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Endogenous Economic Growth, Climate Change and Societal Values: A Conceptual Model

Michael W. M. Roos[1]

Abstract In this paper, I propose an evolutionary model that is an alternative to conventional models of growth and the environment. Global economic growth, the evolution of the human population, CO_2 emissions, and the state of the environment are endogenous. Societal values are the main driver of all economic variables. They determine the different types of investment, the level of aggregate consumption and employment. Societal values evolve over time in response to economic and environmental conditions. The model is applied to generate possible scenarios for the twenty-first century. A baseline calibration generates an average global GDP growth rate of 3.6% p.a. and a global population level of 11.2 billion people in 2100. Mean global temperate in 2100 will be 1.77 °C higher than in 1995. These results are probably too optimistic. Sensitivity analyses show how these outcomes depend on various parameters. If values respond to environmental conditions only, global warming would reach 2.5 °C and a lower impact of investment in carbon efficiency could lead to average temperature increase by 4.8 °C. The model is a novel conceptual framework that can be extended in many dimensions.

Keywords Endogenous growth · Societal values · Climate change · Environment · System dynamics · Evolutionary economics · Post-materialism

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1 Introduction

Although climate change and environmental destruction are serious challenges to global civilization, they are only fringe topics in current mainstream macroeconomics. Fischer and Heutel (2013) argue that that there should be more work on environmental policy in macroeconomics and review some Real Business Cycle models and economic growth models that address environmental issues. Rezai et al. (2013) also call for more macroeconomic research on climate change and identify a particular need for more theoretical analysis and modeling. There is some literature that analyzes the relation between economic growth and the environment in neoclassical growth models, as reviewed in Xepapadeas (2005) and Brock and Taylor (2005). And of course, the integrated assessment models such as DICE (Nordhaus and Sztorc 2013), FUND (Anthoff and Tol 2013) and PAGE (Hope 2011) can be seen as macroeconomic models.

In this paper, I propose a model that is an alternative to conventional models of growth and the environment and takes into account the manifold interaction of economic growth, temperature change, population change, and the evolution of societal values. My model is an example of a novel conceptual framework that can be extended in many dimensions. In the model, global economic growth, the evolution of the human population, CO_2 emissions, and the state of the environment are endogenous. The main driver of all economic variables are societal values which determine the different types of investment, the level of aggregate consumption and employment. Societal values vary on a materialist/post-materialist spectrum and evolve over time in response to changes in the natural environment and in income per capita. When the state of the environment deteriorates or per-capita income rises, society becomes more post-materialistic and invests more into carbon efficiency improvements and the restoration of the environment. However, since the global average temperature depends on the already emitted stock of carbon dioxide, society may respond too slowly to the environmental damage caused by the industrial production of output.

Conventional integrated assessment models like FUND or PAGE are very detailed with respect to the ecological part of the model, but economic growth is simply an exogenous process which is hardly convincing from the perspective of economic theory (see Bonen et al. 2014). In line with the literature on economic growth and the environment, the economic part of the DICE model is a conventional neoclassical Ramsey growth model. Yet there are well-justified methodological critiques against the Ramsey growth model and the related microfoundations paradigm in macroeconomics with representative agents, rational expectations and perfectly rational maximizing agents (Kirman 1992; Hartley 2002; Setterfield and Suresh 2012). In the presence of interaction between heterogeneous agents and market failure due to externalities the representative agent assumption is highly problematic. And as discussed in Roos (2015), climate change and the resulting transformation of the socio-economic system involve radical uncertainty so that maximization and rational expectations are inadequate assumptions.

There are two ways to deal with the critique against the rational representative agent. First, one can build agent-based models in which the interaction of heterogeneous agents with bounded rationality is explicitly modeled and the aggregate behavior of the system may be very different from individual behaviors because of the inter-

action (see Roos 2015). Agent-based models are very flexible and can be applied to a host of different applications. Recently, a number of macroeconomic agent-based models have been published (Assenza and Delli Gatti 2013; Deissenberg et al. 2008; Delli Gatti et al. 2011; Dosi et al. 2010, 2013; Lengnick 2013; Mandel et al. 2009; Salle et al. 2013). Agent-based models are particularly useful if one is interested in the emergence of macroeconomic outcomes from behaviors at the micro- and mesoeconomic level and the bottom-up explanation of phenomena observed at the aggregate level. They are also powerful tools for the analysis of specific policy instruments. But the purpose of this paper is neither to analyze any specific public policy nor to provide a microfounded explanation of some macroeconomic phenomenon or pattern. Instead, I am interested in the interaction between variables at the macroscopic level of the global economy and the Earth's climate and environmental system. I therefore follow the second way to avoid the aggregation problems of representative-agent models by restricting the analysis to the macroeconomic level only.[1] The model presented here is a system dynamics model without microfoundations in the tradition of the limit-to-growth literature (see Meadows et al. 1972, 2004).[2] The purely aggregate structural model approach pursued here has the advantage that it makes the interactions and feedback effects between different parts of the economic system and the environmental system more transparent. It is considerably simpler than an alternative agent-based model that would also combine global production, consumption, investment, labor supply, population dynamics and their effect on climate and the environment. An agent-based model of the same scope would have a huge number of parameters that are hard to calibrate and require many behavioral assumptions that are difficult to justify given the current state of research. Deriving the mentioned relationships and in particular analyzing the effects of various instruments of climate policy in an agent-based model is surely desirable, but requires more basic research on how to work with large macroeconomic agent-based models.

The main methodological novelty of the paper is the introduction of societal values as a driving force of all macroeconomic variables. This modelling approach allows me to endogenize the economic processes without having to resort to dubious microfoundations. Societal values serve as a summary variable for potentially quite complicated social dynamics of individual agents' motives and individual and collective decision processes. They are measurable and have been studied extensively by Ronald Inglehart (1977, 1989, 1995). Introducing social values into a macroeconomic model brings macroeconomics closer to sociology, social psychology, and political science.

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[1] This approach is analogous to what is done in physics. In thermodynamics we can use the ideal gas law that postulates stable relationships between aggregate variables that describe the state of a gas, such as pressure or temperature. The kinetic theory of gases in turn explains temperature by the behavior of gas molecules. While it is definitely helpful to look at the level of atoms (or even at the subatomic level) to explain what temperature is, we can safely ignore the atoms and their interaction and work with the concept of temperature if we are interested in phenomena at the macroscopic level.

[2] A common criticism against system dynamics models is the Lucas critique, which mainstream macroeconomics hopes to avoid by providing microfoundations to macroeconomic models and deriving all macro dynamics from "deep parameters". Hartley (2002) argues convincingly that this approach is flawed since preferences and technology cannot be assumed to be deep parameters. Furthermore, the Lucas critique does not apply to my model, because I do not use any aggregate relationships for policy analysis in the way it was done with the macroeconometric models criticized by Lucas (1976).

While in the recent years microeconomics has been strongly influenced by behavioral economics that studies the behavior of real humans, macroeconomics might benefit greatly from socio-economics (Etzioni 2003). Socio-economics analyzes the relationships between society and the economy and uses insights from history, political science, anthropology, sociology and other fields dealing with social processes.

Conventional analysis in economic growth theory relies heavily on statements about the steady state of the models or the so-called balanced growth path. The focus on steady states is convenient, because it allows the researcher to study the model in analytical terms and to derive closed-form solutions which are clearly very useful. However, steady state analysis that makes statements about the long run is of little help for societal responses to climate change in the next years or decades. Knowing that a balanced growth path with sustainable levels of pollution or carbon dioxide emissions exists in the long run is not helpful if we do not know when and how it will be reached or whether it can be attained at all. Rather than analyzing the properties of some long-run steady state or balanced growth path, I simulate the potential evolution of the global socio-ecological system in the twenty-first century. The model generates scenarios how the system might evolve under plausible initial conditions and parameter values and shows how sensitive these scenarios are to the assumptions. The model is roughly calibrated to empirical data to generate realistic magnitudes of output growth and temperature change over the next century. It is not meant to be predictive in the sense that it makes forecasts about the *most likely* future paths of the endogenous variables, but rather anticipatory in the sense of showing which outcomes are *plausible*.

Another important difference of this paper to other approaches in the literature is that I reject the idea of a social planner. It is common practice in models of growth and climate change or integrated assessment models (see Nordhaus 2013) to determine an optimal policy with the tool of the fictitious social or Ramsey planner whose optimization problem incorporates all market externalities. Comparing the optimality conditions of the representative private agents and those of the social planner, one can derive optimal policy instruments such as taxes or subsidies that would induce the private agents to internalize the external effects of their actions on the environment. Even if such optimal policies could be found—which is hardly possible if the uncertainty about the complex dynamics of the economy and the natural environment is properly acknowledged—,[3] this kind of research does not say anything about the crucial question of how optimal policies could be implemented in the political process. The use of a Ramsey planner always assumes that all the complications of implementing optimal policies have been solved. In contrast to social planning approaches, my model implicitly treats policy as endogenous by assuming that societal values are constraints to and drivers of both private behavior and public policy.[4] It is important to emphasize that the analysis takes place at the aggregate level which implies that all dynamics of the endogenous variables should be interpreted as the outcomes of underlying social

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[3] There are some papers that introduce uncertainty and tipping points into microfounded integrated assessment models and use these models to derive optimal climate policies, e.g. Cai et al. (2013), Lemoine and Traeger (2014).

[4] Note that I treat public policy only implicitly in my model. I do not model any policy instruments explicitly, but this does mean that they are not needed for decarbonization.

processes, but not as the conscious choices of some fictitious social planner that has the power to determine the aggregate variables. The amount of aggregate investment into physical capital, the level of aggregate saving or the growth rate of population are not directly chosen by anybody. The aggregate variables result from many individual decisions which are not modeled explicitly, but captured by the evolution of societal values, which is also an aggregate concept.

The approach pursued in this paper has implications for what can be said about public policy. Instead of suggesting optimal policies or trajectories, that might be highly misleading given the involved uncertainties, the purpose of the model is to raise awareness of how the future of the global economy and the natural environment might look like in the coming decades and how possible trajectories depend on the model assumptions. Integrated assessment models such as Nordhaus and Sztorc (2013) are used to predict how the socio-ecological system might evolve in the future under different assumptions about climate policy. Typically, there is a business-as-usual scenario that extrapolates the current situation into the future and some scenarios in which different policy measures to fight climate change are implemented. The comparison of the policy scenarios with the business-as-usual scenario allows the researchers to evaluate the effectiveness and efficiency of the various policies. This approach is reasonable if the aim is to come to a hypothetical assessment of different policies. However, it treats policy and the fundamentals of agents' behavior as if they were exogenous to the socio-ecological system, which is implausible in the long run. Exogenously imposing some policy action on the system does not take into account how likely it is that such a policy actually will be implemented. My central argument is that effective climate policies—however they might look like in detail—are only implemented if they are in line with society's values. If humanity cares more about consumption than about the protection of the climate system and nature, there will be no political majorities for measures such as a carbon tax, an effective emissions trading system or large scale investment into renewable energy. For this reason, I do not want to derive concrete policy recommendations but rather analyze the evolution of the underlying causes of both private behavior and public policy, such that this approach is positive rather than normative.

The paper is structured as follows. In Sect. 2, I discuss the concept of social values and their relationship with the economy more in depth. Section 3 presents the model description and Sect. 4 contains the documentation of the model calibration. In Sect. 5, I analyze some properties of the model. Section 6 discusses the model and its results and presents some thought on potential extensions and applications and Sect. 7 concludes.

2 Societal Values

It is the central proposition of this paper that both the behavior of economic agents and economic policy depend on societal values. Values are an important concept in social psychology (see Schwartz 2012) and in sociology (see Hitlin and Piliavin 2004). Values are not the same as preferences. In economics, preferences describe the ordering of alternatives, hence they are a relative concept used to make comparisons. In contrast, values convey what is important or desirable in the lives of people (see

Bardi and Schwartz 2003; Hitlin and Piliavin 2004). They can be conceived as ideal ends within an action situation. Therefore, a value can be expressed in absolute terms without making a comparison. For example, people may give importance to power, achievement or stimulation. These values then guide behavior or choice in specific situations.

The political scientist Ronald Inglehart developed a theory of how values in society change over time (Inglehart 1977, 1989, 1997). Using time series data from 26 countries, he observed that a major value shift had been occurring during the past decades with changes in religious beliefs, work motivation, attitudes towards children and families, attitudes towards sexuality, and attitudes towards nature and the environment. Inglehart argues that apart from affecting social life, these changes transform societies economically and politically. In particular, they have given rise to new parties and political movements in many countries such as ecological parties and peace movements.

Inglehart's theory is based on Maslow's idea of a hierarchy of needs and wants. At the bottom of this hierarchy are physiological needs and the need for security, then the need for love and belonging and the need for status and esteem follow. At the top of the pyramid is the need for self-actualization. Inglehart relates these needs and wants with values and distinguishes materialist and post-materialist values. While materialist values give top priority to economic and physical security, post-materialist values give highest priority to self-expression, belonging and non-material quality of life. The values of an individual reflect the relative scarcity of goods in the individual's socio-economic environment. Relatively scarce goods receive higher value (scarcity hypothesis). Furthermore, Inglehart argues that individuals develop stable values during in their formative years when they are young (socialization hypothesis). This implies that a value shift in society is not a temporary life-cycle phenomenon but related to the gradual replacement of older generations by younger ones. The value shift in advanced economies in the past decades can then be explained by the very different socio-economic and technological conditions under which generations before and after the Second World War grew up. Both in the U.S. and in Europe, the interwar years were are period of economic crisis, while the time after WW II was prosperous. Age cohorts that experienced rising social and economic security and affluence after 1945 in their formative years hence developed post-materialist values in contrast to the generation of their parents and grand-parents.

The distinction between materialism and post-materialism is not only a theoretical one, but can also be measured. Inglehart devised an index to measure values empirically with survey data. Among other databases, the post-materialism index is included in the World Values Survey,[5] which was heavily influenced by the work of Inglehart. For the construction of the Inglehart post-materialism index respondents are asked to choose their most important goals from a list of four or twelve given statements. The goals in the 4-item index are: "maintaining order in the nation" (M), "giving the

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[5] The World Values Survey (www.worldvaluessurvey.org) is a large-scale research project of global network of social scientists studying changing values and their impact on social and political life and economic development. It started in 1981 and consists today of nationally representative surveys conducted in almost 100 countries which contain almost 90% of the world's population, using a common questionnaire.

people more say in important political decisions" (P), "fighting rising prices" (M), "protecting freedom of speech" (P). Among the additional items in the 12-item list are the following goals: "a high level of economic growth" (M), "trying to make our cities and countryside more beautiful" (P), "a stable economy" (M), "progress toward a less impersonal and more humane society" (P), "progress toward a society in which ideas count more than money" (P). Theoretically, respondents should make consistent choices from these lists. People who experienced economic or physical insecurity while they were young should pick the materialist goals indicated by (M) above, while people who grew up in economic affluence and security should favor the post-materialist statements (P).

The evidence (see Inglehart 1989) shows that there are pure materialists who only value materialist goals, pure post-materialists who always give highest priority to post-materialist goals and mixed types. The classification along the materialism/post-materialism spectrum is predictive for a broad range of opinions and behaviors. Inglehart (2008) provides evidence that materialists tend to agree with the following statements: "respondent (R) has not recycled something to protect the environment", "R has not attended a meeting or signed a petition to protect the environment", "a good income and safe job are more important than a feeling of accomplishment and working with people you like", "hard work is one of the most important things to teach a child", "leisure is not very important in life", "scientific discoveries will help, rather than harm, humanity", "friends are not very important in life". Inglehart (1995) reports data showing that support from environmental protection both in advanced economies and in developing countries (China, India, Nigeria) is stronger among post-materialists than among materialists. In West Germany, Sweden, France and Britain post-materialism is also strongly correlated with the intention of voting for environmentalist parties. That these intentions also have real effects might be concluded from the negative correlation between the level of urban air pollution and the share of post-materialists in a country also reported in Inglehart (1995). The postulated value shift from materialism to post-materialism after WW II can be observed in many countries with more post-materialist younger generations gradually replacing the materialist older generations.

Inglehart's theory and the empirical findings can be applied to economic questions. König and Wagener (2008) propose a model that explains the decrease in the ratio of capital taxes to labor taxes by a societal shift towards post-materialist values. They use a model in which a shift from materialism to post-materialism is reflected by a higher weight on leisure in the utility function of the representative worker/consumer. More post-materialist agents consume more leisure and are less motivated by monetary incentives to supply more labor, which results in a higher taxation of labor.

As argued in the Introduction, I do not want to provide explicit microfoundations to my model, but I have an implicit model of how values affect the economic variables at the macroeconomic level. Suppose, for simplicity, there are only the two pure types of agents in the economy: materialists and post-materialists. Both types display consistent life-styles in several dimensions of life, i.e. their labor supply decisions, their consumption and their voting behavior are driven by the values that are important to them. Materialists value economic security highly, hence they work hard and strive for high income. I also assume that they consume a lot and support conservative political parties that promote free-market, business-friendly policies in order to achieve high

economic growth. In contrast, people for whom post-materialist values such as self-expression are important work and consume less, enjoy more leisure to have time for social contacts and volunteer activities, and also support left-wing and ecological parties.

Especially the link between pro-environmental values and pro-environmental behavior is well-documented in the empirical literature. Kahn (2007) shows that in Californian communities with higher shares of Green party members, people make "greener" transportation choices than the average consumer. Greens are more likely to use public transit, consume less gasoline and purchase hybrid vehicles. He also shows that green communities support environmental protection ballots more and that the Congress representatives of green communities are more likely to vote environmental positions. Nayum and Klöckner (2014) develop a comprehensive socio-psychological model of the determinants of buying a fuel-efficient car and show that purchase intentions are influenced by normative processes involving personal norms and an ecological worldview. Gilg et al. (2005) present a case study on sustainable lifestyles in Devon, UK. Their study documents that green consumers tend to hold more pro-environmental and pro-social values. Consumers that are committed to environmentally friendly behaviors are more likely to hold biospheric and ecocentric values.

In my model, societal values are reflected by the share of post-materialists in the global civil society, V. From a macroeconomic perspective it is important to notice that values do not only determine behavior at the individual but also at the aggregate level. The more people share similar values, the more relevant these values are at the macroeconomic level. The values endorsed by the majority of the members of a society determine consumption and production both directly through choices of the individuals and indirectly through regulation and policy measures such as taxes or subsidies. With regard to climate protection, both private and public efforts to curb carbon dioxide emission should hence depend on the share of post-materialists in society. A larger share of post-materialists in society (larger V) leads to more political influence of left-wing and green parties and greener consumption choices and thus less carbon dioxide emissions.

3 Model

The model describes a socio-ecological system, in which human decisions and environmental processes interact. The analysis takes place at the aggregate level only and focuses on the system dynamics. This means that the variables cannot be interpreted as "decisions" of any decision-maker but rather as the outcomes of complicated societal processes involving many different and interacting decision-makers which are not modeled. In order to clearly work out the effects at the global level, I keep the analysis as simple as possible and do not consider the level of individual decision-making of households, firms and other agents of society, but rather focus on the dynamics of the aggregated system. There is no presumption that the aggregate decisions are in any sense rational, optimal or welfare-maximizing. Even if the underlying individual decisions are in some sense rational, it would be a fallacy of composition to assume the same for the aggregate outcome of these individual decisions.

The economic submodel is very similar to the standard neoclassical growth models from macroeconomic theory, especially the models of endogenous growth such as Romer (1990). However, in contrast to conventional neoclassical theory, I neither include microfoundations nor focus on the steady state of the model or perform any kind of equilibrium analysis. My main argument against steady state analysis that we typically do not know when and whether at all a steady state can be attained. Furthermore, equilibrium analysis is at odds with the idea of a system breakdown or collapse. Suppose there is an inverted U-shaped relation between global temperature and global production, similar to the environmental Kuznets curve (see Eriksson 2013). The long-run steady state of the model might lie on the declining branch of the temperature-production curve. In order to get to this steady state of the system, it might be necessary to move along the curve because some pre-determined variables require gradual adjustment processes. Yet it is conceivable that the upper part of the temperature-production curve is located in a region of collapse of the environmental system, because a critical temperature threshold has been passed. If the system moves into that region, the dynamics might change and the theoretical steady state might be unattainable. I hence argue that is very important to analyze trajectories of temperature, production and other variables out of a long-run steady state to identify potentially dangerous developments that could lead to a global collapse. The model and the analysis in this paper reflect these considerations, even though I do not explicitly model the possibility of a system collapse.

The model contains multiple feedback effects between global temperature, production, efficiency, population, and societal values. Furthermore, there is a considerable time lag between actions (CO_2 emissions) and consequences (climate change and its effects). The lagged response of temperate on CO_2 emissions generates a stock-flow problem, which can lead to societal responses which are too late and can result in a very strong increase in the global temperature that could ultimately lead to a collapse of global civilization. It seems plausible to assume that societal values respond slowly to experienced changes in the socio-economic and ecological environment, but not to anticipated consequences of climate change in the future. At least since the Rio de Janeiro Earth Summit in 1992 mankind represented by the United Nations knows that climate change is a major problem. Effective actions to fight this problem, however, have been few since and carbon dioxide emissions have risen strongly since then.

I calibrate the model with available data on global production, population, CO_2 emissions etc. While the calibration of the parameters at this stage is a bit rough, all starting values of the endogenous variables are taken from standard macroeconomic data sources.

Figure 1 provides an overview of the model. The model has three submodels: (1) The economic submodel, which is represented by the blue boxes, determines output, the inputs, investment levels and saving/consumption. (2) The climate and nature submodel in green determines the global average temperature change and the state of the natural environment as a consequence of production's carbon emissions and the resulting carbon stock in the atmosphere. (3) The global population and its values are the represented by the orange boxes and are the central variables of the model. The arrows between the boxes show the direction of influence and the numbers stand for the equations which are presented in the following subsections. As can be seen, I
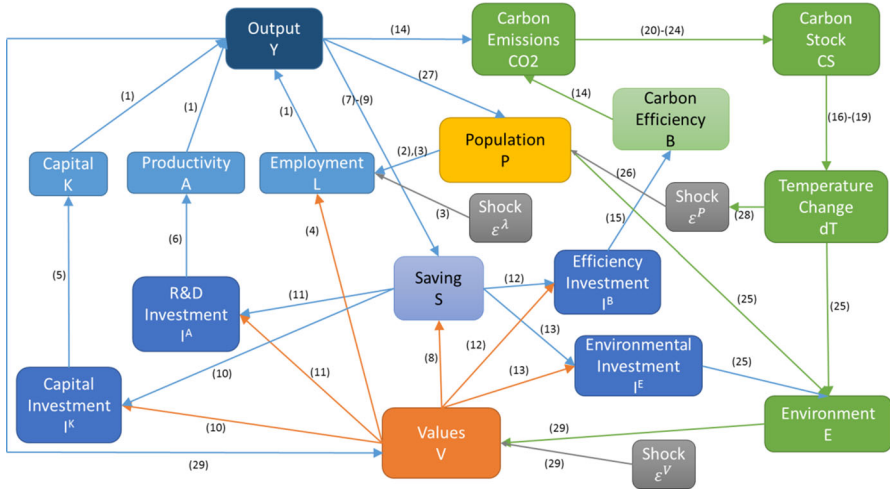
Fig. 1 Model overview

have assumed one-way causations only to keep the model tractable. Furthermore, the model features three stochastic shocks that affect the level of employment, the level of population, and societal values. Note that apart from the shocks, all variables are endogenous.

3.1 Economy

The global economy is characterized by production Y, employment L, investment into the variables physical capital K, productivity A, carbon efficiency B, and the restoration of the natural environment E, aggregate consumption C and aggregate saving S. All of these variables are endogenous.

Output is produced with a neoclassical Cobb–Douglas production function[6]:

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

Employment L depends is a fraction of the total population P:

$$L_t = \lambda_t P_t \tag{2}$$

The employment ratio λ_t fluctuates stochastically around a "natural" level $\bar{\lambda}$:

$$\lambda_t = (1 - \phi)\,\bar{\lambda}_t + \phi\lambda_{t-1} + \varepsilon_t^\lambda \quad \text{with} \quad \varepsilon_t^\lambda \sim N\left(0, \sigma_\lambda^2\right) \tag{3}$$

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[6] For a discussion of the problems with the neoclassical production function and of the related "Cambridge Capital Controversy" see Foley and Michl (1999).

These fluctuations capture business cycle movements and short-run adjustments.[7] The natural level $\bar{\lambda}_t$ depends on society's values V_t and can change over time if these values change. V_t is the share of post-materialists in the global civil society. If everybody holds materialist values ($V = 0$), the natural employment ratio is maximal ($\bar{\lambda}_{max}$). If society is composed of post-materialists only ($V = 1$), the employment ratio is minimal ($\bar{\lambda}_{min}$). As discussed in Sect. 2, post-materialists want to enjoy more leisure and non-labor market activities than materialists (see Inglehart 2008). I assume that $\bar{\lambda}_t$ is a linear function of societal values:

$$\bar{\lambda}_t = \bar{\lambda}_{min} + \left(\bar{\lambda}_{max} - \bar{\lambda}_{min} \right) \left(1 - V_t \right) \tag{4}$$

New physical capital K is built by investment into capital goods in the previous period, I_{t-1}^K. The depreciation rate δ is constant so that the capital stock evolves according to a standard accumulation equation:

$$K_t = (1 - \delta) K_{t-1} + I_{t-1}^K \tag{5}$$

Total factor productivity A_t is deterministic and cumulative. New knowledge is generated by investment into productivity, I_{t-1}^A. Productivity growth is assumed to be a power function of the investment to output ratio:

$$A_t = A_{t-1} \left(1 + a_1 \left(\frac{I_{t-1}^A}{Y_{t-1}} \right)^{a_2} \right) \tag{6}$$

Consumption is modeled as a simple Keynesian aggregate consumption function (without an intercept):

$$C_t = c_t Y_t \tag{7}$$

The marginal propensity to consume c depends on the values of society and is maximal (minimal) if society is most (post-)materialistic.

$$c_t = c_{min} + (c_{max} - c_{min}) (1 - V_t) \tag{8}$$

This captures the idea that consumption in materialistic societies has a strong social function and generates social status. Post-materialists value consumption less for social or environmental reasons.[8] Of course, even in a fully post-materialistic society, there must be a minimum level of consumption. By definition aggregate saving is

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[7] Note that we cannot say anything about the reason why people are unemployed, since the labor market is not explicitly modeled. This is not necessary for the purpose of the paper.

[8] Not being an economist, Inglehart is less interested in the relation between post-materialism and consumption. Yet a couple of recent papers establish a link between materialism and high consumption levels on the one hand and between "frugal consumption" and values that correlate with post-materialism on the other hand (see Pepper et al. 2009; Markowitz and Bowermann 2012; Goldsmith and Flynn 2015; Hoffmann and Lee 2016; Lee and Ahn 2016; Seegebarth et al. 2016).

$$S_t = Y_t - C_t \tag{9}$$

The way in which consumption is modelled here implies that post-materialistic societies save more. This can be justified by less time discounting (because future generations count more) or higher willingness to invest, e.g. in environmental restoration or increases carbon efficiency.

At the global level, world investment must be financed by world savings.[9] The relative allocation of savings on investment types is determined by societal values. A materialistic society invests a lot into physical capital and productivity in order to produce ever more consumption goods.

$$I_t^K = (1 - V_t) \, k S_t \tag{10}$$
$$I_t^A = (1 - V_t) \, (1 - k) \, S_t \tag{11}$$

The parameter k governs the importance of investment into new physical capital relative to investment into productivity improvements. If k is high, the economy is capital-biased, if k is low, it is productivity-biased. The capital-bias of investment is exogenous in this model and could be used for policy-analysis.

If the society's values are predominantly post-materialist, it channels relatively more of its savings into investments that lower the carbon emissions of output production (improve carbon efficiency B) and the restoration of environmental quality. More investment into carbon efficiency improvements could be induced by carbon taxes or other policy instruments, which are favored by environmentalist political parties. As argued in Sect. 2, post-materialists care about the environment and tend to vote for green parties. Using the 58 countries in wave 6 of the World Value Survey, I find a correlation of 0.29 between the share of pure post-materialists in a country and the share of respondents who agree with the statement that protection of the environment should be given priority, even if it causes lower economic growth and some loss of jobs. I hence assume that "green" investment into improved carbon efficiency of production, I^B, and into the restoration of environment, e.g. by planting new trees or the renaturation of rivers, I^E, are proportional to the share of post-materialists.

$$I_t^B = V_t \, (1 - e) \, S_t \tag{12}$$
$$I_t^E = V_t e S_t \tag{13}$$

The parameter e describes the relative importance of environmental restoration compared to carbon efficiency and might be called the environmental bias. This parameter

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[9] In line with neoclassical growth theory, I do not consider the role of money, credit and finance for investment and growth. These aspects are very important in Post-Keynesian macroeconomics (see Lavoie 2006; Davidson 2011). The same applies to the role of the income distribution which is emphasized in Post-Keynesian approaches, but ignored in neoclassical models. Post-Keynesian researchers have very good arguments for the consideration of money and the financial sector in macroeconomic analysis, especially after the global crisis of 2007–2009. I have chosen a more mainstream neoclassical approach here for pragmatic reasons: The main contribution of this paper is to introduce the idea that societal values determine macroeconomic outcomes. I could have done this in a Post-Keynesian model, too, but the neoclassical approach is more accepted in the literature.

could also be used to study the effects of different policy orientations. In a sense the environmental bias captures the relation between prevention and restoration or mitigation and adaptation. The larger e is, the more society tries to repair damages that have already occurred (adaptation). If e is small, there is more emphasis on the prevention of climate-related damages to nature by attempts to reduce carbon dioxide emissions (mitigation).

The assumption (8)–(13) imply two opposite effects of saving and investment on production whose net impact depends on the parameterization. If, by assumption, more materialistic values lead to higher consumption, aggregate savings are lower for given income (level effect). This is a drag on output growth. However, a materialist society spends much of these savings on investment that increases production, namely physical capital and improvements of total factor productivity (productivity effect). In contrast, post-materialist societies have a larger savings rate, but investment is less productive with respect to output. If the productivity effect dominates the level effect, a materialist society has a larger growth rate of output than a post-materialist one.

I assume that the production of output generates carbon dioxide emissions due to the use of fossil fuels:

$$CO2_t = \frac{\gamma}{B_t} Y_t \tag{14}$$

Carbon efficiency B, which is the inverse of carbon intensity, measures how much output can be produced with a given amount of carbon dioxide emission. It can be improved by investment into green technologies such as renewable energies, carbon capture or devices that save fossil fuels and evolves analogously to total factor productivity:

$$B_t = B_{t-1} \left(1 + b_1 \left(\frac{I_{t-1}^B}{Y_{t-1}} \right)^{b_2} \right) \tag{15}$$

3.2 Climate and Environment

The ecological submodel has two components. The first component is a climate model that converts yearly emissions of carbon dioxide into a change of the average global temperature in the atmosphere. The climate submodel is taken from Janssen and de Vries (1998). The second ecological component is a function that describes the effect of the temperature change on the natural environment. The natural environment is represented by a single variable E which measures the value of the world's ecosystem services and natural capital. Like the economic submodel, the ecological submodel is in a neoclassical modeling tradition. There are many good reasons to criticize to such an approach to the analysis of environmental issues (see Rezai et al. 2013), among other the reductionist treatment of complex ecological systems and the reliance on smooth, linear functions that could be severely misleading given the presence of non-linearities and threshold effects in ecological systems. My main justification for choosing this approach anyway is that this is a simple way to present important issues in a unified

formal framework. Modeling the ecological system more realistically and allowing for non-linearities, threshold effects and irreversibilities is surely important, but left for future research.[10]

The climate model in Janssen and de Vries (1998) is a greatly simplified model of climate processes and follows the reduced-form carbon cycle model developed by Maier-Reimer and Hasselmann (1987). The main insight from climate research is that the atmospheric temperature depends on the concentration of carbon dioxide in the atmosphere. Carbon dioxide is emitted into the atmosphere by production processes, but there is also an exchange of carbon between the atmosphere and the oceans via chemical interactions.

The actual global mean surface temperature change[11] dT_t is a function of the potential temperature change and the lagged change in temperature, because oceans take a long time to warm up. The parameter τ determines the delay in the temperature increase:

$$dT_t = dT_{t-1} + \tau \left(dT_t^p - dT_{t-1} \right) \tag{16}$$

The change in the potential temperature dT_t^p is proportional to the change of the so-called radiative forcing, which is defined as the difference of sunlight absorbed by the Earth and energy radiated back to space. The global average temperature is determined by the balance between absorbed and radiated energy. If the radiative forcing is positive, the Earth will heat up, because more radiant energy from the sun is absorbed than radiated back into space. Among other things the radiative forcing changes because of changes of the concentrations of radiatively active gases such as carbon dioxide, methane, or ozone, which are often called greenhouse gases. In this paper, I focus on the impact of carbon dioxide, which is the most important greenhouse gas.

The relation between the change in the radiative forcing[12] caused by CO_2, $dQCO2_t$, and the change in the potential temperature is given by the climate sensitivity, which in principle is an equilibrium outcome of atmosphere-ocean climate models. In the simplified model used here, it is just given by the ratio of two parameters, the mean surface temperature change in the event of a doubled CO_2 concentration, $dT_{2\times CO2}$, and the radiative forcing associated with a doubled CO_2 concentration, $dQ_{2\times CO2}$. The change in the potential mean surface temperature is hence given by:

$$dT_t^p = \frac{dT_{2\times CO2}}{dQ_{2\times CO2}} * dQCO2_t \tag{17}$$

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[10] I am quite convinced that non-linearities that might lead to sudden collapses of parts of or even the whole ecosystem exist. My ecological model is clearly too simple from the perspective of ecological sciences. Since the purpose of this paper is to introduce a new idea in the socio-economic domain, I consider this simplification acceptable.

[11] Note that the change in temperature refers to the difference between the temperature at time t compared to the mean temperature before the start of global warming.

[12] Analogously to the definition of the change in temperature, the change in radiative forcing is the difference in the radiative forcing in the current period t relative to the radiative forcing determined by pre-industrial atmospheric concentrations of CO_2.

The difference in radiative forcing in period t and radiative forcing in the time before the industrial revolution, when large-scale carbon dioxide emissions began, is given by the following function:

$$dQCO2_t = \frac{dQ_{2 \times CO2}}{\ln(2)} * \ln\left(\frac{pCO2_t}{296}\right) \tag{18}$$

In this equation, $pCO2_t$ refers to the current atmospheric carbon dioxide concentration (measured in parts per million, ppm) and 296 ppm was the concentration in the year 1750.

Maier-Reimer and Hasselmann (1987) present a model that describes the storage of carbon dioxide in the ocean and the carbon dioxide exchange between the ocean and the atmosphere. The resulting atmospheric carbon dioxide concentration can be approximated by a highly simplified reduced form equation of the more complicated climate model:

$$pCO2_t = CS1_t + CS2_t * e^{\frac{-(t-t_0)}{362.9}} + CS3_t * e^{\frac{-(t-t_0)}{73.6}} + CS4_t * e^{\frac{-(t-t_0)}{17.3}}$$
$$+ CS5_t * e^{\frac{-(t-t_0)}{1.9}} \tag{19}$$

This equation says that the ocean has different capacities to absorb and store carbon dioxide emissions, $CO2_t$. These capacities can be divided into five classes (CS1 to CS5) with different lifetimes of carbon dioxide, where the lifetimes in the latter four classes are 362.9, 78.6, 17.8, and 1.9 years:

$$CS1_t = CS1_{t-1} + 0.471 * 0.131 * CO2_t \tag{20}$$

$$CS2_t = CS2_{t-1} + 0.471 * 0.201 * e^{\frac{t-t_0}{362.9}} * CO2_t \tag{21}$$

$$CS3_t = CS3_{t-1} + 0.471 * 0.321 * e^{\frac{t-t_0}{73.6}} * CO2_t \tag{22}$$

$$CS4_t = CS4_{t-1} + 0.471 * 0.249 * e^{\frac{t-t_0}{17.3}} * CO2_t \tag{23}$$

$$CS5_t = CS5_{t-1} + 0.471 * 0.098 * e^{\frac{t-t_0}{1.9}} * CO2_t \tag{24}$$

As already stated earlier, I use a very simple description of the natural environment in this model.[13] Following Costanza et al. (1997), I assume that it is possible to measure the value of the ecosystem and its services provided to humanity in a single variable expressed in monetary terms. Costanza et al. (1997) propose an aggregation of different ecosystem services such as water regulation, soil formation, pollination, and human recreation into a single measure analogous to GDP as a measure of human production of goods and services. This approach has been criticized heavily for conceptual, methodological and philosophical reasons (e.g. Ayres 1998; Norgaard et al. 1998; Opschoor 1998). Responding to these authors, Costanza et al. (1998) admit

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[13] Although not done here, the state of the natural environment could be part of a welfare analysis since a good state of the natural environment can be both an end in itself and a means to increase production and consumption.

that their approach has many shortcomings. They accept many of the criticisms as valid, but argue that it is important to know whether environmental services improve or deteriorate because of human actions. While the proposed aggregate approach it is certainly not enough to describe the full complexity of natural ecosystems and their evolution, it is still necessary to get a rough idea of the total value of natural services available to mankind in order to make complete welfare assessments, which typically are strongly informed by the availability of man-made goods and services included in GDP and ignore natural and other non-market services. Costanza et al. (1998) consider their approach as "an initial 'first-approximation' to a complex problem" (p. 68). I regard this pragmatic approach as quite reasonable and hence define the variable E as an aggregate measure of the state or value of the natural environment.

I model the change of the state of the environment E in a way that is analogous to the aggregative modeling of the state of the economy, summarized by aggregate output. This means that I assume a functional relationship between E and other aggregate variables of the model without any explicit consideration of the complicated ecological processes at lower levels. For simplicity, I assume a smooth function without any tipping points or jumps:

$$E_t = E_{t-1} \left(1 - \epsilon_1 dT_t^{\epsilon_2} - \max \left(0, \psi_1 \left(\frac{dP_t}{P_{t-1}} \right)^{\psi_2} \right) + \frac{I_{t-1}^E}{Y_{t-1}} \right) \qquad (25)$$

My first assumption is that temperature increases have a negative impact on the state of the environment, because of negative effects on vegetation and biodiversity or damages by extreme whether events. Such effects are described in chapter 4 of the IPCC's Fourth Assessment Report (IPCC 2007). I assume a power function for this relationship, which might be convex so that the damage becomes stronger and stronger with higher temperature increases. Second, I assume that population growth dP_t damages the state of the environment, because of increased land use for agriculture, residential areas, transportation infrastructure etc. (see Foley et al. 2005). Since I model an aggregate relationship, it is sufficient to relate the change of state of the environment to the change of the population size, but not to the actions of the population. As with the temperature effect, I allow for increasing marginal damages by assuming a power function that could be convex. I further assume that the effect of population changes on the state of the environment is asymmetric, because environmental damages due to population increases are not reversed automatically if the population shrinks again. Of course, if the time horizon is long enough, the ecosystem is likely to recover from damages caused by human land use. However, the recovery of degraded soil, the full regrowth of burnt rainforests or the restoration of water systems can take many centuries, which is beyond the time horizon I want to analyze. I hence assume that the state of the environment only improves by environmental investments, I_{t-1}^E. Examples for such investments could be reforestations and renaturation of rivers and landscapes.

3.3 Population and Societal Values

I assume that the level of population P has two determinants. The long-run yearly growth rate is given by p_t which depends negatively on the level of per-capita income. This is consistent with the empirical evidence from the last 60 years in many countries (see Weil 2013).

$$P_t = P_{t-1}\left(\left(1 - \varepsilon_t^P\right) + p_t\right) \qquad (26)$$

$$p_t = p_0 - p_1 ln \frac{Y_t}{P_{t-1}} \qquad (27)$$

In addition to the long-run trend, the population change is subject to random influences which are driven by the change in the global temperature. I assume that these population shocks are beta-distributed[14] such that the mean and the variance of the distribution increase with the change in temperature. Increases in temperature cause casualties due to floods, severe storms, draughts, heat waves etc. The more the temperature rises, the more likely large population losses become.

$$\varepsilon_t^p \sim beta\,(p_2,\, p_3) \text{ with } p_2 = \begin{cases} 1 & if\ dT_t \le 0 \\ 1 + dT_t & if\ dT_t > 0 \end{cases} \qquad (28)$$

The model is closed by a function that explains how societal values V evolve over time. Since societal values determine aggregate consumption, investment and labor supply, they are the ultimate drivers of the model's dynamics. As explained earlier, V measures the fraction of post-materialists in the global society. I assume that the dynamics of societal values can be described by the following difference equation,[15] which is based on Inglehart's theory of value shift discussed in Sect. 2:

$$V_t = V_{t-1} + v_1 \frac{d(Y_t/P_t)}{\frac{Y_{t-1}}{P_{t-1}}} - v_2 \frac{dE_t}{E_{t-1}} + \varepsilon_t^V \quad \text{with}\ \ \varepsilon_t^V \sim N\left(0, \sigma_V^2\right) \qquad (29)$$

Inglehart's socialization hypothesis says that societal values mainly change from generation to generation, which implies that the value process is quite persistent and does not fluctuate wildly. This effect is captured by the autoregressive term in equation (29). A central proposition of Inglehart's theory is that people develop more post-materialistic values if they grow up with greater affluence. Inglehart (2008) presents empirical support for this proposition by showing that there is a strong positive correlation between the per-capita GNP and the prevalence of post-materialist values across countries. The second term in (29) hence relates the share of post-materialists to the

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[14] The beta-distribution is assume for convenience because it can be restricted to the interval [0,1] which is reasonable in the chosen specification.

[15] Note that V as being interpreted as the share of post-materialists must be in [0, 1]. The computer code contains a restriction that sets V either to 0 or 1 if Eq. (29) generates smaller or larger values.

change in global per-capita income. According to Inglehart's scarcity hypothesis, relatively scarce goods receive higher value in a society. We can therefore assume that there is a relationship between the change in the state of the environment and the share of post-materialists. If the quality of the environment deteriorates, values should shift away from materialism and increase the share of post-materialists, because support for environmental protection is typically seen a post-materialist value. Recent empirical evidence suggests that environmental concern and willingness to pay for environmental protection are related to the experience of environmental degradation in the local communities of people (Knight and Messer 2012; Fairbrother 2013; Mostafa 2013). These arguments justify the negative relation between post-materialism and ecological *improvements* via the third term in Eq. (29). Finally, I assume that there are also other, non-modeled factors that drive a society's value orientation which are summarized by the normally distributed random shocks. Examples for such factors could be the election of a politician with strong materialist or post-materialist values in an important country or public debates about new scientific results concerning climate change. These random influences can be very important in an environment characterized by path-dependency and time-lags, which are present in this model because of the lasting effects of investment and the lagged response of temperature to carbon emissions (see equation 16). Under these conditions, the timing of reductions in carbon dioxide emissions can be crucial for the average temperature at the end of the considered time period. Random event shifting societal values in either direction can hence have a strong impact.

3.4 Process Overview and Scheduling

It is not the purpose of this paper to analyze whether there is a long-run balanced growth path and how this might look like. Instead I am interested in potential paths of the endogenous variables during the twenty-first century. Therefore the model is simulated for discrete time steps of 1 year from year 1995 to 2100.

The sequence of the computation in each time step is as follows:

(1) The human civilization first determines the state variables K, A, and B, which depend on the investment decisions of the previous year. L is also determined. Then production, consumption and saving are calculated.
(2) Production generates CO_2.
(3) The ecosystem determines the global stock of CO_2 as a function of CO_2 emissions and its capacity to absorb atmospheric CO_2. The CO_2 stock, in turn, determines the temperature change.
(4) The new population level is determined.
(5) The temperature change and the population change determine the state of the environment.
(6) Investment is determined.
(7) Societal values V are adjusted.
(8) Model output is generated and recorded.

Table 1 Initial values of endogenous variables

Variable	Meaning	Value	Source	Comment
P	Population level	5,528	PWT8	Mio, in 1995
Y	Economic output	41,128,516	PWT8	Mio US$, in 1995
K	Capital stock	127,000,000	PWT8	Mio US$, in 1995
L	Employment	2,376	PWT8	Mio, in 1995
A	TFP	222	Own calculation	With $\alpha = 0.6$
B	Carbon efficiency	1,869,478	Own calculation	Mio US$ per Gt of of CO_2
λ	Employment ratio	0.43	PWT 8	
V	Value index	0.3	WVS	
CO_2	CO_2 emissions	22.167	EIA	Gt, in 1995
c	Marginal propensity to consume	0.77	IMF 2015	
E	Environment	74,031,329	Costanza et al. (1997)	Mio US$ 1.8 * GDP in 1994

4 Parameterization

The main purpose of this paper is to make a theoretical contribution so that a very elaborate empirical validation is not necessary. However, the model is more credible if it can generate values of the endogenous variables which are of realistic orders of magnitude. The calibration of the parameters and the variables' initial values aims at making the model comparable to Janssen and de Vries (1998) and to reproduce the values of the endogenous variables in their starting year, which is 1995. Where possible, I take the same parameter values and starting values as in Janssen and de Vries (1998). Table 1 contains the initial values of the endogenous variables in 1995.

The macroeconomic variables Y, K, L, and P for the global economy are taken from the Penn World Table version 8.0 (see Feenstra et al. 2013). This data set can also be used to compute the employment ratio λ in 1995.

Assuming a standard value of 0.6 for the labor share in output, α, it is straightforward to compute the total factor productivity A, once output Y, capital K and employment L are given. The marginal propensity to consume, c, is set to 0.77, which is in line with data from the IMF's World Economic Outlook Database.[16] The U.S. Energy Information Administration (EIA) provide the value of total carbon dioxide emissions from the consumption of energy.[17] With an arbitrarily chosen value of 1 for γ, the carbon efficiency variable B directly follows from equation (14). Costanza et al. (1997) estimate the value of the world's ecosystem services to be 1.8 times global GDP in 1994. Using this factor, I can calculate the value of the environment E for 1995. The

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[16] In 1995, global gross national saving was about 23% of GDP, see IMF World Economic Outlook April 2015.

[17] See www.eia.gov.

World Values Survey database[18] contains the materialist/post-materialist index. This variable corresponds very closely to my concept of the societal values V. In Wave 3 of the survey (1995–1999), the share of respondents that is more post-materialist that materialist (responses 3–5 on a scale from 0—"materialist" to 5 "post-materialist") is roughly 30%.

Some of the parameters are taken from data or the literature, other are calibrated to obtain plausible values of the endogenous variables, and some are just chosen more or less arbitrarily. Since it is in some case not clear a priori how to choose appropriate values for the parameters, I define a baseline calibration in which some parameters are arbitrary. The baseline calibration should be interpreted as a starting point for the analysis. It is definitely not the most realistic calibration and its outcomes should not be interpreted as the most likely evolution. I then perform sensitivity analyses of some parameters to see how potentially implausible results depend on those parameters. As stated before, the paper's objective is mainly a theoretical one. For empirical applications or policy analyses the calibration of the model can definitely be improved. This is left for future work. Table 2 lists all model parameters, their calibrated values and the data source (if there was any).

Apart from the persistence parameter ϕ, all employment parameters are calculated from the Penn World Tables. The depreciation rate δ is set to 0.1 and the labor share in the production function α is 0.6 which are common values in the macroeconomic literature. The minimum and the maximum of the marginal propensity to consume are arbitrarily chosen to 0.47 and 0.9 respectively. The parameters in the productivity function (6) are calibrated to obtain a growth rate of TFP of 2% in 1995 which is a plausible long-run value. The degree of capital bias of investment k is calibrated to get investment into productivity equal to 2% of GDP, which roughly corresponds to global R&D spending[19] if V = 0.3.

The World Bank's world development indicator database shows that there was an almost linear decrease in the CO_2 emissions intensity from 1990 to 2010. In 1990, the global economy produced 0.78 kg of CO_2 emissions per PPP\$ of GDP, and in 2010, 0.38 kg of carbon dioxide were generated per \$ of GDP. Fitting a simple linear time trend by OLS yields an R^2 of 0.98. This fit can be reproduced almost perfectly with $\gamma = b_2 = 1$ and $b_1 = 1.8$ assuming that I^B = 2% of GDP each year.

The environmental function (25) and the value function (29) are harder to calibrate with empirical data. I hence choose arbitrary values that generate plausible time paths. The calibrated environmental function generates a yearly loss of environmental quality of 8% if the temperature change is 5 °C, which is consistent with the projection in the Stern review (Stern 2006). The parameters for the climate model are completely taken from the calibration in Janssen and de Vries (1998).

The parameters p_0 and p_1 in the population growth function (27) are estimated by OLS using data from the Penn World Tables 8 for time between 1970 and 2011. p_3 is chosen such that the mean of population is 0.5% if the temperature does not change.

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[18] http://www.worldvaluessurvey.org/WVSOnline.jsp.

[19] see World Bank data: http://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS/countries?display=graph.

Table 2 Parameters

Variable	Meaning	Value	Source
$\bar{\lambda}_{min}$	Min employment rate	0.127	PWT 8
$\bar{\lambda}_{max}$	Max employment rate	0.56	PWT 8
ϕ	Persistence of employment rate	0.9	None
σ_λ	StdDev of employment shocks	0.002	PWT 8
δ	Depreciation rate	0.1	Common in the literature
a_1	Productivity parameter investment sensitivity of TFP	0.15	Calibration to get about 2% TFP growth
a_2	Productivity parameter	0.5	Calibration to get about 2% TFP growth
α	Labor share in Cobb–Douglas production function	0.6	Common in the literature
c_{min}	Min marginal propensity to consume	0.47	None
c_{max}	Max marginal propensity to consume	0.9	None
k	Degree of capital bias	0.85	Calibration to get $I^A =$ 2% of GDP
e	Degree of environmental bias	0.5	None
b_1	Efficiency parameter	1.8	Calibrated to match time series
b_2	Efficiency parameter	1	Calibrated to match time series
γ	Coefficient in CO2 function	1	None
ϵ_1	Temperature on environment temperature sensitivity of E	0.01	None
ϵ_2	Temperature on environment	1.3	None
ψ_1	Population on environment	1	None
ψ_2	Population on environment	1	None
σ_V	Variance of value shocks	0.02	None
v_1	Environment on values	1	None
v_2	Environment on values	1	None
τ	Delay in temperature change	0.05	Janssen and de Vries (1998)
$dQ_{2 \times CO2}$	Radiative forcing associated with a doubled CO2 concentration	4.3	Janssen and de Vries (1998)
$dT_{2 \times CO2}$	Global mean surface temperature change in the event of a doubled CO2 concentration	2.5	Janssen and de Vries (1998)
p_0	Max growth of population	0.027	Own estimation
p_1	Income on population growth	0.0008	Own estimation
p_3	Coefficient of population shocks	199	None

5 Results

I first present some simulation outcomes for the baseline calibration in Table 2. Due to the stochastic influences and the path dependency the model must be simulated

several times. The ability of the model to generate different outcomes even with the same calibration is not a drawback of the model but rather a strength, because the different outcomes alert us to the fact that the future is not perfectly predictable. In the next step, I present three sensitivity analyses concerning the following parameters: the investment sensitivity of TFP, a_1, the temperature sensitivity of the environment, ϵ_1, and the investment elasticity of carbon efficiency, b_2. These parameters are of particular interest because they have strong effects on output growth and on the changes in temperature and the state of the environment. Finally, I isolate the effects of the two determinants of societal values, which are the changes in income per capita and the change of the state of the environment.

5.1 Baseline Calibration

Figure 2 shows the paths of output, population, environmental quality, temperature, carbon emissions, and societal values in 100 model runs. Output grows exponentially in all runs and is 32–50 times higher in 2100 than in 1995 which corresponds to an average yearly growth rate between 3.3 and 3.8%. The median population level in 2100 is 11.2 billion people which is exactly the 2015 U.N. median projection of 11.2 bn. The minimum population is 8.4 billion and the maximum is 13.5 billion.

Somewhat surprisingly, the quality of the environment always improves significantly during the simulated time span. From a value of US$ 74 trillion in 1995 it grows to a value between US$ 711 trillion and US$ 2070 trillion in 2100, where the maximum roughly corresponds to the maximum value of output. The value of envi-
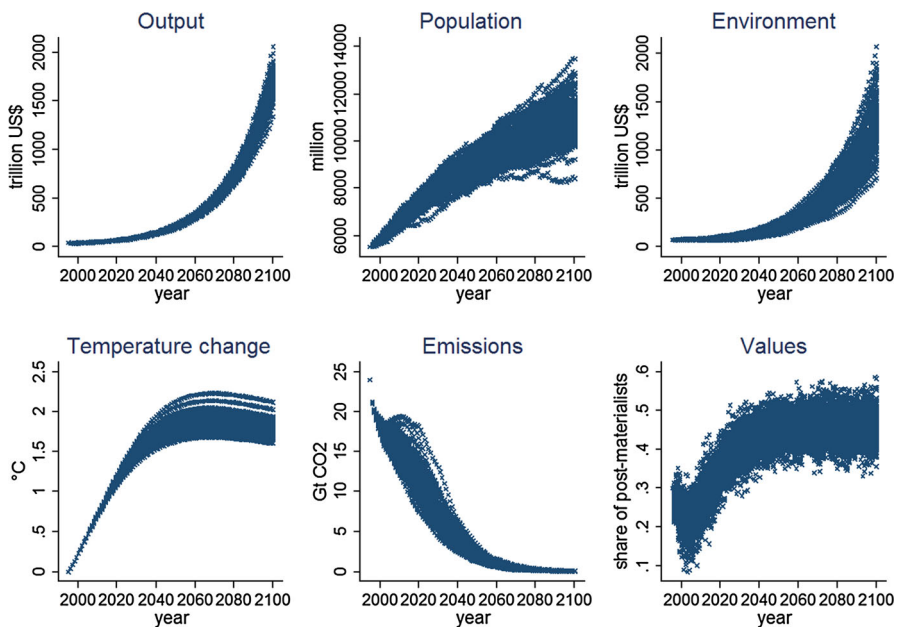

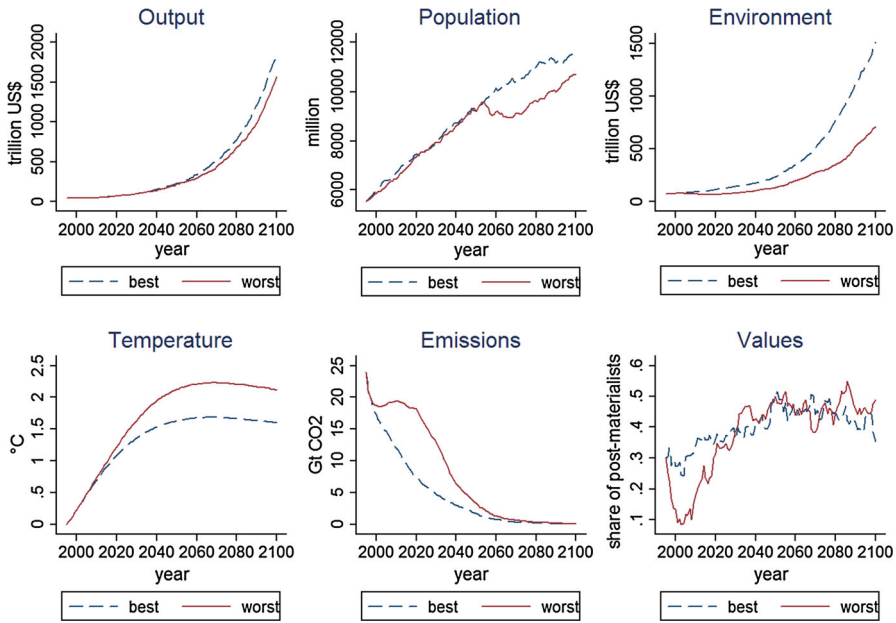**Fig. 2** Outcomes of 100 runs in baseline calibration

Fig. 3 Best and worst case runs concerning temperature

ronmental services grows so strongly, because environmental investment is larger than the environmental damage caused by population growth and global warming.

The smallest temperature increase relative to 1995 is 1.6 °C and the largest 2.12 °C, which means that the critical 2-degrees threshold is almost always passed as this refers to the preindustrial level that was about 0.35 °C lower than in 1995. The median of the temperature increase is 1.77 °C. The global temperature reaches its maximum in the middle of the century and then starts to decline again. By 2100 the global economy is practically decarbonized. The level of yearly CO_2 falls from the level of 22 Gt in 1995 to 0.05 Gt per year on average. In most runs there is a steady decline in yearly emissions during the whole century.

Regarding societal values the most remarkable result is that in most cases the majority of the global population remains materialistic. In about 10% of the cases, V is larger than 0.5 in 2100, with a maximum of 0.58. While V in 2100 is always larger than in 1995—the minimum is 0.35 compared to 0.3 in 1995—values always become more materialistic in the first 10–25 years of the simulation.

Figure 3 illustrates a best-case and a worst-case run. I have chosen the runs with the smallest and the largest increases in temperature here, because global warming is likely to cause the most severe long term consequences due to the melting of artic ice shields, sea level rise and other temperature-related effects. Of course, one could also see the largest decimation of the population or the weakest output growth as worst cases. In both runs, the evolution of output is very similar. In the best-case run output in 2100 is 17% higher than in the worst case. The reason for the lower output in the worst-case run is that the population is smaller. In the 2050s, there is a dramatic decline

in the global population in the worst-case run due to a series of large shocks. In the 2060s, the population stabilizes and starts to grow again, but the negative effect of the shocks is permanent.

The state of the environment improves in both runs, but much stronger in the best case. In all cases the environmental investment more than compensates the damages caused by population growth and global warming. While until 2010 the increase in temperature is quite similar—$0.7\,°\text{C}$ in the best case and $0.73\,°\text{C}$ in the worst case—the temperature paths diverge thereafter. The cause for this divergence is that emissions plateau in the first 20 years of the twenty-first century in the worst-case run whereas they drop considerably in the best-case run.

It is obvious that the different evolution of societal values is the ultimate reason for the differences in emissions, temperature and also the state of the environment in the two runs. From about 2030 on, societal values are very similar in both runs, but before this time there is a big difference. In the worst case, society becomes strongly materialist in the first years of the 2000s, whereas societal values remain close to their initial value of 0.3 in the best case. The turn toward materialism is the result of several negative shocks in the value function. These shocks are unrelated to the state of the environment and the economy and might capture the impact of political propaganda and campaigns of the fossil fuel industry against climate change. In the worst-case run, it takes about 25 years until the global society again is as post-materialist as at the start of the simulation period. This materialistic turn is responsible for the delayed reduction in yearly carbon emissions, which leads to the temperature difference of about $0.5\,°\text{C}$ in the second half of the century. This case demonstrates the effect of negative shocks on societal values.

The comparison of the two runs is informative. It shows that with the same fundamentals given by the starting values and the parameters of the functional relationships the final outcomes can be quite different. In this calibration, random events can lead to a persistent temperature difference of $0.5\,°\text{C}$. In the worst case, the world might look quite different in the long run due to unmodeled consequences of the higher temperature such as higher sea level rise.

5.2 Sensitivity Analysis

The baseline calibration generates results that appear somewhat unrealistic in three respects: the growth rate of output of at least 3.3% per year is very high, the state of the environment always improves considerably, and carbon emissions fall right from the start due to strong improvements in carbon efficiency, which leads to a fairly moderate increase in temperature. In this subsection, I perform sensitivity analyses of parameters that drive output growth, the evolution of the state of the environment and the reduction in carbon emissions.

I first look at how the system responds to a change in the investment sensitivity of total factor productivity. In the baseline calibration, a_1 is set to 0.15, which—together with $a_2 = 0.5$—generates a yearly growth rate of TFP of 2.12% if investment into A is equal to 2% of output. For the sensitivity analysis, I compare the baseline case with lower values of $a_1 = \{0.075, 0.1, 0.125\}$, which correspond to an average annual TFP
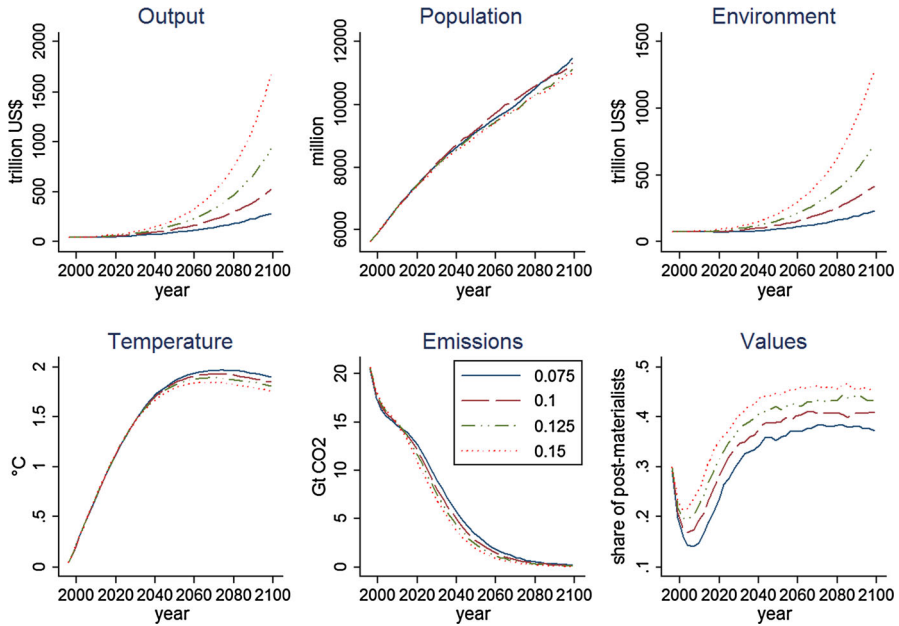
Fig. 4 Effects of the investment sensitivity of TFP, a_1

growth rate of 1.06, 1.41, and 1.77% respectively. Figure 4 summarizes the results. Each of the graphs is the median path of the respective variable over 100 runs.

Varying the investment sensitivity of TFP has quite strong effects on output, on the environment and on societal values, but not so much on the other variables. The differences in the level of production are most pronounced. In the baseline calibration, the median level of output in 2100 is US\$ 1740 trillion which is about 42 times higher than the initial level in 1995. In the lowest calibration of a_1, average output in 2100 is US\$ 296 trillion, which is only 7 times higher than the output of 1995. The effects on the environment are of comparable magnitude. The value of ecological services ranges from US\$ 276 trillion to US\$ 1335 trillion for $a_1 = 0.075$ and $a_1 = 0.15$ respectively. The similarity of the effects on both output and the environment implies that environmental investment is the main determinant of the state of the environment in this parameterization. Higher output provides more resources for environmental investment. The evolution of values is very similar in all four calibrations, but there is a level effect which is due to the differences in output. This level effect, however, is not large enough to generate big difference in the emissions paths and hence the temperature paths.

The second sensitivity analysis concerns the temperature sensitivity of the environment ϵ_1. As the baseline value (0.01) leads to a weak response of the environment to global warming, I choose higher values, $\epsilon_1 = \{0.04, 0.07, 0.1\}$. The results are shown in Fig. 5.

This parameter affects all variables significantly. Not surprisingly, the state of the environment is worse the higher ϵ_1 is. With $\epsilon_1 = 0.1$ the median value of the environ-
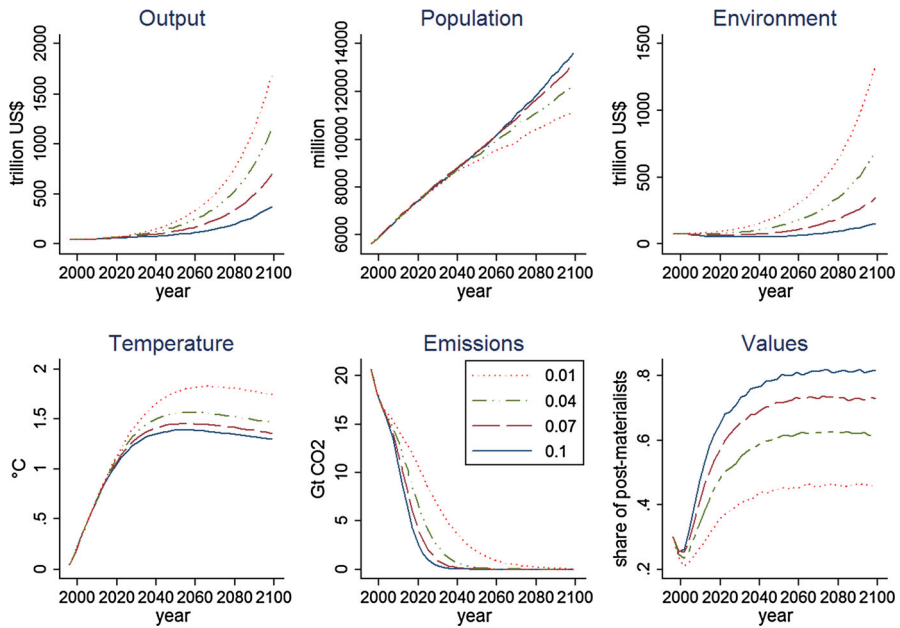
Fig. 5 Effects of the temperature sensitivity of the environment, ϵ_1

ment is just US\$ 160 trillion in 2100 compared to US\$ 1390 trillion in the baseline and has a U-shaped trajectory. In this case, the median of E declines to a minimum of US\$ 53.2 trillion in 2037 and passes the initial value of US\$ 77 trillion again in 2070. When ϵ_1 is high, the initial deterioration of the environmental quality causes a strong shift towards post-materialist values, which can even go up to a median level of 0.8. High shares of post-materialists imply large investments in the improvement of carbon efficiency which accelerate the reduction of emissions considerably. Even with a relatively low ϵ_1 of 0.04 the global economy is practically decarbonized by 2050. The faster decarbonization also slows down global warming, which, in turn, causes less climate-related negative population shocks. The price of the containment of global warming is considerably lower growth of output. $\epsilon_1 = 0.1$ results in a median output of US\$ 392 trillion in 2100.

Figure 6 shows what happens if it is harder to improve the carbon efficiency of the production process. In this sensitivity analysis, b_2 is taken from the set $\{1, 1.2, 1.4, 1.6\}$ where 1 is the baseline parameter and larger values of b_2 imply smaller improvement in carbon efficiency at the same level of investment.

As Fig. 6 shows, lower effectiveness of investments into carbon efficiency has dramatic consequences. Obviously, the reduction of carbon emissions is much harder then. If b_2 exceeds 1.2, carbon emissions first increase for some time before they start to fall. If $b_2 = 1.6$, emissions peak in the 2050s at a median level of about 44 Gt per year and are only slightly below (17.5 Gt) the initial level of 22 Gt in 2100. Higher carbon dioxide emissions translate directly into higher temperatures. In the most unfavorable setting, global temperature in 2100 is 4.8 °C higher than in 1995, which has
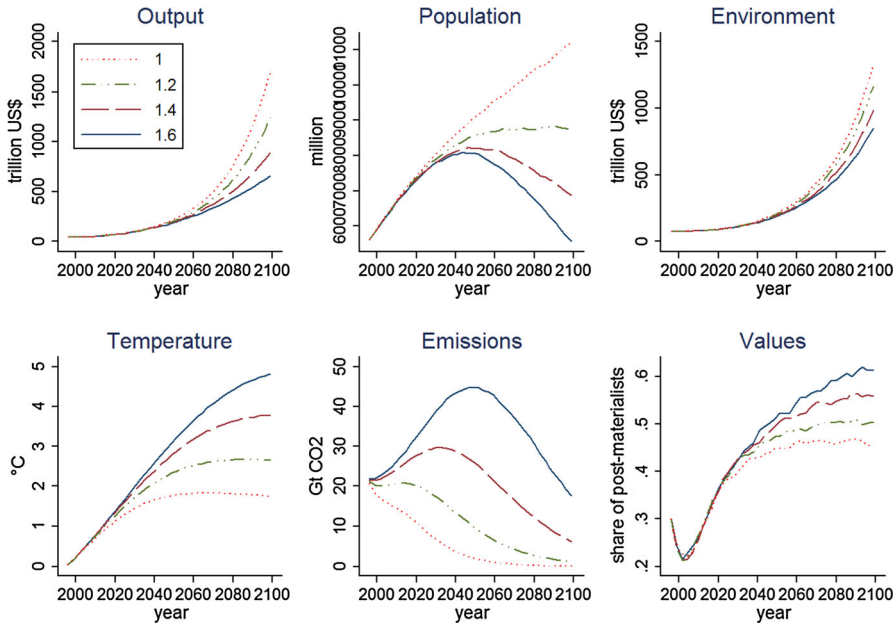
Fig. 6 Effects of the investment elasticity of carbon efficiency, b_2

severe effects on population. Somewhat surprisingly, the evolution of environmental conditions is relatively unaffected by variations of this parameters despite the large differences in temperature. A potential reason is that higher temperature causes population losses which reduces the pressure on the environment. In all cases, the median share of post-materialists is practically identical until the 2030s, after which there is divergence due to the divergence in output per capita and in the quality of the environment. Despite the significant divergence of population levels, per capita income is always higher if b_2 is smaller implying that the higher share of post-materialists for larger values of b_2 is caused by the lower levels of E. Output growth depends negatively on b_2 for two reasons: temperature-related population shocks reduce the labor force more strongly for larger b_2 and more post-materialist societies invest less in the physical capital and in productivity improvements. Output amounts to US\$ 672 trillion in 2100 if $b_2 = 1.6$ which is only 38% of what is reached in the baseline calibration.

5.3 Determinants of societal values

According to Inglehart's theory the share of post-materialists in the global society should depend on income per capita and on the state of the environment. In the baseline calibration, both variables rise over time so that there are opposing forces at work in the value function (29). In the following sensitivity analysis I isolate both forces by setting either the influence of income (v_1) or the influence of the environment (v_2) equal to zero. For a comparison, I also include the baseline case ($v_1 = v_2 = 1$) and the
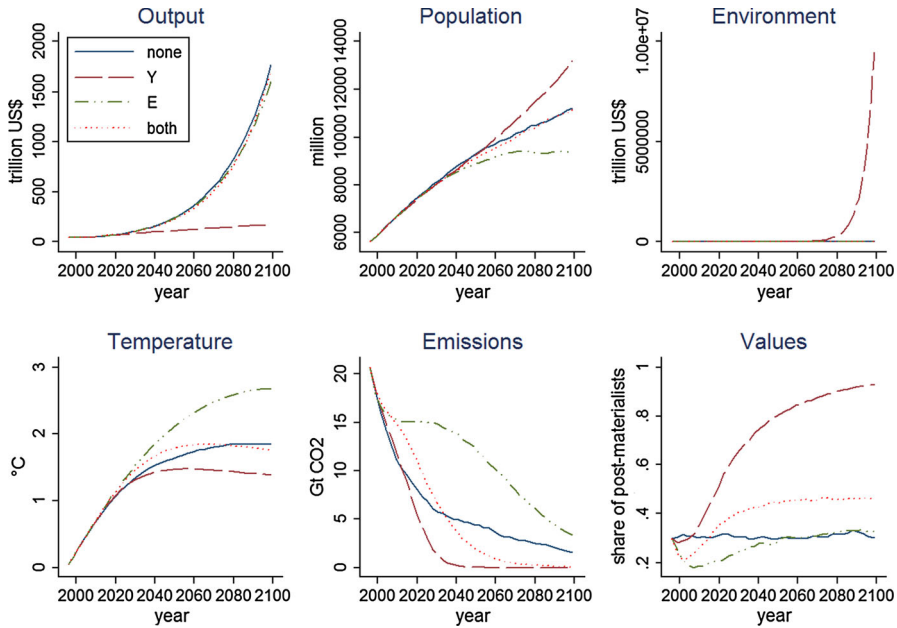
Fig. 7 Impact of income Y ($v_1 = 1$) and the environment E ($v_2 = 1$) on values

case, in which the value function is just a random walk and none of the fundamental factors is at work ($v_1 = v_2 = 0$). Figure 7 presents the results.

The bold lines show the case in which societal values change randomly without impact of either changes in income per capita or changes of the environment. Not surprisingly the median share of post-materialists over the 100 runs is roughly constant at the initial level. Of course, in single runs the trajectories will go up and down, but since the shocks are random they cancel out. We can hence interpret this case as a business-as-usual scenario in which no value change occurs. If societal values do not change over time, the baseline calibration of the other parameters leads to a steady decline of carbon dioxide emissions and an intermediate degree of global warming that stabilizes at $1.85\,°C$ above the level of 1995. This result is very close to the baseline case with $v_1 = v_2 = 1$ which is represented by the dotted line. With similar temperature paths, the population paths, the environmental evolution and output growth are also very similar in the two cases with either $v_1 = v_2 = 0$ or $v_1 = v_2 = 1$. The main difference between these two scenarios is that when both influences are present, values decline first and then increase to level that is above the initial one. As a consequence carbon dioxide emissions are above those in the ($v_1 = v_2 = 0$)-case and then below and emissions close to zero are reached earlier (in the 2080s).

The asymmetric scenarios with $v_1 = 1, v_2 = 0$ (income-only scenario) or $v_1 = 0, v_2 = 1$ (environment-only scenario) are different. In the income-only scenario, there is a steady and strong increase in societal values and the share of post-materialists reaches 92.6% in 2100. The very high share of post-materialists leads to quick decarbonization, a small increase in temperature, high population, an extremely strong
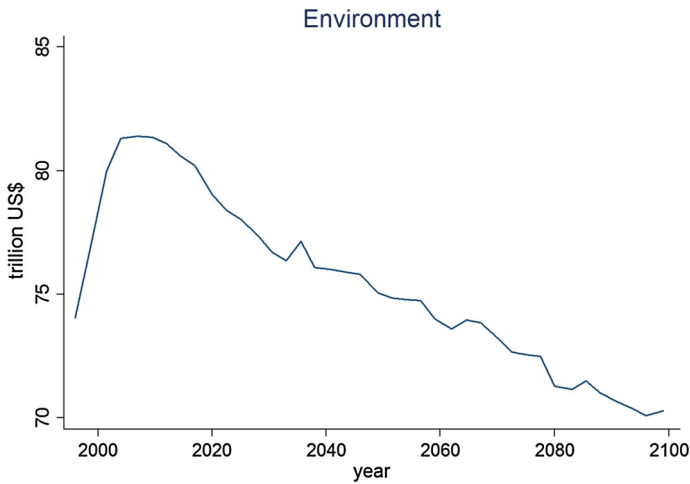
Fig. 8 State of the environment in the environment-only scenario ($v_1 = 0$, $v_2 = 1$)

improvement of the environment, and very low output growth. The environment-only scenario leads to the opposite outcomes. Values initially decrease, recover only slowly and never exceed the initial level significantly. Because of the slow reduction of emissions, global warming reaches more than 2.5 °C in the second half of the century with negative impact on the population. Output grows as in the two symmetric scenarios, but the evolution of the state of the environment is different in the environment-only scenario. While the value of ecological services rises over time due to significant environmental investments in all other scenarios, it only increases in the first decade in the environment-only scenario and declines thereafter. This can be seen in Fig. 8.

If societal values depend only on environmental changes but not on the change of income per capita we get interesting dynamics. In this case, society develops a more post-materialist attitude if people observe that the state of the environment deteriorates. Conversely, society becomes more materialist, if there are environmental improvements. This kind of response to the current state of the ecosystem has negative long-run consequences. Early improvements of environmental quality reduce environmental awareness and shift society's priorities toward materialist values. The resulting neglect of the threat of global warming and the insufficient decarbonization efforts lead to a big increase in temperature damaging the ecosystem in the long term. The value shift triggered by the temperature-related damages to the ecosystem is too late and too weak in order to contain global warming below the 2-degree goal. In this way, environmental awareness has self-defeating consequences.

6 Discussion and Potential Extensions

The model produces a rich set of outcomes, most of which appear quite plausible. One might argue that in the baseline calibration an average global growth rate of output of 3.6% p.a. during the whole century is too large. However, as the sensitivity analysis has

shown, this is easy to fix by reducing the investment sensitivity of TFP (a_1) slightly. With a_1 equal to 0.1 instead of 0.15 the average yearly growth rate of output is just 2.4% which might be more realistic.

The median temperature increase of 1.7 °C in the baseline calibration appears quite low but is still in line with the most recent IPCC projections. In its 2014 report, the IPCC projects an average increase of the global mean surface temperature between 1.0 °C in the lowest scenario and 3.7 °C in the highest scenario by 2100 (IPCC 2014, p. 60). The relatively low temperature increase is due to the fast reductions of carbon dioxide emissions right from the start of the simulation. This result is counterfactual, since actual emissions have been rising in the past 20 years. Setting $b_2 = 1.6$ makes investments into improved carbon efficiency less effective and leads to an emissions paths that is closer to the actually observed path. As shown in Fig. 6, this scenario features a much larger increase in temperature of 4.8 °C and much weaker growth of output, even with strong productivity growth.

Probably the most unrealistic outcome is the strong improvement of the environmental quality in many runs. This result can be corrected by increasing the temperature sensitivity of the environment ϵ_1, which would also reduce output growth.

There are numerous ways how modify the model. It is possible to incorporate new effects such a direct impact of temperature on the stock of capital or on output. This modification appears quite plausible, because natural disasters caused be climate change are likely to destroy physical capital and output and also require resources to repair the damages. One could also include environmental services as an input into the production function. Especially food production depends heavily on environmental services such as pollination. The value function, which is a main driver of the model dynamics, should be varied, too, for instance by including other or additional determinants. Since most of the functional forms are fairly arbitrary, experimenting with alternative functional forms would show how robust the results are.

7 Conclusion

In this paper I present a model of economic growth and climate change. In this model output growth, productivity growth, population growth and the evolution of carbon emissions are all endogenous. Together, these variables endogenously determine the global average temperature and the condition of the natural environment. The central novelty of this paper is that aggregate economic outcomes are determined by the value system of the global society, which in turn responds to climate change through its effect on the natural environment and to changes in income per capita. The assumption of societal values as main determinants of aggregate investment and consumption is well founded in theoretical and empirical research. Relating the evolution of aggregate variables such as aggregate investment or consumption to another aggregate entity such societal values instead of preferences of individuals simplifies the model design significantly and avoids the highly problematic assumption of representative agents which is the usual way to relate macro variable to factors at the micro level. At the same time this approach makes it possible to endogenize a large number of variables

in a consistent way and it is amenable to empirical testing, because data on societal values are available for many countries and years.

The main results of the baseline model for the 21st century are as follows. The average yearly growth rate of GDP is 3.6%. In 2100, the global population reaches a level of 11.2 bn people, the global temperature is 1.7 °C higher and the quality of the environment is 17 times higher than in 1995. The share of post-materialists in the global society is 50% higher than in 1995.

It is important to emphasize that these number should not be interpreted as reliable predictions. Predictions of the state of a non-linear dynamic system such as the economy and its interaction with nature over long time horizons are extremely uncertain, no matter which kind of model is used. Even with a much more thorough calibration, the calculated numbers would hardly be more reliable. Yet this does not mean that the numbers are irrelevant. The quantitative results provide an intuition for the mechanisms in the model and allow to compare it with other models. We also get an impression of the parameters' importance from the predictions. As the sensitivity analyses have shown, some parameters can have strong effects on the simulation results. Setting the investment elasticity of carbon efficiency, b_2, to 1.6 instead of 1 has enormous effects on temperature and output. Using this parameter value increases global warming until 2100 from 1.7 to 4.8 °C and reduces the output level in 2100 from US\$ 1770 trillion to US\$ 672 trillion.

In general, I would argue that the predictions of this model are too optimistic, irrespective of the chosen calibration. The ecological submodel is very simple and does not feature sudden regime shifts and breakdowns. Furthermore, there is no direct relationship between production and the ecosystem, for example via pollution or the use of non-renewable resources. Incorporating these aspects is likely to both reduce output growth and environmental quality.

The main purpose of this paper is to propose a conceptual model that might open a discussion and that can be the basis for future work. It is not the purpose of this paper to present a policy or even a prediction model. So far economic reasoning about economic growth and climate change is limited by methodological conventions. In equilibrium models with well-informed optimizing agents it is very difficult to analyze a large number of endogenous interacting variables. These model quickly become intractable and hence must focus on a few variables and mechanisms. However, the issue of sustainable production and growth is a very complicated one with many dimensions of equal importance that should be studied together in a unified framework. Otherwise, the potentially important feedback effects that might reinforce or dampen individual effects cannot be captured. My model is a suggestion how such a unified framework might look like. It is an attractive feature of the model that it is relatively simple and transparent, but can nevertheless produce rich results.

References

Anthoff, D., & Tol, R. (2013). The climate framework for uncertainty, negotiation and distribution (FUND): Technical description version 3.7. https://05f0e81c-a-5f9963c9-s-sites.googlegroups.com/a/fund-model.org/fund-model/Fund-3-7-Scientific-Documentation.pdf.

Assenza, T., & Delli Gatti, D. (2013). E pluribus unum: Macroeconomic modeling for multi-agent economies. *Journal of Economic Dynamics and Control*, *37*(8), 1659–1682.

Ayres, R. U. (1998). The price-value paradox. *Ecological Economics*, *25*(1), 17–19.

Bardi, A., & Schwartz, S. H. (2003). Values and behavior: Strength and structure of relations. *Personality and Social Psychology Bulleting*, *29*(10), 1207–1220.

Bonen, A., Semmler, W., & Klasen, S. (2014). *Economic damages from climate change: A review of modeling approaches*. Schwartz Center for Economic Policy Analysis, The New School, Working Paper 2014-3

Brock, W. A., & Taylor, S. M. (2005). Economic growth and the environment: A review of theory and empirics. In P. Aghion, S. & N. Durlauf (Eds.), *Handbook of economic growth* (Vol. 1, pp. 1749–1821). Amsterdam: Elsevier.

Cai, Y., Judd, K., & Lontzek, T. (2013). *The social cost of stochastic and irreversible climate change*. NBER Working Paper No 18704.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*, 253–260.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., et al. (1998). The value of ecosystem services: Putting the issues in perspective. *Ecological Economics*, *25*(1), 67–72.

Davidson, P. (2011). *Post Keynesian macroeconomic theory* (2nd ed.). Cheltenham: Edward Elgar.

Deissenberg, C., van der Hoog, S., Dawid, H. (2008). *EURACE: A massively parallel agent-based model of the European Economy*. Working Paper, HAL Id: halshs-00339756. https://halshs.archives-ouvertes.fr/halshs-00339756.

Delli Gatti, D., Desiderio, S., Gaffeo, E., Cirillo, P., & Gallegati, M. (2011). *Macroeconomics from the bottom-up*. Berlin: Springer.

Dosi, G., Fagiolo, G., & Roventini, A. (2010). Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles. *Journal of Economic Dynamics and Control*, *34*(9), 1748–1767.

Dosi, G., Fagiolo, G., Napoletano, M., & Roventini, A. (2013). Income distribution, credit and fiscal policies in an agent-based Keynesian model. *Journal of Economic Dynamics and Control*, *37*(8), 1598–1625.

Eriksson, C. (2013). *Economic growth and the environment*. Oxford: Oxford University Press.

Etzioni, A. (2003). Toward a new socio-economic paradigm. *Socio-Economic Review*, *1*(1), 105–118.

Fairbrother, M. (2013). Rich people, poor people, and eenvironmental concern. Evidence across nations and time. *European Sociological Review*, *29*(5), 910–922.

Feenstra, R. C., Inklaar, R., & Timmer, M. P. (2013). *The next generation of the Penn World Table*. www.ggdc.net/pwt.

Fischer, C., & Heutel, G. (2013). Environmental macroeconomics: environmental policy, business cycles, and directed technical change. *Annual Review of Resource Economics*, *5*(1), 197–210.

Foley, D. K., & Michl, T. R. (1999). *Growth and distribution*. Cambridge: Harvard University Press.

Foley, J. A., Defries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S., et al. (2005). Global consequences of land use. *Science*, *309*, 570–574.

Gilg, A., Barr, S., & Ford, N. (2005). Green consumption or sustainable lifestyles? Identifying the sustainable consumer. *Futures*, *37*(6), 481–504.

Goldsmith, R. E., & Flynn, L. R. (2015). The etiology of frugal spending: A partial replication and extension. *Comprehensive Psychology*, *4*(1), 9–20.

Hartley, J. E. (2002). *The representative agent in macroeconomics*. London: Routledge.

Hitlin, S., & Piliavin, J. A. (2004). Values: Reviving a dormant concept. *Annual Review of Sociology*, *30*, 359–393.

Hoffmann, S., & Lee, M. S. W. (2016). Consume less and be happy? Consume less and be happy! An introduction to the special issue on anti-consumption and consumer well-being. *Journal of Consumer Affairs*, *50*(1), 3–17.

Hope, C. (2011). The social cost of CO2 from the PAGE09 model. Economics: the open-access, open-assessment E-journal (2011-39). http://www.economics-ejournal.org/economics/discussionpapers/2011-39.

Inglehart, R. (1977). *The silent revolution. Changing values and political styles among western publics*. Princeton: Princeton University Press.

Inglehart, R. (1989). *Cultural shift in advanced industrial societies*. Princeton: Princeton University Press.

Inglehart, R. (1995). Public support for environmental protection: Objective problems and subjective values in 43 societies. *Political Science and Politics*, 28(1), 57–72.

Inglehart, R. (1997). *Modernization and postmodernization. Cultural, economic, and political change in 43 societies*. Princeton: Princeton University Press.

Inglehart, R. (2008). Changing values among western politics from 1970 to 2006. *West European Politics*, 31(1–2), 130–146.

IPCC. (2007). *Intergovernmental Panel on Climate Change. Fourth Assessment Report: Impacts, adaptation and vulnerability*. Cambridge: Cambridge University Press.

IPCC. (2014). *Intergovernmental Panel on Climate Change. Fifth Assessment Report: Synthesis report*. Cambridge: Cambridge University Press.

Janssen, M., & de Vries, B. (1998). The battle of perspectives: A multi-agent model with adaptive responses to climate change. *Ecological Economics*, 26, 43–65.

Kahn, M. E. (2007). Do greens drive Hummers or hybrids? Environmental ideology as a determinant of consumer choice. *Journal of Environmental Economics and Management*, 54(2), 129–145.

Kirman, A. P. (1992). Whom or what does the representative individual represent? *Journal of Economic Perspectives*, 6(2), 117–136.

Knight, K., & Messer, B. L. (2012). Environmental concern in cross-national perspective: The effects of affluence, environmental degradation, and world society. *Social Science Quarterly*, 93(2), 521–537.

König, T., & Wagener, A. (2008). *(Post-)materialist attitudes and the mix of capital and labour taxation*. Leibniz Universität Hannover Discussion Paper No. 404.

Lavoie, M. (2006). Do heterodox theories have anything in common? A post-Keynesian point of view. *Intervention. Journal of Economics*, 3(1), 87–112.

Lee, M. S. W., & Ahn, C. S. Y. (2016). Anti-consumption, materialism, and consumer well-being. *Journal of Consumer Affairs*, 50(1), 18–47.

Lemoine, D., & Traeger, C. (2014). Watch your step: Optimal policy in a tipping climate. *American Economic Journal: Economic Policy*, 6(1), 137–166.

Lengnick, M. (2013). Agent-based macroeconomics: A baseline model. *Journal of Economic Behavior and Organization*, 86, 102–120.

Lucas, R. E. (1976). Econometric policy evaluation: A critique. *Carnegie-Rochester conference series on public policy* (Vol. 1, pp. 19–46).

Maier-Reimer, E., & Hasselmann, K. (1987). Transport and storage of CO_2 in the ocean. An inorganic ocean-circulation carbon cycle model. *Climate Dynamics*, 2(2), 63–90.

Mandel, A., Fürst, S., Lass, W., Meissner, F., & Jaeger, C. (2009). *Lagom generiC: An agent-based model of growing economies*. ECF Working Paper 1/2009.

Markowitz, E. M., & Bowermann, T. (2012). How much is enough? Examining the public's beliefs about consumption. *Analyses of Social Issues and Public Policy*, 12(1), 167–189.

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens III, W. W. W. (1972). *The limits to growth*. Universe Books.

Meadows, D. H., Meadows, D. L., & Randers, J. (2004). *Limits to growth. The 30-year update*. London: Routledge.

Mostafa, M. M. (2013). Wealth, post-materialism and consumers' pro-environmental intentions. A multi-level analysis across 25 nations. *Sustainable Development*, 21(6), 385–399.

Nayum, A., & Klöckner, C. A. (2014). A comprehensive socio-psychological approach to car type choice. *Journal of Environmental Psychology*, 40, 401–411.

Nordhaus, W. (2013). Integrated economic and climate modeling. In P. B. Dixon & D. W. Jorgenson (Eds.), *Hanbook of computational general equilibrium modeling, volume 1A–1B, chapter 16*. Amsterdam: Elsevier.

Nordhaus, W., & Sztorc, P. (2013). DICE 2013R: Introduction and user's manual. 2nd edition.

Norgaard, R. B., Bode, C., & Values Reading Group. (1998). Next, the value of God, and other reactions. *Ecological Economics*, 25(1), 37–39.

Opschoor, J. B. (1998). The value of ecosystem services. Whose values? *Ecological Economics*, 25(1), 41–43.

Pepper, M., Jackson, T., & Uzzell, D. (2009). An examination of values that motivate socially conscious and frugal consumer behaviours. *International Journal of Consumer Studies*, 33(2), 126–136.

Rezai, A., Taylor, L., & Mechler, R. (2013). Ecological macroeconomics. An application to climate change. *Ecological Economics*, *85*, 69–76.

Romer, P. M. (1990). Endogenous technological change. *Journal of Political Economy*, *98*(5), S71–102.

Roos, M. W. M. (2015). *Macroeconomics of radical uncertainty*. Ruhr Economic Papers #592.

Salle, I., Yildizoglu, M., & Sénégas, M.-A. (2013). Inflation targeting in a learning economy: An ABM perspective. *Economic Modeling*, *34*, 114–128.

Schwartz, S. H. (2012). An overview of the Schwartz theory of basic values. *Online Readings in Psychology and Culture*, *2*(1), 11. doi:10.9707/2307-0919.1116.

Seegebarth, B., Peyer, M., Balderjahn, I., & Wiedmann, K.-P. (2016). The sustainability roots of anticonsumption lifestyles and initial insights regarding their effects on consumers' well-being. *Journal of Consumer Affairs*, *50*(1), 68–99.

Setterfield, M., & Suresh, S. G. (2012). *Aggregate structural macroeconomic modelling: a reconsideration and defence*. Trinity College Department of Economics Working Paper 12-07.

Stern, N. (2006). *The Stern review: The economics of climate change*. London: HM Treasury.

Weil, D. N. (2013). *Economic growth*. Boston: Pearson Education.

Xepapadeas, A. (2005). Economic growth and the environment. In K.-G. Mäler & J. R. Vincent (Eds.), *Handbook of environmental economics* (Vol. 3, pp. 1219–1271). Amsterdam: Elsevier.