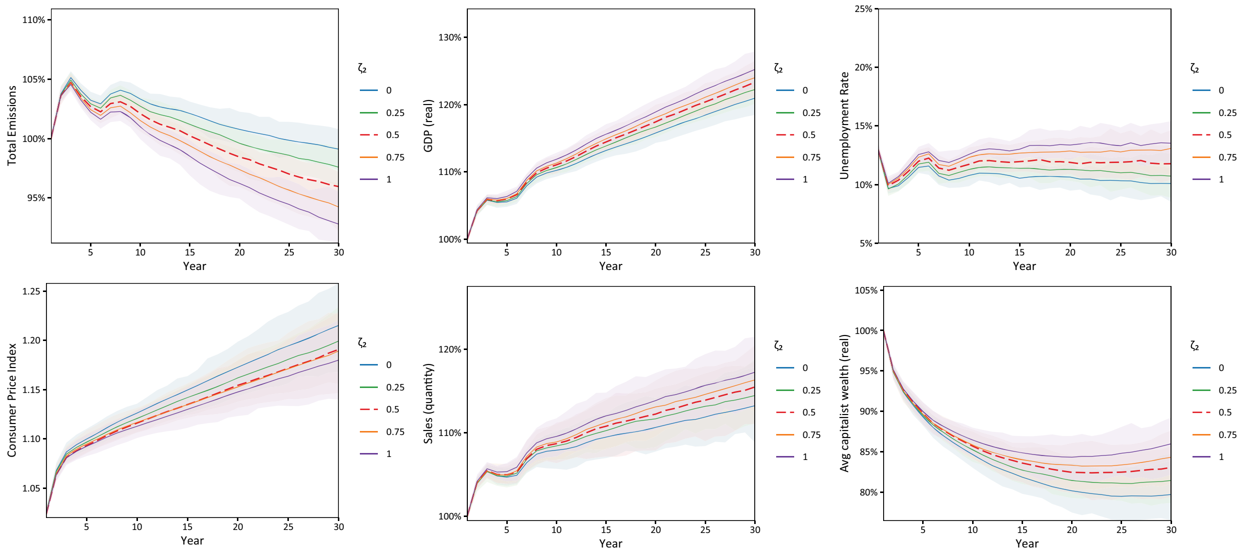


**Fig. A.4.12.** Simulation results for Sensitivity Experiment 12: variation of $\zeta_2$ (R&D maximum spillover).

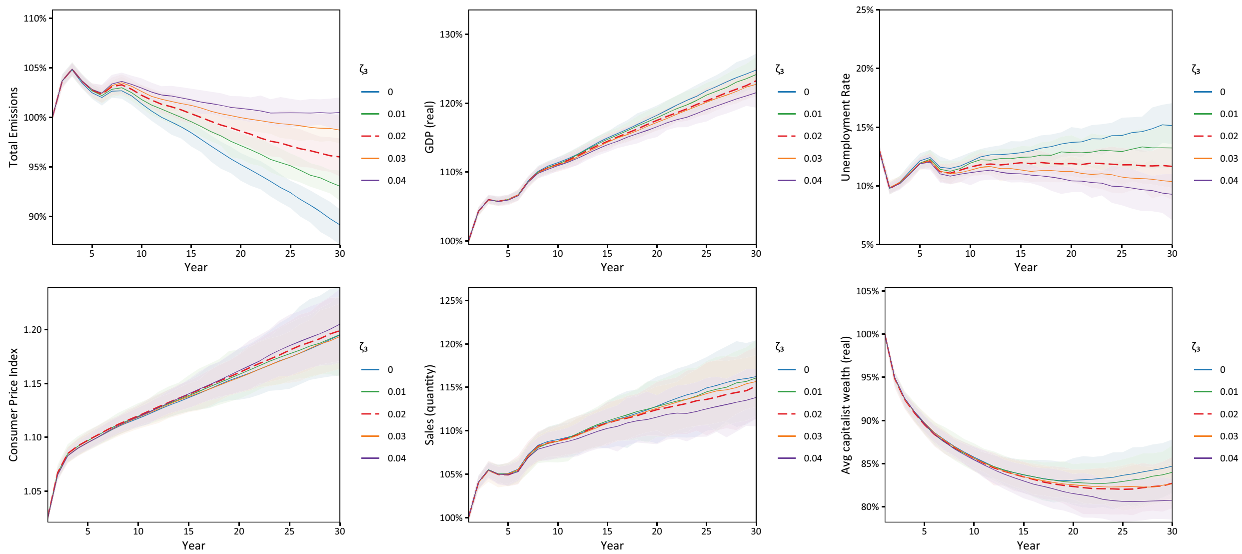


**Fig. A.4.13.** Simulation results for Sensitivity Experiment 13: variation of $\zeta_3$ (R&D early mover advantage).

***Sensitivity Experiment 12***: Variation of $\zeta_2$ (R&D maximum spillover)

Here we obtain similar results as in experiment 11. Higher spillover effects lead to lower total emissions and carbon intensity but at the cost of more unemployment and inequality, as presented in Fig. A.4.12.

***Sensitivity Experiment 13***: Variation of $\zeta_3$ (R&D early mover advantage)

The early mover advantage is modeled as a discount factor on R&D success, implying lower productivity gains from R&D investment the longer the firm waits with such investment. A higher early mover advantage translates into a lower real GDP and higher total emissions (and worse carbon intensity), as presented in Fig. A.4.13. In addition, a higher $\zeta_3$ leads to less inequality of wealth.

***Sensitivity Experiment 14***: Variation of $\phi_1$ (Firm credit risk parameter)

The more a firm can expose itself to private debt for investment purposes – in relation to its capital – the faster it is able to grow via increases in production capacities. In this sensitivity experiment, we have tested the credit risk parameter between 40% and 60%, as presented in Fig. A.4.14.

Higher values for $\phi_1$ result almost directly into more final sales, higher levels of real GDP therefore and correspondingly more total emissions. Otherwise, lower levels of the credit risk parameter translate into an unstable economic developmental path, where firms are not able to adapt to changes in demand in the short run. Excess demand cannot get satisfied and

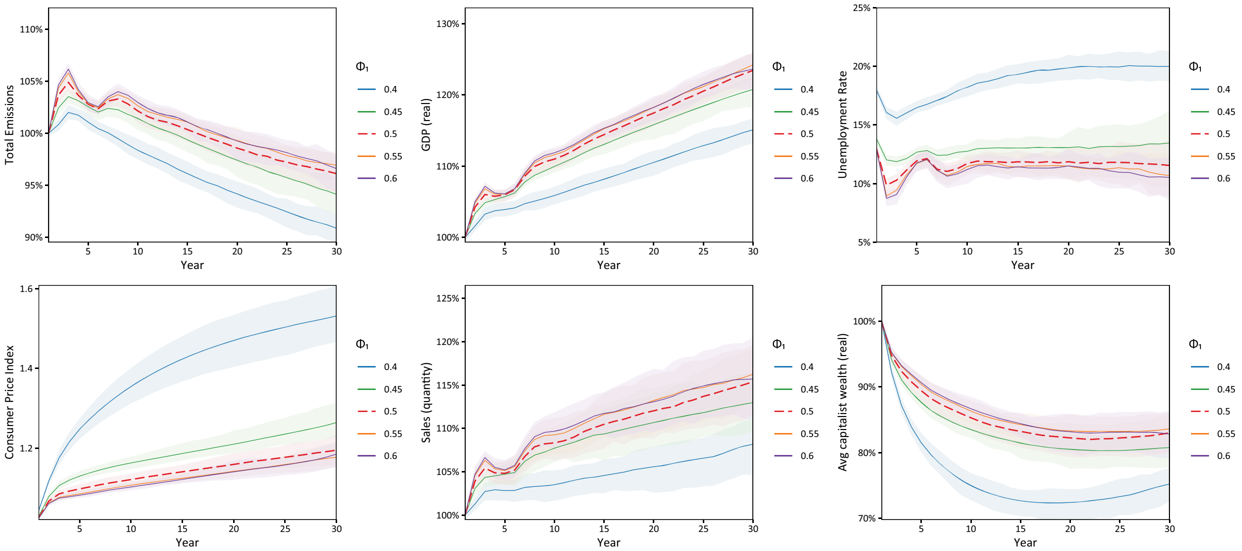


**Fig. A.4.14.** Simulation results for Sensitivity Experiment 14: variation of $\phi_1$ (firm credit risk parameter).

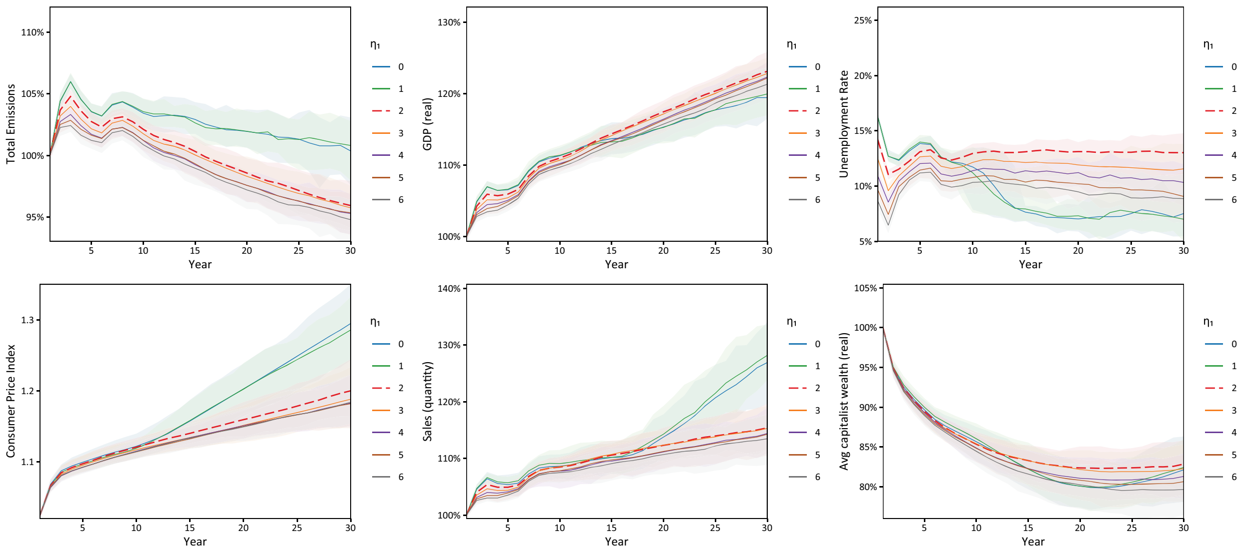


**Fig. A.4.15.** Simulation results for Sensitivity Experiment 15: variation of $\eta_1$ (duration of the protection against dismissal).

consumers change their preferred vendors at a very frequent level which otherwise comes with serious inflationary dynamics. Since the final sales are super low, the employment of workers cannot get sustained and we face unemployment levels higher than 15% (at $\phi_1 = 0.4$). For the parameter calibration, it was very important to avoid such very unstable and unique economic dynamics, that is why we set $\phi_1 = 0.5$ as a reasonable value of the credit risk parameter.

***Sensitivity Experiment 15***: Variation of $\eta_1$ duration of the protection against dismissal

The final univariate sensitivity experiment we have conducted deals with the duration of the protection against dismissal. We assume government enforces this protection for a number of months. In this experiment we have tested the protection duration between 0 and 6 months, as presented in Fig. A.4.15.

In the medium and long run, no protection or just a one month protection result into a very unstable labor market, where firms change their labor force far too often, which obviously results in lower unemployment, but at the cost of a much lower capacity utilization (~20% lower than in the other cases with a higher duration). This low capacity utilization causes inflationary dynamics and consequently higher levels of total emissions. Therefore, we set the parameter to two months of labor protection, in accordance with Seppecher (2012).

***Multivariate Sensitivity Experiment 16***: Variation of $\zeta_1$ (R&D base success) with different tax levels under the scenario T

This is the first of three multivariate variations, experiments indicating the interdependency of crucial parameter constellations and their resulting economic dynamics. This experiment deals with variations of the R&D base success rate, combined

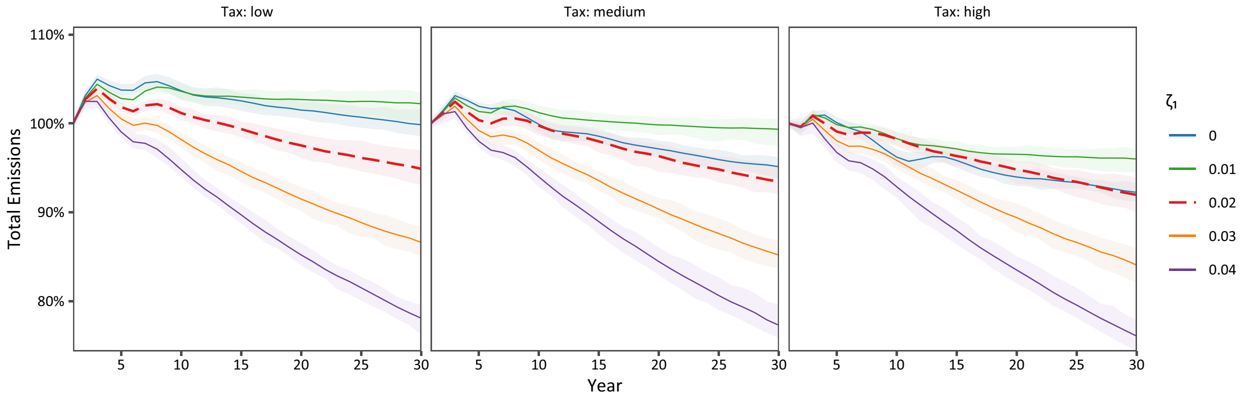


**Fig. A.4.16a.** Simulation results for total emissions under multivariate sensitivity Experiment 16: variation of $\zeta_1$ (R&D base success) with different tax levels under the scenario *T*.

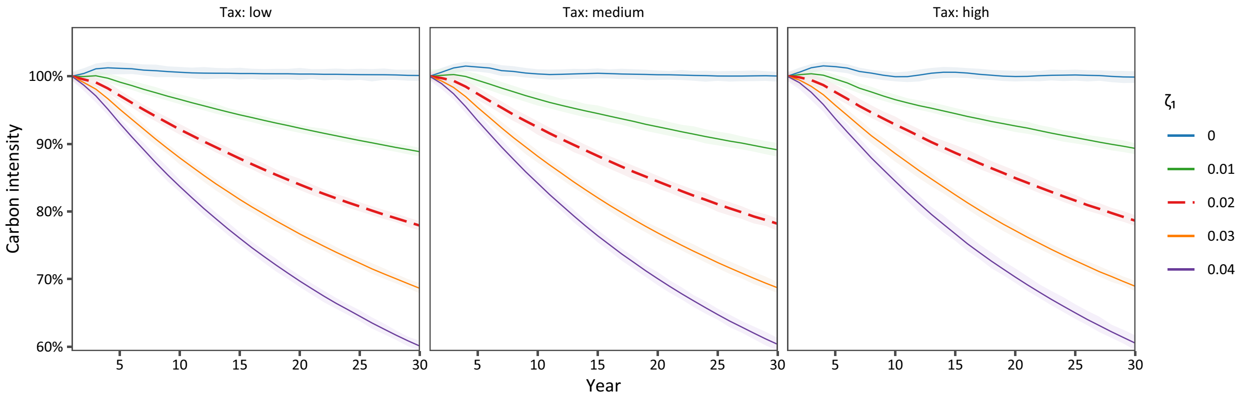


**Fig. A.4.16b.** Simulation results for carbon intensity under sensitivity Experiment 16: variation of $\zeta_1$ (R&D base success) with different tax levels under the scenario *T*.

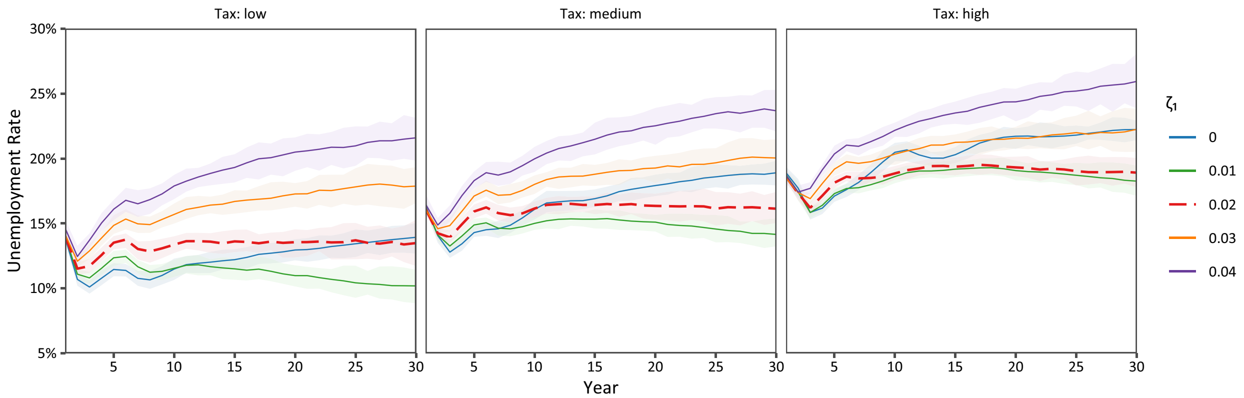


**Fig. A.4.16c.** Simulation results for unemployment rate under multivariate sensitivity Experiment 16: variation of $\zeta_1$ (R&D base success) with different tax levels under the scenario *T*.

with variations of the tax level, because it reflects the core of the environmental extension of the model. As given in the following Figs A.4.16a-16g, the resulting parameter permutations show similar results as made in the univariate experiment 12 on the parameter $\zeta_1$. However, the multivariate experiments are performed with the scenario setting *T*, which reflects our basic climate policy scenario, i.e., a carbon tax at different levels (low, medium, high). Funds from the tax are redistributed to households as we extensively explained in the main article.

The variation of the R&D base success rate leads to different levels of total emissions (see Fig. A.4.16a), where a higher rate translates directly into less emissions, as we have already shown with experiment 12. However, an additional variation of the tax level indicates that at the highest carbon tax level, if R&D investments are not successful at all ($\zeta_1 = 0$), emissions

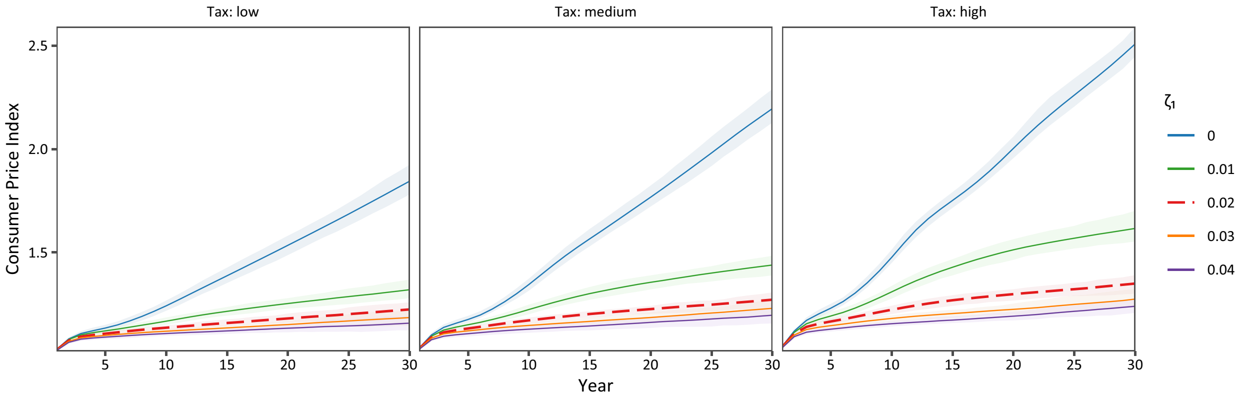


**Fig. A.4.16d.** Simulation results for consumer price index under multivariate sensitivity Experiment 16: variation of $\zeta_1$ (R&D base success) with different tax levels under the scenario *T*.

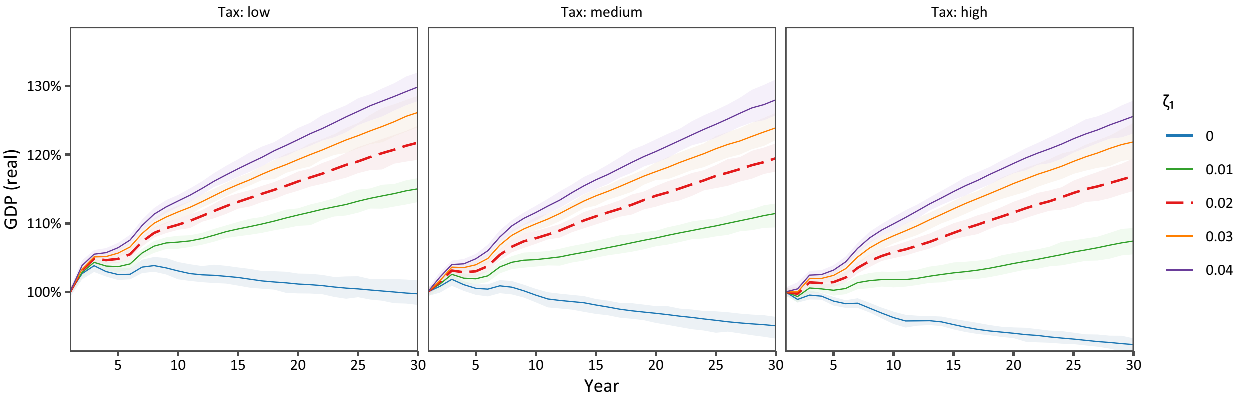


**Fig. A.4.16e.** Simulation results for GDP under multivariate sensitivity Experiment 16: variation of $\zeta_1$ (R&D base success) with different tax levels under the scenario *T*.

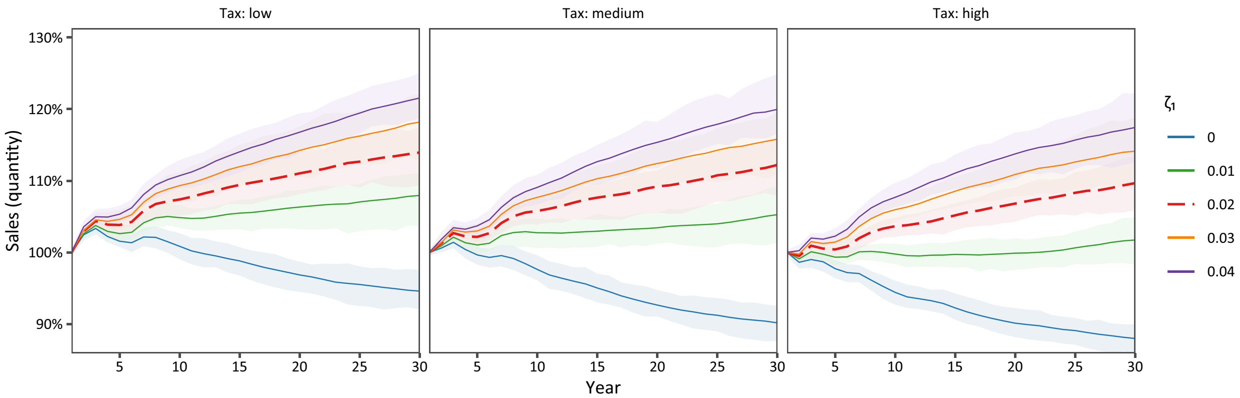


**Fig. A.4.16f.** Simulation results for sales under multivariate sensitivity Experiment 16: variation of $\zeta_1$ (R&D base success) with different tax levels under the scenario *T*.

drop below the time series of a 2% success rate ($\zeta_1 = 0.02$). This rather extraordinary case realizes, because firms ca'nnot adapt to the excess demand, cannot realize their R&D investments and raise prizes therefore.

We observe extremely stark inflationary dynamics, making the economy unstable, see Fig. A.4.16d. The effect can be seen also in total income (GDP real – Fig. A.4.16e) as well as total sales (Fig. A.4.16f) . This translates into more unemployment compared to $\zeta_1 = 0.02$ that we adopted for the main simulation.

Eventually, if investments do not result into successful R&D improvements in either labor or carbon productivity, we obtain a more equal distribution of wealth across classes, but obviously at a high cost since emissions and carbon intensity

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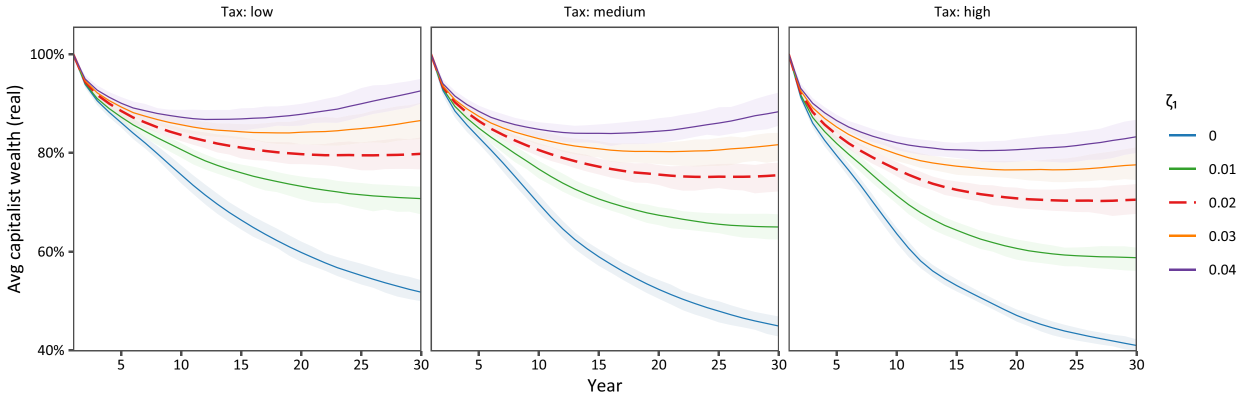


**Fig. A.4.16g.** Simulation results for average capitalist wealth under multivariate sensitivity Experiment 16: variation of $\zeta_1$ (R&D base success) with different tax levels under the scenario *T*.

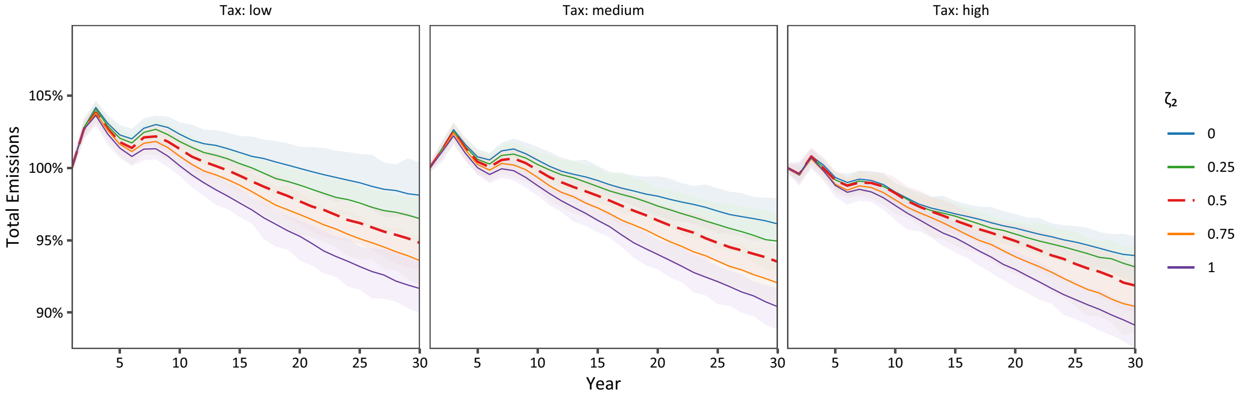


**Fig. A.4.17a.** Simulation results for total emissions under multivariate sensitivity Experiment 17: variation of $\zeta_2$ (R&D maximum spillover) with different tax levels under the scenario *T*.

are at the highest level (see Fig. A.4.16g). Overall, the experiment shows that the parameter calibration for the R&D base success rate of $\zeta_1 = 0.02$, delivers stable economic dynamics.

***Multivariate Sensitivity Experiment 17***: Variation of $\zeta_2$ (R&D maximum spillover) with different tax levels under the scenario T

This sensitivity experiment shows simulation runs with multivariate parameter constellations, with a focus on the research spillover effect. We start testing at $\zeta_2 = 0$ indicating a somewhat hypothetical case where firms invest in R&D but do not get a successful process innovation in return. This special case just increases the cost burden of firms. Further variations are made for 25%, 50%, 75% and a full 100% success at different tax levels (low, medium, high). This experiment adds upon the results from sensitivity experiment 12 where we have performed univariate experiments around this parameter for the BAU scenario. In general, the economic dynamics are similar to those in the related univariate experiment 12.

The higher the R&D research spillover is assumed, the more total emissions can get reduced at all tax levels, having the lowest level of emissions at 100% spillover within the high tax scenario (see Fig. A.4.17a). The higher the tax level the more narrow will be the ribbon of the simulation results, since output gets substantially reduced and thereby overall volatility.

Even though total emissions are at far lower levels in the high tax scenario, we do not observe lower levels of carbon intensity, which looks almost identical across the various tax levels per parameter setting (see Fig. A.4.17b). In the medium and high tax case, real GDP (Fig. A.4.17e) as well as final sales (Fig. A.4.17f) drop significant, implying a decrease in output that is cancelling out the emission effect in the carbon intensity. The lower output results moreover in a higher unemployment that is also very narrowly distributed across different settings for $\zeta_2$, since the labor market is less volatile (Fig. A.4.17c).

From 0 to 25% spillover, combined with a high tax scenario, we can observe very high inflationary dynamics (Fig. A.4.17d). Firms cannot adjust to the excess demand, as due to high costs they cannot expand and thus instead raise prices.

Eventually, very low spillover effects combined with a high carbon tax may lead to a more equal distribution of wealth (Fig. A.4.17g), but at very high environmental and economic costs. The 50% research spillover effect delivers the most stable economic dynamics for the variables above and promises a steady economic developmental path to study the more nuanced climate policy packages in the main simulation experiments of the article, in addition to the empirical evidence from the

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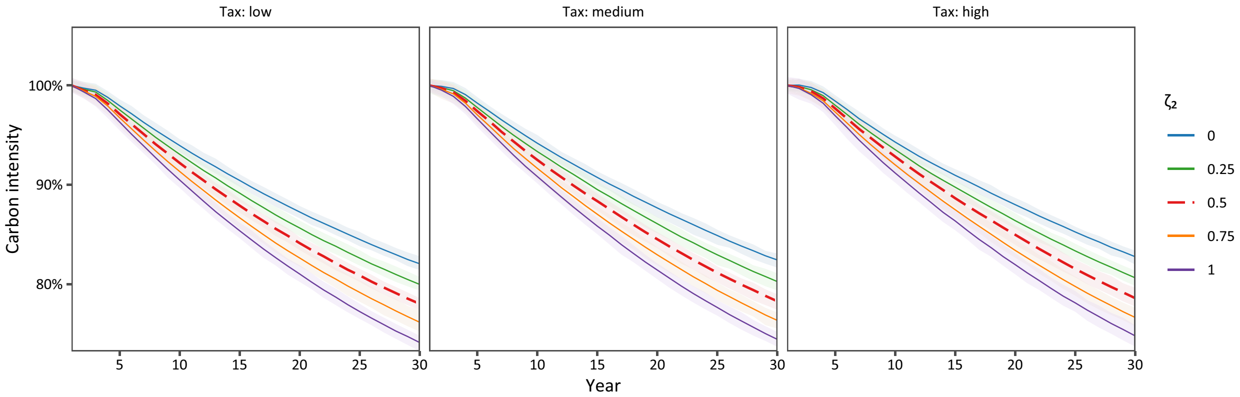


**Fig. A.4.17b.** Simulation results for carbon intensity under multivariate sensitivity Experiment 17: variation of $\zeta_2$ (R&D maximum spillover effect) with different tax levels under the scenario *T*.

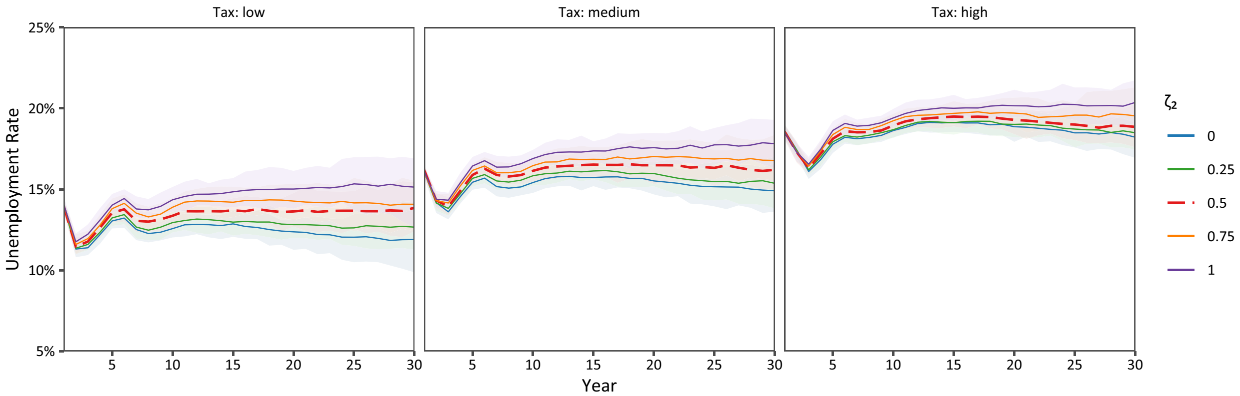


**Fig. A.4.17c.** Simulation results for unemployment rate under multivariate sensitivity Experiment 17: variation of $\zeta_2$ (R&D maximum spillover) with different tax levels under the scenario *T*.

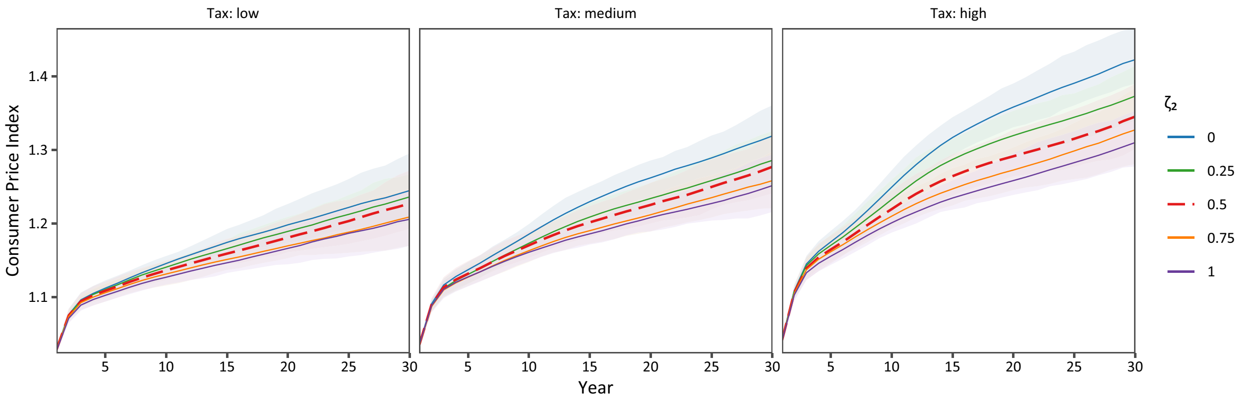


**Fig. A.4.17d.** Simulation results for consumer price index under multivariate sensitivity Experiment 17: variation of $\zeta_2$ (R&D maximum spillover) with different tax levels under the scenario *T*.

literature as given in Appendix 2 in the main article. In view of this, the research spillover effect is set to $\zeta_2 = 0.5$ for the main simulation.

***Multivariate*** **S*ensitivity Experiment 18***: Variation of $\zeta_3$ (R&D early mover advantage) with different tax levels under the scenario T

Sensitivity experiment 19 represents the final experiment in this analysis and shows results from combining parameter variations of the research early mover advantage $\zeta_3$ at different tax levels. It adds upon experiment 13 where this parameter was changed in univariate terms.

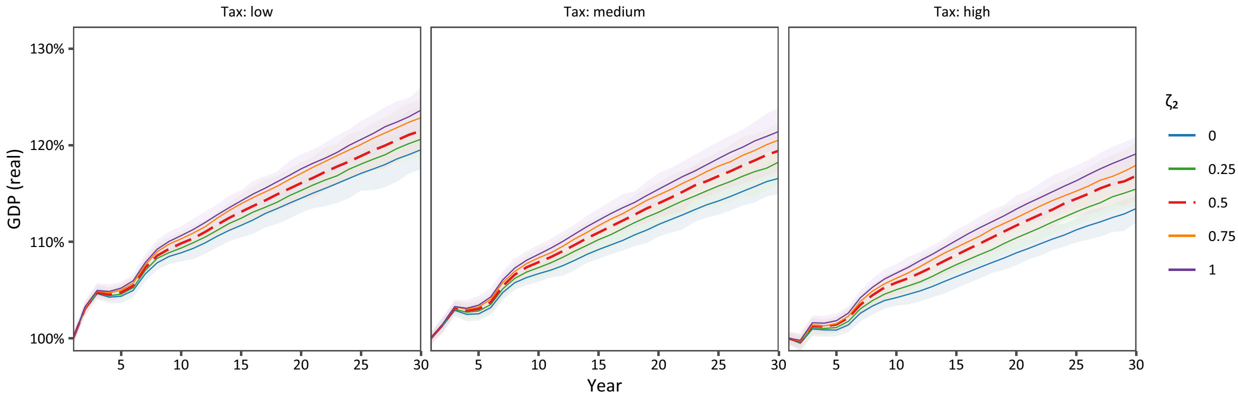


**Fig. A.4.17e.** Simulation results for GDP under multivariate sensitivity Experiment 17: variation of $\zeta_2$ (R&D maximum spillover) with different tax levels under the scenario *T*.

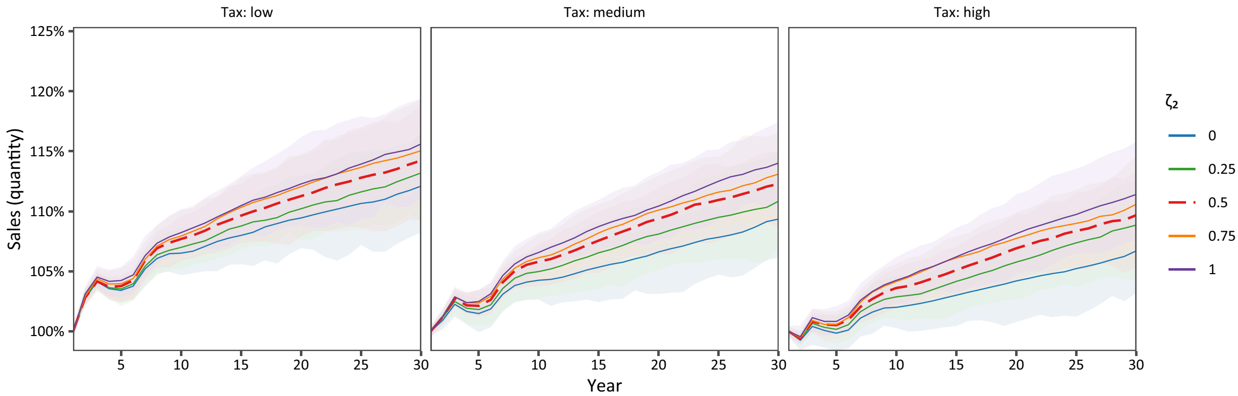


**Fig. A.4.17f.** Simulation results for sales under multivariate sensitivity Experiment 17: variation of $\zeta_2$ (R&D maximum spillover) with different tax levels under the scenario *T*.

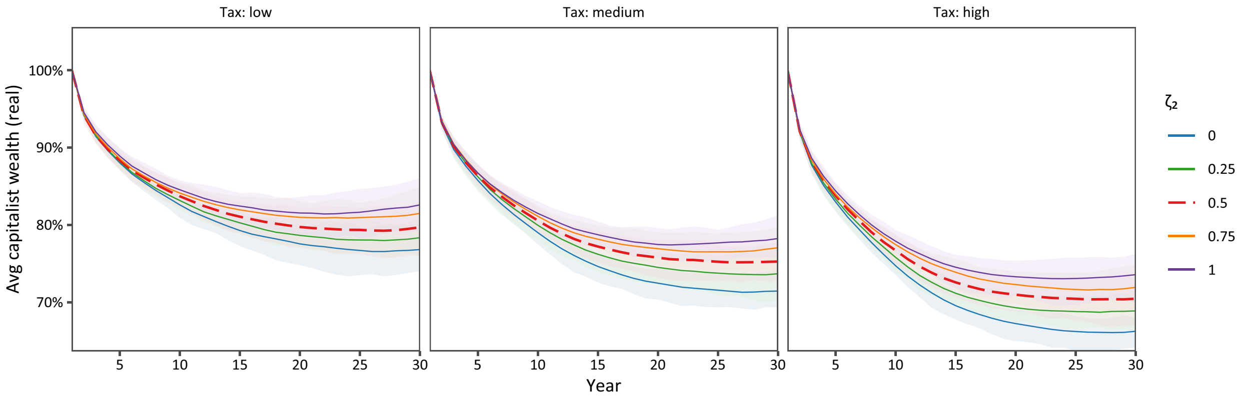


**Fig. A.4.17g.** Simulation results for average capitalist wealth under multivariate sensitivity Experiment 17: variation of $\zeta_2$ (R&D maximum spillover) with different tax levels under the scenario *T*.

Basically, a low early mover advantage results into less total emissions and vice versa for higher settings (see Fig. A.4.18a), since firms still have a good success rate even when they enter the process innovation later than others. We see again narrower ribbons at higher tax levels sue to the already mentioned drop in output, causing with less volatility at all markets.

Carbon intensity mimics the results from the previous multivariate experiment (Fig. A.4.18b). Where we can indicate again almost the same levels at higher tax rates, but with less real GDP (Fig. A.4.18e) and total sales (Fig. A.4.18f) at those levels. This notion translates again into higher unemployment. The unemployment reacts inversely to the previous experiment. Lower settings for the early mover advantage lead to higher unemployment (Fig. A.4.18c), since firms can realize their R&D projects more effectively and yield technological advances, resulting again into unemployment.

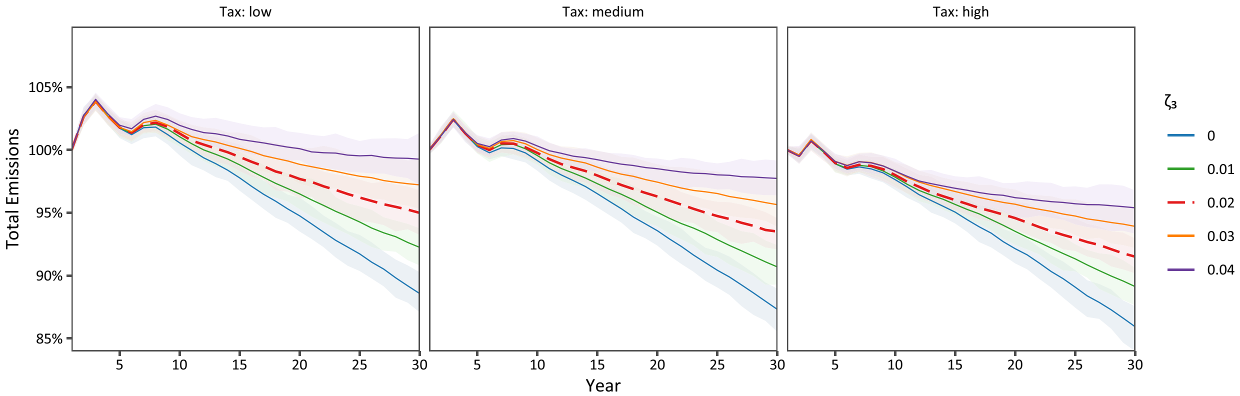


**Fig. A.4.18a.** Simulation results for total emissions under multivariate sensitivity Experiment 18: variation of $\zeta_3$ (R&D early mover advantage) with different tax levels under the scenario *T*.

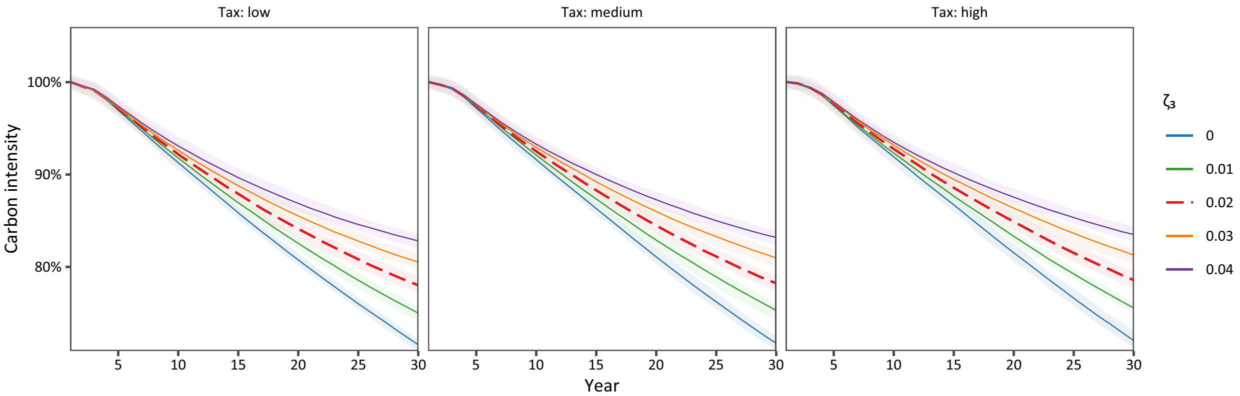


**Fig. A.4.18b.** Simulation results for carbon intensity under multivariate sensitivity Experiment 18, variation of $\zeta_3$ (R&D early mover advantage) with different tax levels under the scenario *T*.

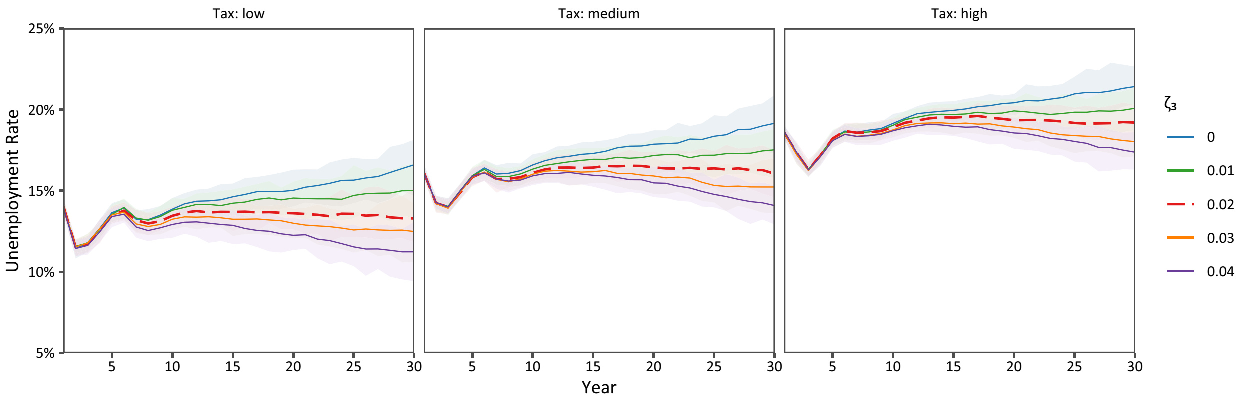


**Fig. A.4.18c.** Simulation results for unemployment rate under multivariate sensitivity Experiment 18: variation of $\zeta_3$ (R&D early mover advantage) with different tax levels under the scenario *T*.

On the contrary, if firms are sanctioned more for starting late with investments in R&D (e.g., $\zeta_3 = 0.04$), they will raise prices much faster in order to compensate the higher cost burden (Fig. A.4.18d); even more at higher tax rates.

Output behaves similar as in the previous multivariate sensitivity experiments. Once we look into real GDP (Fig. A.4.18e) as well as final sales (Fig. A.4.18f), we see that output drops on the one hand at higher tax rates, leading to even lower real GDP at higher early mover advantages.

The experiment shows furthermore again that the distribution of wealth is better off at higher tax rates (carbon also redistributing across classes, as we also outline extensively in the main article) and at higher early mover advantages (Fig. A.4.18g), when firms face higher costs for the R&D investment at the end of the day.

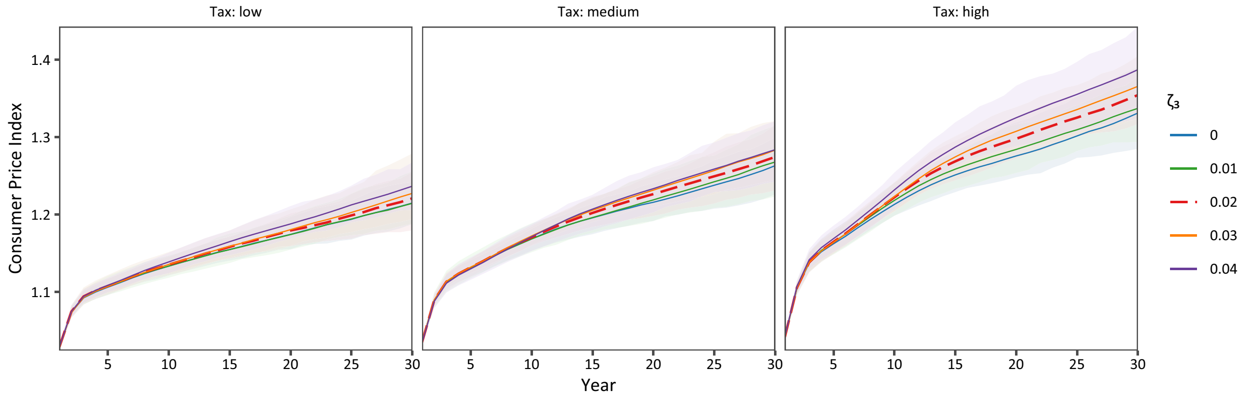


**Fig. A.4.18d.** Simulation results for consumer price index under multivariate sensitivity Experiment 18: variation of $\zeta_3$ (R&D early mover advantage) with different tax levels under the scenario *T*.

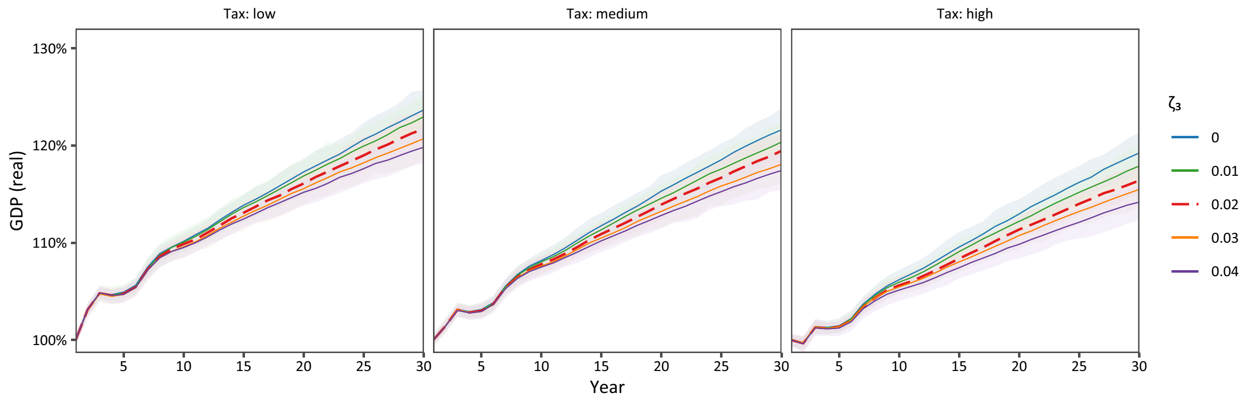


**Fig. A.4.18e.** Simulation results for GDP under multivariate sensitivity Experiment 18: variation of $\zeta_3$ (R&D early mover advantage) with different tax levels under the scenario *T*.

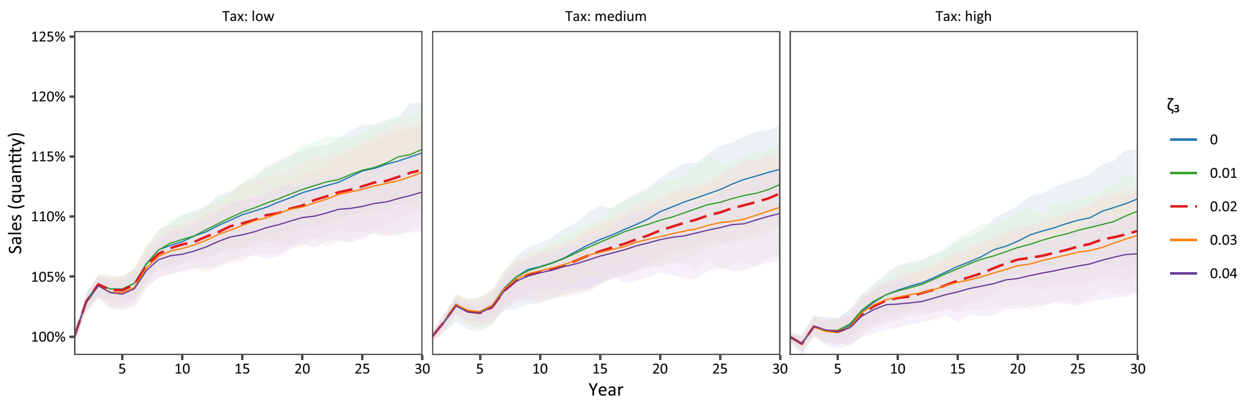


**Fig. A.4.18f.** Simulation results for sales under multivariate sensitivity Experiment 18: variation of $\zeta_3$ (R&D early mover advantage) with different tax levels under the scenario *T*.

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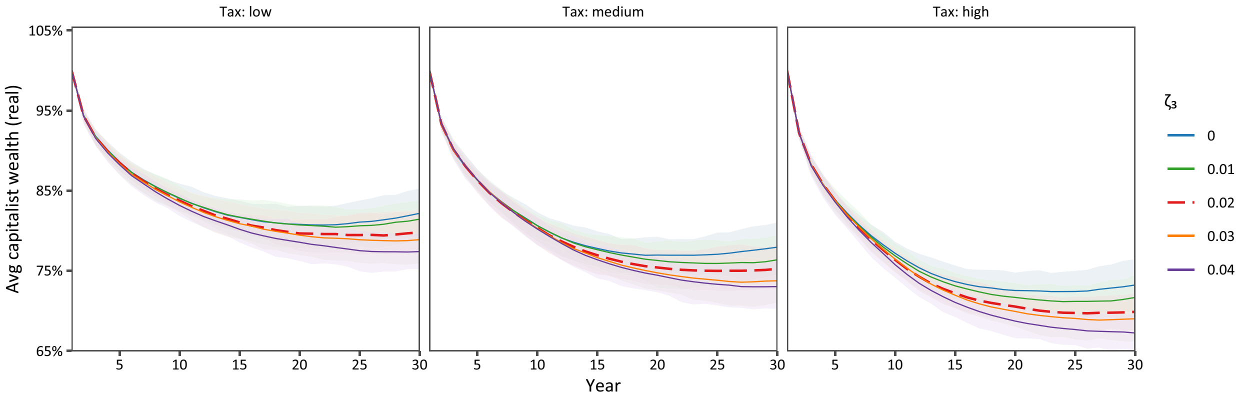


**Fig. A.4.18g.** Simulation results for average capitalist wealth under multivariate sensitivity Experiment 18; variation of $\zeta_3$ (R&D early mover advantage) with different tax levels under the scenario *T*.

Overall, this sensitivity experiment informs us reasonably on calibrating the early mover advantage at $\zeta_3 = 0.02$, i.e., a 2% discount per simulated year.

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