RAIS | RESEARCH ASSOCIATION for INTERDISCIPLINARY STUDIES
August 2021

DOI: 10.5281/zenodo.5506934

Climate Growth Theory

Julia M. Puaschunder[1, 2]

[1]*The New School, Department of Economics, Eugene Lang College, New York, NY 10003, USA, Julia.Puaschunder@newschool.edu, www.juliampuaschunder.com*
[2]*Columbia University, Graduate School of Arts and Sciences, Julia.Puaschunder@columbia.edu, http://blogs.cuit.columbia.edu/jmp2265*

ABSTRACT: The climate change crisis has gained unprecedented urgency in the most recent decade. Overall, climate change has already led to and will continuously lead to environmental tipping points and irreversible lock-ins that will decrease the overall productivity and common welfare. When taking a closer look at the macroeconomic growth prospects as measured in Gross Domestic Product (GDP) per country, a changing climate will affect countries differently, when considering different mean temperatures but also differences in the GDP sector composition per country and a differing peak temperature at which a GDP sector can be most productive. In the first economic 'classic' theories of Adam Smith, Thomas Robert Malthus, David Ricardo, Karl Marx and Joseph Schumpeter land productivity was considered as an underlying growth driver. In the evolution of Modern Growth Theory (MGT), these theories and insights got abandoned. With climate change pressuring economic productivity and the rising impact of global warming expected to determine economic output more and more so in the future, this paper calls for a reintegration of climate and temperature into standard growth theory. In light of the enormous effect of temperature and climate on economic productivity that is likely to rise in the years to come but also with reference to the highly unequally distributed economic winning and losing prospects in-between countries and over time, this article argues for an integration of temperature and climate in contemporary Growth Theory, called Climate Growth Theory. Micro- and macroeconomic attempts to integrate productivity differences between countries based on energy supply, climate and overall favorable working conditions will be presented alongside most recent models to integrate temperature and climate into macroeconomic growth models and sustainable consumption patterns.

KEYWORDS: Climate Change, Economics of the Environment, Endogenous Growth Theory, Energy, Environmental Governance, Environmental Justice, Exogenous Growth Theory, Green New Deal, Intergenerational Equity, Monetary Policy, Multiplier, Non-renewable energy, Renewable energy, Sustainability

Introduction

Attention to the climate change crisis has unprecedented urgency. Climate change has already led to and will continuously lead to environmental tipping points and irreversible lock-ins that will decrease the overall productivity and common welfare (Puaschunder 2020b). With climate stability becoming constraint over time, a broad range of temperature will become a scarcity and therefore more precious in the future to come (Puaschunder 2020b). With more and more attention expected to climate and temperature for economic production, this paper argues that temperature as an indicator for the favorability of a country's climate will become an essential economic growth determinant even more so in the future.

When taking a closer look at the macroeconomic growth prospects as measured in Gross Domestic Product (GDP) per country, a changing climate will affect countries differently, when considering different mean temperatures per country but also differences in the GDP sector composition by country and a differing peak temperature at which a GDP sector can be productive (Puaschunder 2020b).

Standard neoclassical growth theory begins with the classicals' productivity theories of Adam Smith, Thomas Robert Malthus, David Ricardo, Karl Marx and Joseph Schumpeter. Some of the classics address the necessity of having a favorable environmental climate to produce, especially in the theories of ground rent of Ricardo and Malthus that later get picked up by Nicholas Kaldor but also in environmentally-induced food shortages (Malthus 1798; Walpole, Sinden & Yapp 1996).

In the evolution of Modern Growth Theory (MGT), these insights about the impact of climate and temperature became sidelined with the major focus on capital (K) as the means of production and labor (L) becoming the main focus of attention for productivity estimations. With climate change pressuring economic productivity and the rising impact of global warming expected to determine economic output more and more so in the future, this paper calls for a reintegration of climate and temperature into standard growth theory.

Modern Growth Theory of the 20th century is primarily focused on the two input factors: capital (K) and labor (L). Traditional economic growth theories considered capital and labor as essential growth factors for every economy. Exogenous growth theory is centered on exogenous shocks – like new technology innovations or natural crises, such as pandemics – as major drivers or downturns of economic growth measured in their impact on capital and labor productivity. Endogenous growth theory subsequently drew attention to dynamic variable interactions between capital and labor but also system-inherent growth derived from ideas, innovation and learning. Growth concepts were opened up for innovation generated in productive group interaction and learning inside firms in teams, learning-by-doing while performing tasks and learning-by-using of new technology (Puaschunder, Gelter & Sharma 2020). Most novel extensions of Modern Growth Theory since the outbreak of the novel Coronavirus (COVID-19) pay attention to health of Labor (Puaschunder 2020c). Group and team learning to create a risk-free working culture, environment, industry and country are expected to flourish growth in a COVID-19-struck economy (Puaschunder 2020c). In endogenous growth theory terms, team hygiene and group monitoring of the collective health status but also learning-to-preventing holds future economic growth potential (Puaschunder et al. 2020).

This paper will address the wider impact of temperature and climate on economic productivity. The economic prospects of a warming earth have recently outlined in the Mapping Climate Justice idea (Puaschunder 2020b). Paying attention to novel arising climate change inequalities in economic productivity, the Mapping Climate Justice Theory outlines macroeconomic gains and losses of a warming earth per country in order to find ways how to share the expected benefits around the world or conserve the financial assets for future generations. Attempts to integrate productivity differences between countries based on climate and overall favorable working conditions have existed in Modern Growth Theory and international development resulting in the Kaldor-Hicks's efficiency debate finding that any losing territories could be compensated by gains in the wake of a changing condition, such as climate. In light of the enormous effect of temperature and climate on economic productivity that is likely to rise in the years to come but also with reference to the highly unequally distributed economic winning and losing prospects in-between countries and over time, this article argues for an integration of temperature and climate in contemporary Growth Theory, called Climate Growth Theory.

Climate change

Never before in the history of humankind have environmental concerns in the wake of economic growth heralded governance predicaments as we face today. Climate change presents societal, international and intergenerational fairness as challenge for modern economies and contemporary democracies (Puaschunder 2019a, b). In today's climate change mitigation and adaptation efforts, high- and low-income households, developed and underdeveloped countries as well as overlapping generations are affected differently (Puaschunder 2018, 2020b).

Modern Growth Theory is primarily focused on external drivers of economic growth such as innovation or internal learning mechanism of Labor. Macroeconomic growth theory has recently addressed the economics and politics of climate change. Global warming is believed to have an extraordinary impact on the economic, social and eco-system effects of market economics. In the current empirical trends and international efforts to combat climate change, an understanding of the economic impetus of climate change has gained unprecedented attention. With the growing awareness of climate and temperature becoming more and more important drivers of economic in the future, an integration of climate in economic productivity has become essential.

In the financialization of climate policies, fair climate change benefits and burden sharing within society, in-between countries but also over generations are necessary. Climate change induced inequalities are proposed to be alleviated with a climate taxation-bonds strategy that incentivizes market actors to transform the energy sector and mitigate as well as adapt to climate change. Understanding economic outcomes of climate change will aid in trends prediction but also open gates to redistribute prospective economic gains in a way that the climate change burden is shared equally around the globe.

To address the economic effects of climate change, standard economic growth theory could draw from the historic sources on theories of land rent and value. Economic theories extension to climate-related aspects set the stage for integrating the factor climate and temperature into growth concepts. After a historical overview of growth theories, modern macroeconomic growth models with attention to climate change and energy efficiency will be presented with regards to climate-related differences between countries and over time.

Growth theory

Historical foundations of economic growth calculus date back to the economics classics in the work of Adam Smith, Thomas Robert Malthus, David Ricardo and Karl Marx. The early accounts of labor theories of value and theories of land rent prepare first ideas on how input factors generate economic productivity. In Malthus (1815) agriculture production yields a surplus. Wage and fertility dynamics guarantee that the price of corn remains steadily above its costs of production. Scarcity of fertile land plays a major role for economic growth.

David Ricardo followed up on the argument with adding that land differs in quality and is limited in quantity, which explains rent (Dorfman 1989). Ricardo incorporated Malthus' Theory of Rent with his Theory of Profits, which led to a first discourse on the Theory of Distribution (Dorfman 1989). Ricardo's *On the Principles of Political Economy and Taxation* (1817) concludes that land rent grows as population increases and connects growth with comparative advantage – a nation's advantage in producing in comparison to other nations serving the better producing country's economic growth. Subsequent famous advocacy against imposing British tariffs in the so-called Corn Laws of David Ricardo argued against protectionism for national agriculture protection, which became the spring feather for international trade advocacy (Case & Fair 1999). Qualitative ideas – such as Schumpeter's creative destruction – are later mathematically formalized in growth theories and models of Solow (1973), Lucas (1988), Aghion and Howitt (1992).

Modern growth theory (MGT) starts in the 20th century. From Sir Henry Roy Forbes Harrod to Robert Solow to Paul Michael Romer, growth theory in the 20th century became more apolitical, equilibrium-focused with an application of a set of mathematical tools in the development of the ideas of the classicals. Environmental conditions and the productivity of land became abandoned in the development of a more mathematical formalization of economic growth. The Solow Growth Model uses the Aggregate Production Function, in which net national product Y is a function of Capital K and Labor L in $\boxed{Y = F(K, L)}$. The aggregate production function is fixed, meaning how the product depends on capital and labor does not change over time.

The starting point of MGT can be attributed to Harrod (1939) and Evsey Domar (1946), who studied business cycles as drivers of growth. Roy Harrod wrote in *An Essay in Dynamic Theory* (1939) to move away from a static theory of equilibrium towards dynamic economic analysis. At the heart of the start of MGT was the level of a community's income as the most important determinant of its supply of savings. The rate of increase of its income is an important determinant of its demand for saving. Demand was always seen as equal to supply ex post. Fundamental determinants of continuous growth were captured in the warranted rate of growth as the ideal growth rate, where there is no leakage and all savings are invested. The warranted growth rate in the economy is primarily affected by the propensity to save and the overall state of technology in a country. Capital-output ratios, savings rates and the natural rate of growth, where labor productivity and population growth are integrated, all serve as determinants of the maximum-sustainable rate of growth regarded as the welfare optimum.

MGT is thus primarily focused on capital, whose marginal product is constant and there are constant returns to scale. Harrod (1939) argues growth in a developed capitalist economy will exhibit the possibility of steady state growth at full employment, the improbability of steady state growth at full employment and the instability of the warranted growth rate, which Solow (1973) later interprets as the knife edge. Growth is considered as not stable and moves in a dynamic approach, where the actual growth rate can move away from the warranted rate of growth. The warranted growth rate need not be equal to the natural growth rate because there is no automatic mechanism which will ensure this. The further the actual rate deviates from the warranted, the stronger the forces become creating a continuous movement away from the warranted rate of growth (multiplier mechanism). Only when the actual growth rate equals the warranted rate of growth, will the economy achieve full employment equilibrium. This inherently instable nature of dynamic equilibrium calls for policy to combat the tendency to oscillate. Evsey Domar (1946) adds that maintaining full employment requires growth, specifically of income.

Overall, Harrod and Domar (H-D) considered growth without isolating it from fluctuations and maintained a link with "classical" growth theory. Harrod and Domar's models are based on the Leontief production function, which means output is limited by either the output of capital employed or the output of labor employed and there is just one way to combine labor and capital to produce output, so the marginal product of labor and capital are not well determined.

Robert Merton Solow and Trevor Swan introduced the Solow-Swan model as a hallmark of neoclassical growth theory (Solow 1956, 1957; Swan 1956). The Solow-Swan growth model is based on the neoclassical Cobb-Douglas production function of capital and labor assumed to be freely substitutable. If the price of labor is relatively high compared with capital, then capital can be freely substituted in place of labor until equality is reached once again. In the Solow-Swan model, a balanced growth steady state solution for the model exists. The balanced rate of growth in the model is constant and equal to the exogenous labor force growth rate. In the long run, the growth rate is independent of the savings rate. At the steady state, savings per unit labor (actual investment) equals break-even investment. An increase in capital no longer creates economic growth due to diminishing returns to capital. Thus, any attempt to boost growth by encouraging people to save more will ultimately fail. The only way left to grow is to invent new technologies. In the long-run, the growth of an economy depends on technological progress, which is by definition exogenous within the Solow-Swan framework. Just like the Harrod-Domar model, the fact that the main driving force behind long-run economic growth is exogenous. In Solow's model there is no instability, the economy will be pushed back into equilibrium because of the substitution effects of K and L, flexible labor markets and market clearing. Differences (in the short-run) in income levels across countries is explained by rich countries having higher saving (investment) rates in relation to population growth than poorer countries. Permanent (long-run) cross-country differences can only result from differences in rate of technological progress and access to the same technology.

Lacking empirical validations of exogenous growth models, led to the conclusion that some influence factors are missing to explain cross-country differences in income. Durlauf and Johnson (1995) take into account structural factors and initial conditions, casting doubt on the empirical validity of the Solow growth model. Hall and Jones (1999) show that differences in social infrastructure play an important role in explaining differences output per worker between countries. Neoclassical growth theory literature was superseded by endogenous growth theory or the new growth theory.

Endogenous Growth Theory emerged during the apparent sudden rise of a new group of inter-related Asian 'Tigers' (Singapore, Hong Kong, Taiwan, Korea) as fully-fledged members of the league of developed nations that could not be explained with exogenous growth theory. The idea of externalities and spillover effects originally formalized by Arrow (1962) who argued that externalities arising from learning-by-doing and knowledge spillover positively affect labor productivity on the aggregate level of the economy. Endogenization of knowledge and technology actually leads to an explanation of growth. Knowledge and technology are characterized by increasing returns unlike physical capital. In Romer's New Growth Theory (1986) persistent growth is explained by the impact of externalities on economic development. Romer (1990) considered the creation of new knowledge as a source of growth. In the late 1980s, Romer and Lucas incept endogenous growth theory, in which economic growth is determined by the production of knowledge and ideas. Building on Uzawa (1965), Lucas (1988) emphasized human capital creation as a source of growth. In Aghion and Howitt (1992, 1998), the Schumpeterian process of creative destruction becomes central to growth.

Both Lucas and Romer include knowledge (human capital) in their respective models to embody technological change. The growth in human capital is what spurs technological change within the model. There are little defining characteristics of the process in which knowledge transforms into technological change. Romer suggests that investment in R&D, along with the given state of technology, will spur innovation that leads to growth. The use of existing and the creation of new ideas is introduced as the driver of growth in the long-run. Lucas emphasizes that human capital can grow from education as well as learning-by-doing. Endogenous growth models are built on microeconomic foundations, where households maximize utility subject to budget constraints, while firms maximize profits. Policy implications are a mix of goods to accumulate human capital, subsidies for skills development and create incentives for workers to accumulate human capital.

Nicholas Kaldor's (1961) original stylized facts assume continued growth in the aggregate volume of production and in the productivity of labor at a steady rate. High correlation between share of profits in income and the share of investment in output are found and a steady share of profits and wages in societies and/or time periods in which the investment coefficient (share of investment in output) is constant. Constant wage share and constant growth imply a rising absolute real wage.

Over the entire world and in the prospect of time, for thousands of years, growth in both population and per capita GDP has accelerated, rising from virtually zero to the relatively rapid rates observed in the last century. Romer (1986, 1990) adds new stylized facts in pointing at increased flows of goods, ideas, finance, and people — via globalization as well as urbanization — have increased the extent of the market for all workers and consumers. Variation in the rate of growth of per capita GDP increases with the distance from the technology frontier.

Real Business Cycle (RBD) modelers stress role of technology shocks in driving business cycles and long run growth, whereas Keynesians and New Keynesians emphasize demand shocks. At core of arguments is the size of the multiplier, i.e., how much the increase in government spending leads to an increase in output.

As for macroeconomic methods effective as growth measurement, the Dynamic Stochastic General Equilibrium (DSGE) is often employed by monetary and fiscal authorities for explaining historical time-series data, policy analysis, as well as future forecasting purposes (Vitek 2017). DSGE methodology attempts to explain aggregate economic phenomena, such as economic growth, business cycles and effects of monetary and fiscal policy on basis of macroeconomic models derived from microeconomic principles. DSGE models are commonly used by central banks and have influence on public policy making.

There have been a number of empirical studies using new growth theory, with the early phase of empirical work being largely focused on cross-section studies. In cross-sectional studies, the growth rate is taken over long-time horizons, which allows elimination of business cycle effects, which may dominate fluctuations in economic variables at high frequencies to suit the long-run or secular trend study of growth. Over long-time horizons, cross-sectional studies are less likely to be affected by structural breaks. The data is relatively easily available for several countries at one point in time, compared to long time series for separate countries.

A time-series approach takes into account micro-behavior, though embedded in a macro environment, which can be allowed to change over time. In growth models with dynamic optimization by households and firms, first order conditions lead to a system of differential equations of state and control variables. The parameters of the model can then be estimated through time-series analysis and compared to the data.

Economic growth in light of climate change

Economics of climate change historically stems from sustainability research. There are many different definitions of sustainability, but all have two points in common: First, there is a recognition that resource and environmental constraints affect the patterns of development and consumption in the long run. Second, sustainability is concerned about intergenerational equity. One of the most famous and first definitions was stated by the Brundtland Commission in 1987: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Solow (1973) defines sustainability as "an obligation to conduct ourselves so that we leave to future the option or the capacity to be as well off as we are" (Greiner & Semmler 2008). Pearce, Barbier & Markandya (1990) point out that "natural capital stock should not decrease over time." Pezzey (1961) defines sustainable economic growth as "non-declining output or consumption over time" and sustainable economic development as "non-declining utility over time" (Greiner & Semmler 2008). In all these definitions it becomes obvious that there is a trade-off between economic growth versus sustainability. The presented standard economics growth models do not integrate sustainability calculus. Temperature and climate change have employment effects and industry-specific professional impacts (Kato et al. 2014).

Since the late 1960s and early 1970s, there was growing concern that economic growth has increasingly depleted the available natural resources, leading to ultimate environmental degradation. As economic decisions are restricted by the finiteness of natural resources and by the limited capacity of the nature to absorb pollution, attention is devoted to the question of whether it is possible and desirable to continue present patterns of economic growth. A general consensus in the debate is that there is a trade-off among environmental and economic goals: economic activity that ignores its effects on the environment is not sustainable.

Economists such as Meadows, Meadows, Randers & Behrens (1972) in *The Limits to Growth* or Daly (1987) have put forward predictions about a "sudden and uncontrollable decline in both population and industrial capacity" if no "conditions for ecological and economic stability that is sustainable far into the future" are established. General consensus is that there are trade-offs among environmental and economic goals, and that economic activity that ignores the biological or social system is not sustainable.

Economic growth models that integrate natural resources over time started with the Hotelling model, which includes system dynamics (Hotelling 1931 in Chari & Christiano 2014; Shogren 2013). The Hotelling (1931 in Chari & Christiano 2014) oil extraction model assumes that the market for the exhaustible resource is perfectly competitive. A representative supplier of the resource solves an intertemporal optimization problem where the problem is to find the optimal rate of extraction given the price trajectory. The solution to that problem, which is equivalent to the social optimum, shows that the price of the resource grows at the interest rate that is used to discount profits. This rule is the so-called Hotelling's rule which is at the heart of the economics of non-renewable resources. The oil market does not seem to be characterized by perfect competition as producers have a certain control over prices.

The Intergovernmental Panel on Climate Change (IPCC) and related work of Ottmar Edenhofer's (2007, 2014, 2021) at the Mercator Research Institute on Global Commons and Climate Change (MCC) integrate natural resources in energy consumption for economic welfare calculus. Gevorkyan and Semmler (2016) or Nyambuu and Semmler (2020) calculate energy sector influences on economic growth and overall welfare, even with finite horizons. Energy supply depends on climate as is experienced in price volatility of renewable and non-renewable commodities (Gevorkyan & Semmler 2016; Nyambuu & Semmler 2020).

Growth models with non-renewable resources take into account the extent to which economic growth process is restricted by the finiteness of resource stocks and whether sustained consumption and utility levels are feasible. Exhaustible natural resources are used as an input for the production of a good that is then either consumed or added to the capital stock to enhance future production. Their growth rate is nil, and non-renewables are unrecyclable and used up as input in production. Natural resources are considered as essentials, that is, production is impossible without them. Economists like Dasgupta and Heal (1974), Stiglitz (1974), and Solow (1973) analyze the optimal depletion of exhaustible natural resources in the context of a growth model where the resource is used as an input for the production of a composite commodity.

Pindyck (1978) builds a model with exploratory activity as the means of accumulating or maintaining a level of reserves, and treats depletion by assuming that reserve additions ("discoveries") resulting from exploratory activity fall as cumulative discoveries increase. Thus, producers must simultaneously determine optimal levels of exploratory activity and production resulting in an optimal reserve level that balance revenues with exploration costs, production costs, and the "user cost" of depletion. Pindyck (1981) examines the optimal production of oil when its price is determined exogenously (e.g., by a cartel such as the OPEC), and is subject to stochastic fluctuations away from an expected growth path. Uncertainty about future price affects the optimal production rate.

Empirical facts indicate that production and consumption of all fossil fuels have increased over time. As production of these non-renewable resources continues to rise significantly, the growth rate of reserves will not be able to keep pace. Greiner and Semmler (2008) presented a model with monopolistic owner of the resource who knows only a certain part of the total stock of the resource and who discovers new reserves at a certain rate. Assuming that the price of the resource depends on the current extraction rate and on cumulated extraction, the model also reproduces the hump-shaped extraction rates and U-shaped prices.

Semmler and colleagues (for example see Maurer, Preuss & Semmler 2014; Maurer & Semmler 2015; Nell, Semmler & Rezai 2009; Nyambuu & Semmler 2014, 2017, 2020; Popp 2015; Semmler, Braga, Lichtenberger, Toure & Hayde 2021; Semmler, Lessmann & Tahri 2020; Semmler, Maurer & Bonen 2016) use large-scale macroeconomic models to calibrate country- and institution-specific circumstances for determining the relative share of public capital to be committed to growth-enhancing infrastructure, mitigation of, and adaptation to climate change. Semmler and colleagues demonstrated that the public sector and governing institutions play a central role in overcoming free-rider problems and initiated market opportunities associated with externalities like climate change.

Semmler (2021) concludes that climate policies and phasing in of renewable energy creates job distraction but also job creation. There will be structural change and employment changes. Climate change mitigation and adaptation financialization will need modeling of shifts in industry structure, employment and skills. Transformation needs support by fiscal, monetary, industrial, labor market and compensation policies.

From a microeconomic growth perspective, preferences are often evolving historically and are impacted by sociological and cultural factors, for example through role models and adapting the behavior of others (Puaschunder 2020a). Conspicuous consumption in the sense of Veblen (1899) is an example which leads to a certain preference adoption. Population segments may copy the behavior of other population segments as Veblen suggested. Activities of green political movements may influence the behavior of households, purchasing and using less carbon intensive goods and services. Preferences may also be given incentives to change through regulations and standards, norms and conventions, development policies, voluntary agreements and information instruments. If standards and rules are set for construction of housing and for fuel efficiency of cars then preferences are likely to change over time (Braga, Fischermann & Semmler 2020).

Climate change and environmental influences also have disparate impacts on income compensation. Low-income households have higher cost through carbon pricing and are less likely to substitute away from rising fossil energy prices.

A growth theory and climate change connection is made by Kato, Mittnik, Semmler & Samaan (2014) who talk about structural change in the light of climate change building on models of growth and structural change (Kuznets 1957; Kaldor 1957; Pasinetti 1983) in the tradition of Keynesian-oriented growth models. Pasinetti (1983) argues that structural change occurs through a change in final demand driven by the income elasticity of demand (Engel curves). Kuznets-Kaldor-Pasinetti incorporated into a recent optimal growth model that allows for structural change (Kongsamut, Rebelo & Xie 2001). Three types of preferences are driving structural change: Preferences for agricultural goods, manufactured goods and services. Resources are continuously shifting in a so-called generalized balanced growth path. Since models of this type allow to trace the impact of climate policies on structural change along the growth path, they are used as starting point to model the impact of climate policies on growth, and the structure of output and employment.

In the absence of such measures, intergenerational equity as a natural behavioral law may establish temporal justice as a prerequisite of sustainable development (Puaschunder 2018). In order for a mitigation policy to be accepted and work effectively, it is recognized and emphasized that attention should be paid to fairness within the generation and, notably, across generations.

With respect for the standard Solow Growth Model that uses the Aggregate Production Function, climate could be added as a variable. The net national product Y would then be a function of Capital K and Labor L and Climate C in $\boxed{Y = F(K, L, C)}$.

Standard growth models remain limited for finding an intergenerational fair solution to alleviate the economic growth vs. sustainability predicament. The Canonical Nordhaus Model (IAM, DICE Model) is based on the assumption that economic growth leads to anthropogenic

CO_2 emissions causing global warming (Francis & Ramey 2002; Nordhaus 1994, 2008, 2013). Building on Nordhaus (2008, 2013) novel approaches of inclusive growth for climate justice over time are put forward by Jeffrey Sachs (2015), Willi Semmler and Lucas Bernard (2015), Sergey Orlov, Elena Rovenskaya, Julia Puaschunder and Willi Semmler (2018) and in Puaschunder's Mapping Climate Justice idea (2020). Time series inform models like in Orlov, Rovenskaya, Puaschunder & Semmler (2018) set the stage for Puaschunder's (2020b) Mapping Climate Justice, which compares different countries' peak condition for economic production in the light of climate change. The Mapping Climate Project presents macroeconomic results that introduce the gains of a warming earth in order to find ways how to share the expected benefits around the world or conserve the financial assets for future generations (Puaschunder 2020b). The results offer a novel contribution to contemporary carbon taxes and green bond solution strategies to help raise substantial revenue to subsidize countries for decarbonization (Marron & Morris 2016; Puaschunder 2018). All these market innovations can help in the standard predicament between economic growth versus climate stabilization in light of the connection between GDP growth and CO_2 emissions.

Orlov, Rovenskaya, Puaschunder & Semmler (2018) build on growth models in their evaluation of 'Green bonds, transition to a low-carbon economy, and intergenerational fairness.' Thereby current generations will have to carry the burden of paying for the transition to a low carbon economy, while the next generations will enjoy its benefits for free. Such intergenerational uneven treatment is one of the reasons why politicians are hesitant to go ahead and implement the carbon tax that is likely to be un-favored by the public – and the democratically-elected governments might not want to make the current generation worse off in terms of taxation.

Green Bonds solution (or climate bonds) have been suggested as an innovative approach to finance mitigation costs – and possibly future damages – thereby making climate policies more feasible, speeding up the transition to a low carbon economy, increasing welfare and ensuring greater intergenerational equity and fairness (Flaherty et al. 2017; Sachs 2015). Green bonds can be issued by companies, municipalities, states and sovereign governments, by international institutions to raise money and finance mitigation, as well as a variety of future-oriented long-term environmental and climate related projects and activities (Flaherty et al. 2017; The World Economic Forum Report 2015). As a debt instrument, by which investors lend money to an entity, bonds allow to borrow funds from the populace for a defined period of time at a variable or fixed interest rate. Historically, bonds have been used to fund large-scale projects ranging from infrastructure to wars. For example, the UK used loans to finance their participation in World War II, whereby the US was the creditor – the repayment of this loan was stretched out until recently. The first green bonds were issued by the European Investment Bank in 2006. In 2016 the bond market reached a level as high as 80 billion USD that are used to fund environment-friendly projects. To provide evidence of whether green bonds can be effective in reducing intergenerational unfairness and hence in enhancing the acceptance of more aggressive mitigation, Sachs (2015) was the first to use a stylized modeling framework. He considered and analyzed an overlapping-generations model, in which individuals' wages are negatively affected by the amount of greenhouse gases in the atmosphere, as well as by the mitigation efforts of the government. Policy makers, aiming to balance the interests across generations, can affect the wealth distribution by applying bonds and taxes policies.

Orlov, Rovenskaya, Puaschunder & Semmler (2018) examine whether green bonds can be used to finance mitigation in an economy, in which abatement decisions are made endogenously with the aim to maximize the social welfare function over a finite (long enough) time horizon. They employ the DICE model and extend it by adding green bonds, which can be used to compensate the economic losses from mitigation. Once a certain level of emission reduction is achieved, the economic activity is being taxed and bonds are being repaid. Orlov et al. (2018) provide quantitative estimates of the key policy effects to demonstrate the effectiveness of green bonds in terms of the emission reduction, the welfare improvement and the intergenerational inequity minimization. The model proposes a new tradeoff between a greater consumption today and investment in capital, which will enable a greater consumption in future. In addition to the economic dynamics, the DICE model also contains a simple representation of the global carbon cycle as well as climate and economic losses from climate change. The model is global and full participation of the world's greenhouse gas emitting nations is assumed. The DICE model illuminates another tradeoff that is the one between a greater investment, more production, higher greenhouse gas emissions, more pronounced global warming and hence greater economic losses on the one hand, and a higher abatement, lower economic losses and hence a lower consumption on the other hand. By choosing the investment/saving rate and abatement policies, a policy-maker maximizes the integrated discounted welfare derived from per capita consumption and hence finds an optimal level of global warming and its effects to be accepted, as well as the resultant optimal economic path.

The inclusion of bonds introduces another policy variable, namely, a tax to repay the bonds, together with two further tradeoffs. The first tradeoff is associated with the total amount of bonds to be issued: a larger amount would help ensure a higher emission reduction and hence would also mitigate a larger portion of the climate change losses, but on the other hand it is a larger amount of bonds inflated by the interest rate that will need to be repaid later. The second tradeoff relates to the taxation rate and the duration of the taxation period, during which the bonds should be fully repaid including the interest rate: a lower rate implies a longer repayment period and hence a higher total interest. Additional financial resources, which can be borrowed from future generations in the form of green bonds, might be used to compensate the mitigation costs now.

Puaschunder (2020b) emphasizes in a macroeconomic model that GDP-related climate change gains and losses will be distributed unequally throughout the world. A climate change winners and losers index was based on the economic prospects under climate change around the world (Puaschunder 2020b). This index captures how far countries are deviating from their optimum productivity levels on a time scale based on the optimum temperature for GDP productivity. The index attributed economic gain and loss prospects based on the medium temperature per country in relation to the optimum temperature for economic productivity per GDP sector composition per country. As economic gains and losses from a warming earth are distributed unequally around the globe, ethical imperatives lead to the pledge to redistribute economic gains due to climate change to territories that lose from global warming in the quest for climate justice. Climate justice comprises fairness within society, between countries but also over generations in a unique and unprecedented tax-and-bonds climate change gains and losses distribution strategy.

The most novel extension of the model describes an international climate change fund with diversified interest rates that could be based on a country's initial position on the climate change gains and losses index spectrum in combination with CO_2 emissions levels. An overall redistribution key would determine per country transfers based on the climate change winner or loser status as well as the contribution to the climate change problem measured by per country CO_2 emissions. The bonds should be issued based on taxes from countries that are high climate change winners on the winners and loser index spectrum as well as have high rates of CO_2 emissions. A high bond payout should be offered to countries with climate change losing prospect as well as low CO_2 emissions. Moderate bond outputs should be given to countries in the middle of the climate change winners and loser index spectrum as well as medium rates of CO_2 emissions.

The range of interest rates offered by a country could also be weighted by the country's overall climate flexibility in relation to other countries as this determines the future comparative advantage to other nations in the world. The countries would be able to offer an interest rate spread based on their climate flexibility, hence their range of temperature spreads from highest temperature to the lowest within the country, which determines their future climate diversification potential and trade degrees of freedom.

The idea of diversified interest rate regimes is also extendable to sector-specific bond interest rate regimes as well as per country climate flexibility levels. Within a country, the bonds could be offered by commissioning agents, such as local investment banks, who could offer industry-specific diversified interest rate maturity bond yields based on the environmental sustainability of an industry, e.g., as measured by the European Sustainable Finance Taxonomy. The more sustainable an industry performs, the higher bond payouts should be offered in sector-specific interest rate regimes within a country. Bond yield differences between industries could set market incentives for a transitioning to renewable energy productivity solutions.

Diversified repayment of bonds is a new incentivization method aimed at ensuring to share the burden but also the benefits of climate change over time, within countries and markets but also within society in an economically efficient, legally equitable and practically feasible way.

References

Aghion, Philippe & Peter Howitt. 1992. "A Model of Growth Through Creative Destruction." *Econometrica 60*(2): 323-351.

Aghion, Philippe & Peter Howitt. 1998. *Endogenous Growth Theory*. Cambridge, MA: Massachusetts Institute of Technology Press.

Arrow, Kenneth J. 1962. "Economic welfare and the allocation of resources for invention." In R. R. Nelson (Ed.) *The Rate and Direction of Inventive Activity*. Princeton: Princeton University Press.

Braga, João Paulo, Thomas Fischermann & Willi Semmler. 2020. „Ökonomie und Klimapolitik: So könnte es gehen." *Die Zeit*, March 5, 2020. Retrieved at https://www.zeit.de/zustimmung?url=https%3A%2F%2Fwww.zeit.de%2F2020%2F11%2Feuropaeischer-green-deal-emissionshandel-wirtschaft-klimaschutz.

Case, Karl E. & Ray C. Fair. 1999. *Principles of economics*. London: Prentice-Hall.

Chari, V.V. & Lawrence J. Christiano. 2014. *The Optimal Extraction of Exhaustible Resources: Conventional theory can't explain historic commodity price fluctuations, but modified models may provide better guidance*. Minneapolis, The Federal Reserve Bank of Minneapolis, December 11, 2014. Retrieved at https://www.minneapolisfed.org/article/2014/the-optimal-extraction-of-exhaustible-resources

Daly, Herman E. 1987. "The economic growth debate: What some economists have learned but many have not." *Journal of Environmental Economics and Management* 14(4): 323-336.

Dasgupta, Partha & Geoffrey Heal. 1974. "The Optimal Depletion of Exhaustible Resources." *The Review of Economic Studies*, *Symposium on the Economics of Exhaustible Resources 41*: 3-28.

Domar, Evse. 1946. *Capital Expansion, Rate of Growth, and Employment, Econometrica* 14 (2): 137–147.

Dorfman, Robert. 1989. "Thomas Robert Malthus and David Ricardo." *Journal of Economic Perspectives 3*(3): 153-164.

Durlauf, Steven & Paul Johnson. 1995. "Multiple Regimes and Cross-Country Growth Behaviour." *Journal of Applied Econometrics 10*(4): 365-384.

Flaherty, Michael, Arkady Gevorkyan, Siavash Radpour & Semmler, W. 2017. "Financing climate policies through climate bonds: A three stage model and empirics." *Research in International Business and Finance 42*: 468-479.

Francis, Neville & Valerie A. Ramey. 2002. *Is the Technology-Driven Real Business Cycle Hypothesis Dead?* Cambridge, MA: National Bureau of Economic Research, Working Paper 8726.

Gevorkyan, Arkady & Willi Semmler. 2016. "Oil price, overleveraging and shakeout in the shale energy sector: Game changers in the oil industry*." Economic Modeling 54*: 244-259.

Greiner, Alfred & Willi Semmler. 2008. *The Global Environment, Natural Resources, and Economic Growth*. Oxford: Oxford University Press.

Hall, Robert E. & Charles I. Jones. 1999. "Why Do Some Countries Produce So Much More Output Per Worker Than Others?" *The Quarterly Journal of Economics 114*(1): 83-116, Feb.

Harrod, Roy Forbes, Sir. 1939. "An Essay in Dynamic Theory." *The Economic Journal 49 (*193):14-33, March.

Harold Hotelling. 1931. "The economics of exhaustible resources. *Journal of Political Economy, 39*: 137–175, April 1931.

Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (2007). AR4. https://www.ipcc.ch/assessment-report/ar4/.

Intergovernmental Panel on Climate Change (IPCC). 2014. *Climate Change 2014, Mitigation of Climate Change Working Group III Contribution to the 5th Assessment Report of the Intergovernmental Panel on Climate Change.* Retrieved at https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_frontmatter.pdf.

Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report (2021). AR6 Climate Change 2021: The physical science basis. Retrieved at https://www.ipcc.ch/report/ar6/wg1/

Kaldor, Nicholas. 1957. "A Model of Economic Growth." *The Economic Journal 67*(268): 591-624.

Kaldor, Nicholas. 1961. "Capital Accumulation and Economic Growth." In F.A. Lutz and D.C. Hague (Eds.), *The Theory of Capital*, St. Martin's Press, pp. 177–222.

Kato, Mika, Stefan Mittnik, Daniel Samaan & Willi Semmler. 2014. "Employment and output effects of climate policies." In L. Bernard & W. Semmler (Eds.), *The Oxford Handbook of the Macroeconomics of Global Warming*, pp. 445-476. Oxford: Oxford University Press.

Kongsamut, Piyabha, Sergio Rebelo & Danyang Xie. 2001. "Beyond balanced growth." *Review of Economic Studies* 68(4): 869-882.

Kuznets, Simon. 1957. "Quantitative Aspects of the Economic Growth of Nations: II. Industrial Distribution of National Product and Labor Force." *Economic Development and Cultural Change* 5(4): 1-111.

Lucas, Robert E. 1988. "On the mechanics of economic development." *Journal of Monetary Economics 22*:3-42.

Malthus, Thomas Robert. 1988. *An essay on the principle of population*. London: Johnson.

Malthus, Thomas Robert. 1815. *An Inquiry into the Nature and Progress of Rent, and the Principles by which it is Regulated*. London: John Murray.

Marron, Donald B. & Adele C. Morris. 2016. *How to Use Carbon Tax Revenues*. Washington D.C.: Tax Policy Center.

Maurer, Helmut, Johann Jakob Preuss & Willi Semmler, W. 2014. "Scenarios in a model of economic growth and climate change." In L. Bernard & W. Semmler (Eds.), *The Oxford Handbook of the Macroeconomics of Global Warming*, pp. 82-113. Oxford: Oxford University Press.

Maurer, Helmut & Willi Semmler. 2015. "Expediting the transition from non-renewable to renewable energy." *Discrete and Continuous Dynamic Systems*, *35*(9): 4503-4525.

Meadows, Donella H., Dennis L. Meadows, Randers Jørgen & William W. Behrens. 1972. *The Limits to Growth; A Report for the Club of Rome's Project on the Predicament of Mankind.* New York: Universe Books.

Nell, Edward, Willi Semmler & Armon Rezai. 2009. *Economic growth and climate change: Cap-and-trade or carbon tax?* Schwartz Center for Economic Policy Analysis working paper 2009-4. Retrieved at https://www.economicpolicyresearch.org/images/docs/research/climate_change/SCEPA%20Working%20Paper%202009-4.pdf, 2009.

Nordhaus, William D. 1994. *Mapping the global commons: The economics of climate change.* Cambridge, MA: MIT Press.

Nordhaus, William D. 2008. *A question of balance: Weighing the options on global warming policies*. New Haven: Yale University Press.

Nordhaus, William D. 2013. *The climate casino: Risk, uncertainty and economics for a warming world*. New Haven: Yale University Press.

Nyambuu, Unurjargal & Willi Semmler. 2014. "Trends in the extraction of non-renewable resources: The case of fossil energy." *Economic Modelling 37*: 271-279.

Nyambuu, Unurjargal & Willi Semmler. 2017. "Emerging markets' resource booms and busts, borrowing risk and regime change." *Structural Change and Economic Dynamics 41*: 29-45.

Nyambuu, Unurjargal & Willi Semmler. 2020. "Climate change and the transition to a low carbon economy: Carbon targets and the carbon budget." *Economic Modelling 84*: 367-376.

Orlov, Sergey, Elena Rovenskaya, Julia Margarete Puaschunder & Willi Semmler. 2018. *Green bonds, transition to a low-carbon economy, and intergenerational fairness: Evidence from an extended DICE model.* International Institute for Applied Systems Analysis Working Paper WP-18-001, 2018. IIASA, Laxenburg, Austria, European Union.

Pasinetti, Luigi L. 1983. *Structural Change and Economic Growth: A Theoretical Essay on the Dynamics of the Wealth of Nations*. Cambridge, UK: Cambridge University Press.

Pearce, David Edward Barbier & Anil Markandya. 1990. *Sustainable Development: Economics and Environment in the Third World*. London: Edward Elgar.

Pindyck, Robert. 1978. "The Optimal Exploration and Production of Nonrenewable Resources." *Journal of Political Economy 86*(5): 841-861.

Pindyck, Robert. 1981. "The Optimal Production of an Exhaustible Resource When Price is Exogenous and Stochastic." In: *The Impact of Rising Oil Prices on the World Economy*, Part of the *Scandinavian Journal of Economics Book Series (SJE)*, pp. 137-148.

Popp, David. 2015. "Climate-friendly technological change for developing countries." In Bernard, L. & Semmler, W. (Eds.), *The Oxford Handbook of the Macroeconomics of Global Warming*, pp. 321-348. Oxford: Oxford University Press.

Puaschunder, Julia Margarete. 2018. *Intergenerational Responsibility in the 21st Century*. Wilmington, US: Vernon Arts & Science, 2018.

Puaschunder, Julia Margarete. 2019a. *Corporate and Financial Intergenerational Leadership*. Lady Stephenson, Newcastle upon Tyne, UK: Cambridge Scholars Publishing.

Puaschunder, Julia Margarete. 2019b. *Intergenerational Equity: Corporate and Financial Leadership*. Cheltenham, UK & Northampton, MA: Edward Elgar.

Puaschunder, Julia Margarete. 2020a. *Behavioral Economics and Finance: Nudging and Winking to make Better Choices*. Cham: Springer Nature.

Puaschunder, Julia Margarete. 2020b. *Governance and Climate Justice: Global South and Developing Nations*. New York, New York: Palgrave Macmillan. Cham, Switzerland: Springer Nature.

Puaschunder, Julia Margarete. 2020c. "The future of the city after COVID-19: Digitionalization, preventism and environmentalism." *ConScienS Conference Proceedings*, September 28-29, 2020, pp. 125-129, Research Association for Interdisciplinary Studies.

Puaschunder, Julia Margarete. Martin Gelter & Siegfried Sharma. 2020. "COVID-19-Shock: Considerations on Socio-Technological, Legal, Corporate, Economic and Governance Changes and Trends." *Proceedings of the 16th International Research Association for Interdisciplinary Studies (RAIS) Conference on Social Sciences and Humanities*. Princeton, NJ, August 17-18, pp. 82-93.

Ricardo, David. 1817. *On the Principles of Political Economy and Taxation*. London: John Murray.

Romer, Paul M. 1986. "Increasing Returns and Long-Run Growth." *Journal of Political Economy 94*(5): 1002-1037.

Romer, Paul M. 1990. "Endogenous Technological Change." *Journal of Political Economy* 98(5): 71-102.

Sachs, Jeffrey D. 2015. "Climate change and intergenerational well-being." In Bernard, L. & Semmler, W. (Eds.), *The Oxford Handbook of the Macroeconomics of Global Warming*, pp. 248-259. Oxford: Oxford University Press.

Semmler, Willi. 2021. *Economics of Climate Change*. Lecture notes, New York: The New School for Social Research.

Semmler, Willi, João Paulo Braga, Andreas Lichtenberger, Marieme Toure & Erin Hayde. 2021. *Fiscal policies for a low-carbon economy*. Washington, D.C.: World Bank Report. Retrieved at https://documents1.worldbank.org/curated/en/998821623308445356/pdf/Fiscal-Policies-for-a-Low-Carbon-Economy.pdf.

Semmler, Willi, Kai Lessmann & Ibrahim Tahri. 2020. *Energy transition, asset price fluctuations, and dynamic portfolio decisions*. Retrieved at https://ssrn.com/abstract=3688293.

Semmler, Willi, Helmut Maurer & Anthony Bonen. 2016. *An extended integrated assessment model for mitigation and adaptation policies on climate change*. Pisa: Scuola Superiore Sant'Anna working paper. Retrieved at https://www.santannapisa.it/sites/default/files/iampaper_mitgateadapt_oct2016_0.pdf.

Shogren, Jason F. 2013. *Encyclopedia of Energy, Natural Resource, and Environmental Economics*, Elsevier Science.

Solow, Robert M. 1973. *Is the End of the World at Hand? Challenge* 16(1): 39-50 March/April.

Solow, Robert M. 1956. "A contribution to the theory of economic growth." *Quarterly Journal of Economics 70*(1): 65-94.

Solow, Robert M. 1957. "Technical change and the aggregate production function." *Review of Economics and Statistics 39*(3): 312-320.

Stiglitz, Joseph. 1974. "Growth with Exhaustible Natural Resources: The Competitive Economy." *Review of Economic Studies* 41(5): 139-152.

Swan, Trevor W. 1956. "Economic growth and capital accumulation." *Economic Record 32*(2): 334-361.

Uzawa, Hirofumi. 1965. "Optimum Technical Change in An Aggregative Model of Economic Growth." *International Economic Review 6*(1): 18-31.

Veblen, Thorstein. 1899. *The Theory of the Leisure Class*. New York: MacMillan, Retrieved at http://moglen.law.columbia.edu/LCS/theoryleisureclass.pdf.

Vitek, Francis. 2017. *Policy, Risk and Spillover Analysis in the World Economy: A Panel Dynamic Stochastic General Equilibrium Approach*. Washington, D.C.: International Monetary Fund.

Walpole, Sandra, Jack Sinden & Tim Yapp. 1996. "Land quality as an input to production: The case of land degradation and agricultural output." *Economic Analysis and Policy 26*(2): 185-207.