Examining Sustainable Growth in Detail

Nicolas Paul Cerkez*†

September 14, 2018

Abstract

This paper presents a review of the existing literature on sustainable growth. The article's goals are to assess our understanding on issues related to sustainable growth and to identify important open questions and directions for future research.

1 Introduction

Sustainable growth encompasses aspects of almost all social sciences and hence, successful research requires a deep understanding of a very large literature. The aim of the present paper is to provide an in depth look at the most relevant papers in each of the relevant fields to give scholars an idea of the scope and breadth required in future research.

Adding to this daunting task is the fact that economists and other social scientists attempt to overcome "the challenges" concerning sustainable growth from fundamentally different starting points. This results in various strands of literatures that are disconnected in terms of methodology, outcomes, philosophy, and often also ideology. In order to clarify such "initial conditions" issues, section 2 of this paper is devoted to defining what sustainable growth is and what its goal is, or should be, according to different schools of thought.

Section 3 motivates the discussion of sustainable growth by going into the never-ending debate on whether there are limits to growth. This debate concerns itself with the question whether resource constraints will eventually be binding and end economic growth as we know it. The various views can be grouped into three categories: scholars arguing that (i) there are no limits to growth, mainly on the merit of technological innovation and substitution; (ii) resource constraints will exert a drag on growth, but not halt it all together; and (iii) we should stop pursuing growth as soon as the costs of doing so exceed the benefits. The argument of the second group is furthermore connected to the literature on the Environmental Kuznets Curve, a curve arguing that economic growth initially harms the environment but, after some time, will be good

*Department of Economics, UCL; Email: nicolas.cerkez.16@ucl.ac.uk.

†I would like to thank Tiago Cavalcanti, Michael Grubb, Zeina Hasna, and seminar participants at Cambridge University for helpful commends and suggestions. Senthuran Bhuvanendra provided helpful pointers to the relevant philosophical literature and Gavin Hassal provided a useful draft on the empirical evidence of endogenous technological change.

for the environment. The evidence for this, as I will show, is rather scarce. I end the section by looking at two "new forms" of growth: green growth and growth without resources ("the weightless economy").

Economic and alternative, mainly ecological, approaches to economic growth are analyzed in section 4. I start by reviewing neoclassical macroeconomic growth models, including their microeconomic foundations, that do not include natural resources in the production function, starting from the classical Solow model and ending with the findings of recent years. Next, I show that the advances in macroeconomic growth theory were usually accompanied by research that incorporates natural resources in the production function. A very similar timeline between the two can be established. Given the importance of technological change and productivity for the issue of sustainability, I give special emphasis to research in those areas. Additionally, I mention the modeling approaches that environmental economists have traditionally used (Integrated Assessment Models), highlight their short-comings and suggest how recent advances in dynamic stochastic general equilibrium models and agent-based models may be more suitable for the task. Lastly, I summarize the work of alternative approaches, mainly coming from ecological macroeconomists, to economic growth. While ecological macroeconomics has only recently received increased attention, it is nonetheless possible to establish a similar timeline to the advances in mainstream macroeconomics.

Growth affects the environment. But does the environment also affect economic growth? It turns out that this relationship is anything but clear. Section 5 looks at this in more detail, with a specific focus on energy. Given the importance of energy in today's world, it is useful to look at energy in some more detail. Of specific importance here is the energy efficiency gap, which argues that at the individual and aggregate level we do not consume the optimal amount of energy, and research into energy prices, expenditures and elasticities.

Sustainable growth, as is hopefully already clear by now, covers a very broad literature. This information needs to be structured in some way in order to understand (a) what information is important and (b) how various pieces of information are connected to one another. In other words, it is important to have some sort of framework to put all the pieces of information mentioned in the previous sections together. Section 6 covers such frameworks.

Lastly, any issue within the social sciences is of philosophical nature. By definition, any solution proposed is therefore based on one or more philosophical schools of thought. Section 7 aims to give an overview of the most pressing philosophical issues concerning sustainable growth.

Section 8 concludes and suggests the most important areas for future research.

2 Definitions and Measurement Issues

2.1 Defining Sustainability

Even though policy-makers and activists love to use the word "sustainability", it is anything but clear what the precise definition of it is. This is problematic for a number of reasons, one of which is that it can lead to misunderstandings in the policy discourse. To start with, it is crucial to differentiate between sustainable development and sustainable growth. The latter is a subset of the former.

The Brundtland report defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland et al., 1987). One interpretation of this phrase is closely tied to Hicks (1946)'s definition of income as "the maximum amount that could be spent without reducing real consumption in the future." This interpretation argues that the Brundtland report suggests that "we, the present, should consume within our income" (Heal, 2000). A slight reformulation of Hick's definition of income suggests maximizing consumption subject to maintaining the capital stock.[1] This is in line with the work of Pearce et al. (2013) and Daly (1991*b*), who argue that maintaining in tact natural capital is a condition for sustainability.

A related yet distinct way of looking at this comes from Rawls (1971). He argues that overall welfare can be maximized by maximizing the welfare of the poorest generation. Drawing on this, Solow (1974*b*) defines intergenerational equity as constant utility over time, while Pezzey (1989) extends this to nondecreasing utility over time. The latter includes the possibility of increases in well-being. A further possibility is to define it as nondecreasing inter-temporal welfare (Dasgupta and Mäler, 2000).

A different way of looking at sustainability is to define it "as a constraint on changes in opportunities, rather than changes in outcomes" (Pezzey and Toman, 2005). This is fundamentally different in that it asks what future generations will inherit from us as opposed to what they will enjoy.

Notwithstanding the above, the default way of looking at sustainability from an economics perspective is provided by the discounted utilitarian framework. This framework, based on work by Jeremy Bentham, argues that the optimal consumption path is defined as the one which provides the greatest discounted value of net benefits.[2]

Sustainable growth as a concept is more narrow than sustainable development and refers to the idea that we are seeking growth without exhausting the natural resources of our planet. Since natural resources are part of the capital stock (natural capital), it is therefore possible to define sustainability in terms of capital stocks: "an economy is sustainable if the total value of all its capital stocks, evaluated at shadow prices, is constant or increasing" (Heal, 2017). In other words, as long as capital is nondecreasing, people's income, defined as the return on capital, is sustainable.

There are furthermore two types of sustainability: a weak and a strong one.[3] In terms of capital stocks, weak sustainability requires that the total capital stock is nondecreasing, while strong sustainability requires that natural capital be nondecreasing (Heal, 2017). The latter of the two is of course a much stronger criterion. It turns out that these definitions are linked to the debate whether natural and man-made capital are substitutes or complements, something that will be discussed in section 3.5.[4]

Concerns about sustainability not only come up in academia. Since the Stockholm

[1] Hamilton and Hepburn (2014) suggest that a nations wealth can be divided into six forms of capital: (i) physical capital, (ii) human capital, (iii) natural capital, (iv) intellectual property, (v) social/institutional capital, and (vi) net financial assets.

[2] Heal (2000) provides a more in depth overview of various definitions and approaches to sustainability.

[3] There are variants within strong and weak sustainability, which I will not describe here. See Pezzey and Toman (2005) for a more detailed overview of this.

[4] Weak sustainability is only possible if the elasticity of substitution between natural and man-made capital is high enough and hence proponents of the "weak sustainability"-view tend to argue that natural and other forms of capital are substitutes. Advocates of the "strong sustainability"-view argue that the two are complements.

Conference (UN Conference on the Human Environment) in 1972 the United Nations (UN) have emphasized the importance of addressing environmental issues in an international framework and implicitly introduced non-economists into the debate. Sustainability issues have been addressed since 1992, the date of the first UN Conference on Sustainable Development (UN Conference on the Environment and Development). More recently, the 2015 Sustainable Development Goals (SDGs) advocate 17 goals the world must achieve in order to "be sustainable".

2.2 Defining the Objective

There is much debate between economists and non-economists about the definitions of sustainable development and growth. This leads to a broader question of what the actual objective of sustainability is, i.e. "what are we actually maximizing?".[5]

An agent in an economist's world maximizes the (discounted expected) utility of today's and future consumption, and possibly some other components in her utility function. The solution to the economists problem, amongst others, describes the agent's future consumption path. In this classic set-up, the agent does not worry about sustainability issues.[6] The agent's wealth[7] is therefore defined as the (expected discounted) present value of future consumption.

There are various criticisms of this basic set-up. Some have questioned why governments should be interested in sustainability issues if private agents are only interested in maximizing the present value of consumption.[8] Suggesting a diplomatic middle ground, Pezzey and Toman (2005) suggest that "we must assume that individuals choose their own actions to maximize some form of present value, but vote for a government which applies a sustainability concern, both by measuring sustainability, and taking action to achieve it if necessary."

Other criticisms question the focus on consumption and material wealth. Jackson (2016), for example, suggests that the fundamental task of the economy is to "deliver and enable prosperity". For him, prosperity and material wealth are not synonymous. Rather, prosperity is equated with the idea of flourishing physically, psychologically, and socially.[9] Other, slightly less inclusive, proposals have criticized using GDP as a measurement and favor other measurements of well-being, such as, amongst others, happiness or life satisfaction.

[5]For some, sustainable growth is an oxymoron: growth depletes the environment and hence sustainable growth is an impossibility.

[6]While it is true that agents in classical economic problems do not think about sustainability issues, it is possible (and, as the next two sections will show, has been done) to include environmental components either into the utility function or into the constraint of the individual/household.

[7]Wealth is a stock; GDP is a flow. The flow of income is the return on the stock of wealth. See Hamilton and Hepburn (2014) for a discussion of this.

[8]Beckerman (1994) goes so far to suggest that adding a sustainability constraint to an individuals maximization problem is morally repugnant. Taken to the extreme this means that individuals never have an incentive to consider sustainability options and governments don't have an incentive for policy interventions should the economy be "unsustainable".

[9]This does not imply that we don't need material things at all. In fact, Jackson (2016) establishes a paradox: on the one hand we are able to flourish more with fewer material things while on the other hand, "material goods provide a vital language through which we communicate with each other about the things that really matter," such as family or identity.

It would be false, however, to presume that economists are not aware of sustainability issues. Arrow et al. (2004) question whether consumption is excessive according to different measures of sustainability and suggest that this is indeed the case. Furthermore, recent work by Arrow et al. (2012), Hamilton and Hepburn (2014), and Lange et al. (2018) emphasizes the importance of using wealth as an indicator of sustainability to complement GDP. Arrow et al. (2012) suggest that the right measure for a society's wealth is the concept of comprehensive wealth, which, they argue, varies greatly across countries. They show that often neglected contributors to wealth such as technological change, natural capital, and health capital fundamentally alter the conclusions one draws about whether a nation is achieving its sustainability goals.

In essence, all of this concerns much broader questions about how to measure the standard of living of people and, to really push it, how to value things. Attempting to answer both of these is out of the scope of this paper.[10] My point is to show that it is anything but clear what the objective of sustainability should be: for economists it tends to be economic growth, for other social scientists it involves more inclusive measurements of well-being, such as prosperity, happiness, and life satisfaction. The latter are multi-dimensional measurements of sustainable growth, while the former is one dimensional. It is obvious where the advantages lie: the multi-dimensional view is more inclusive and most likely provides a better, more realistic picture of overall well-being. The latter is much easier to measure.[11] Hence, researchers often face a trade-off between the tractability and precision of the measurement they use and the inclusiveness, or the realism, of the measurement representing well-being.

2.3 Defining the Scope of this Paper

If one thing is clear by now, it should be that little is clearly defined. This is unfortunate and poses many problems for a paper attempting to give an overview over various fields covering one topic. Hence, it makes sense to define the scope of the paper precisely.

As mentioned, sustainable growth is a subset of sustainable development. The focus of this review is on sustainable growth, which I define, including weak and strong sustainability, à la Heal (2017), as was done above.

The implications of this are that I focus on GDP as a measure of growth. Keeping in mind that sustainable growth is a subset of sustainable development, this carries with it the following: (a) it does not mean that GDP is a measurement for well-being; (b) it does not exclude the possibility that sustainable growth is indeed an oxymoron;

[10]In regard to the former, let me say that, for example, Sen (1984) suggests that there are at least three ways measure the standard of living across generations: as some notion of (i) the utility of a person, (ii) opulence, and (iii) freedom. In regard to the latter, an interesting starting point would be to compare the theories of value of Adam Smith, David Ricardo, and Karl Marx. Smith (1776), seeing a dual character in things, differentiates between labor embodied, the value of inputs into production, and labor commanded, the value a product commands in the market. Ricardo (1817) supports the idea of labor embodied but disagrees with the idea of labor commanded, while Marx (1867), seeing an exchange- and use-value in commodities, argues that a web of human relations underlies his concept of socially necessary labor time.

[11]It is very difficult, for example, to measure life satisfaction empirically. Deaton (2008) analyzing survey data about life satisfaction, correctly points out that there are two ways of interpreting the data: "[A survey] might elicit an evaluation of the respondent's complete life, as seen from 'the present time', or perhaps more likely, an evaluation of today's contribution to the lifetime stream." In general, there are many issues associated with measurements of life satisfaction and other multi-dimensional concepts of well-being.

and (c) it does not exclude any of the alternative ways of looking at sustainability, such as the concept of prosperity. Well-being as well as prosperity are multi-dimensional concepts, of which income is certainly one dimension. Sustainable growth, the way I define it here, concerns itself with exactly this one dimension, which itself, as we will see, contains many sub-dimensions.[12]

Another issue to keep in mind is that sustainable growth, while obviously including environmental issues, is concerned with a "macro-view" of such problems. Research looking at "micro-effects", such as, for example, the effect of increased temperatures on learning outcomes or violence, is not of concern here.[13] Equally so, growth is a subset of macroeconomics as a whole. Hence, this review, is not concerned with non-growth related issues.[14]

Lastly, this review is largely of theoretical nature. Hence, many "applied" issues are neglected. This does not imply that they don't matter, but it helps to narrow down the scope of the paper. For example, recent research has emphasized the effects that climate change could have on the financial sector (Carney, 2015; Batten et al., 2016; Batten, 2018). This research identifies three channels through which climate change could affect the financial sector: physical risks, transition risks, and liability risks. While the importance of the financial sector for sustainability and growth is not questioned here, it is nonetheless not the main focus of the review. Other issues neglected, for example, concern cooperation and coordination problems in international environmental agreements (see Barrett (1994) for one problem and Nordhaus (2015) for a recent proposal to overcome it).

3 Limits to Growth

3.1 There are no Limits to Growth

The first group in the Limits to Growth (LtG) debate argues that resource constraints don't pose any limits to economic growth. A strong proponent of this view was Julian Simon, who vehemently argued that population growth and resource scarcity will not impede economic growth (Simon, 1980, 1981). Simon was so sure of himself that he made a bet with biologist Paul Ehrlich, whose views I describe below, about the price of five raw materials, chosen by Ehrlich, declining between 1980 and 1990. Simon won the bet since commodity prices did indeed decline over the 20th century. Had the bet been extended into the 21st century, however, the outcome would have differed.

Unlimited growth is also supported by most mainstream economic growth models, whether they include natural capital or not. While early models have to resort to exogenous technological shocks to explain growth since capital accumulation cannot sustain growth forever because of diminishing returns (Solow, 1956; Stiglitz, 1974; Dasgupta and Heal, 1974; Solow, 1974*a*), even later models endogenizing technological progress find conditions under which unlimited growth is possible (Aghion and Howitt, 1998; Grimaud, 1999; Michel and Rotillon, 1995). Often, the intuition behind

[12]Some recent books about the broader topic of sustainability are, for example, Raworth (2017) and Sachs (2015). Recent books on climate change are Wagner and Weitzman (2016) and Llavador et al. (2015).

[13]See Dell et al. (2014), Carleton and Hsiang (2016), and Houser et al. (2015) for an overview of these "micro-impacts" and Hsiang (2016) for an overview of econometric concerns within "climate economics".

[14]See, for example, Mankiw and Reis (2018) for a brief history of other macroeconomic issues.

behind the findings of this latter group is that increasing returns to ideas overcome the diminishing returns to capital.

In forthcoming work, Cameron Hepburn, Alexander Pfeiffer, Felix Pretis, and Alexander Teytelboym construct a panel dataset from 1957 to 2015 of reserve-to-production ratios of around 50 minerals and ask "are we running out of resources?". While they don't rule out price spikes and short-term supply constraints for individual minerals, they argue that in the aggregate concerns about resource constraints are misplaced. Bardi (2014) agrees that the issue is not the imminent scarcity of resources but argues that rising extraction costs could pose problems. Either way, scientists and international organization are producing criticality reports and caution that we might be running out at least of a few minerals (Vidal et al., 2013; EU Commission, 2017).

3.2 There is an Environmental Drag

The second group of the LtG debate suggests that resource constraints will dampen economic growth. There are two components to the environmental drag: a tighter constraint on natural resources and an increase in pollution (Bowen and Hepburn, 2012).

The first was investigated by Nordhaus et al. (1992). They analyze the drag on growth from scarce resources, indicating that the largest drag comes from limited energy supplies (0.155 percent per year). This environmental drag can be overcome by technological progress, so Nordhaus et al., as long as technological progress exceeds one-quarter of one percent a year. Bruvoll et al. (1999) look at the second component by analyzing Norway's economy. Their environmental drag leads to a reduction of 0.1 percentage point per year of economic growth, and a 0.23 percentage points reduction per year in wealth, including environmental wealth.

The second law of thermodynamics[15], which says that all physical processes increase entropy, is related to this retardation of growth, as Georgescu-Roegen (1975, 1986) points out. He argues that humans can only transform matter or energy, but not create or destroy it. This suggests that an increase in total output (economic growth) can only be achieved by using more energy (the primary input into production), which implies environmental degradation. It also hints at the possibility that sustainable growth is an oxymoron. Underlying assumptions here are the complementarity between energy and other inputs into production, a fixed technology and fixed human behavior. As I show later in the text, these assumptions are anything but certain. Intuitively, it is anything but clear why more GDP is problematic if energy intensity decreases in proportion or if more energy is based on more solar power.

3.3 There are Limits to Growth

The third group of the LtG debate argues that as soon as the costs imposed by economic growth exceed the benefits it provides, we must stop pursuing growth.

As early as 1798, Malthus (1798) predicted that population growth, which he assumed to grow exponentially, would outrun, amongst others, food supplies, which he

[15] There are four laws of thermodynamics: the first says that total energy is constant; the second says that entropy never decreases; the third says that the absolute zero of temperature cannot be reached; and the "zeroth" says that thermodynamic equilibrium is a transitive condition.

assumed to grow arithmetically, and drive living standards to a bare minimum. A similar argument is put forward by Ehrlich (1978) who argues that population growth causes a disproportionate negative impact on the environment and advocates analyzing population growth issues globally and jointly with resource utilization and depletion. Ehrlich and Holdren (1971) coin the $IPAT$ equation ($I = PAT$), which relates the impact on the Earth system to the population size, income per capita (affluence) and technology. While Ehrlich's ideas have not received much attention in economics, Dasgupta and Dasgupta (2017) investigate fertility behavior and find support for at least some of Ehrlich's claims. They suggest that our demand on Nature's goods and services exceeds Nature's ability to supply those in the aggregate and show that even "reasoned reproductive decisions at the individual level can result in collective failure." Their analysis thus exposes weaknesses of family planning interventions when they are based entirely on individuals' reproductive rights.

If there is one report, or book, that brought the debate about LtG into the public spotlight it is *Limits to Growth* (Meadows et al., 1972). This report, updated with similar conclusions twice (Meadows et al., 1992; Meadows and Randers, 2012), predicts that continuing "business as usual" will result in a collapse of the global order by the middle of the 21st century.[16] The reports are heavily criticized by economists for a variety of reasons, of which the most important ones are that the World3 model in Meadows et al. (1972) rules out technological change and substitution possibilities between abundant inputs and scarce resources.[17] Yet, using data from 1970 to 2000, Turner (2008) compares three scenarios from the LtG report[18] with reality and finds that its predictions, especially for the business-as-usual scenario, have largely held up. Gordon (2012), looking at growth from a historical perspective, suggests that the "rapid progress made over the past 250 years could well be a unique episode in human history, rather than a guarantee of endless future advance at the same rate". He identifies "six headwinds" that could slow economic growth, one of which are energy and environmental concerns. Interestingly, however, he suggests that the standard of living may still increase, albeit at a slower pace.

Georgescu-Roegen, as mentioned, backed many of his arguments by the laws of thermodynamics and hence implied that economic growth must inevitably lead to environmental degradation. Such views are echoed by other ecological economists, which, while overlapping in many ways, can be grouped into three categories (Kallis et al., 2012): (1) steady-state economics (Daly, 1973, 1997*a*, 2017), (2) new economics of prosperity (Jackson, 2016), and (3) de-growth (Latouche, 2009; Martínez-Alier et al., 2010).

Daly argues for a steady-state economy (we must replace ""more is better" with the sounder axiom that "enough is best"") and says that there must be a constant physical stock of capital assets capable of being maintained by a rate of material throughput that always lies within the regenerative capacities of the ecosystem (Daly, 1973). Prosperity advocates emphasize four principles that provide the foundations for a transformation: enterprise as service, work as participation, investment as a commitment to the future, and money as a social good (Jackson, 2016). De-growth,

[16] Schumacher (1973) and Mishan and Mishan (1967) make similar arguments.

[17] See Nordhaus et al. (1992) for a more extensive criticism.

[18] The three scenarios are: the "standard run" scenario (business-as-usual), the "comprehensive technology" scenario, and the "stabilized world" scenario.

represents a "society built on quality rather than on quantity, on cooperation rather than on competition [...] humanity liberated from economism for which social justice is the objective" (Latouche, 2003). At first sight, the three categories sound very similar, but, while overlapping, they are very distinct. Yet, they all face one dilemma: while "de-growth" may be needed for the environment, "de-growth" also leads to mass unemployment and a plethora of other problems. Proposals such as universal basic income serve as a possible solution to at least some of these problems.

3.4 The Environmental Kuznets Curve

The Environmental Kuznets Curve (EKC) posits that economic growth at first harms the environment, but in the long-run is good for the environment. It was proposed by Grossman and Krueger (1991) and is based on the Kuznets curve, which describes a similar relationship between economic growth and inequality (Kuznets, 1955). There is an important distinction between the EKC and the LtG debate: the EKC literature asks whether economic growth can lead to environmental improvements while the LtG literature asks whether the environment will impose limits to growth (Bowen and Hepburn, 2012). The two are not mutually exclusive.

The theoretical literature on the EKC is scarce. In an early theoretical contribution, Stokey (1998) argues that utility from consumption with diminishing returns increases more rapidly than utility from environmental quality with increasing returns, implying an EKC as income increases over time. A more recent theoretical contribution is Copeland and Taylor (2013), who base their analysis on their theory of the relationship between trade and the environment. They provide four explanations for the EKC: (1) a "sources of growth" explanation, implying that some factors that cause growth are good for the environment (e.g. human capital) while others are bad (e.g. physical capital accumulation); (2) a "policy response" explanation, implying that if the "income elasticity of marginal damage rises with income, then pollution can first rise and then fall with neutral growth"; (3) a "threshold" explanation, implying that there is a threshold that limits the responsiveness of pollution policy to income gains at low income levels; and (4) an "increasing returns to scale in the abatement technology" explanation, implying that the EKC can arise from the increasing scale of production.

The empirical literature on the EKC turns out to be very confused. In general, it seems that the relationship holds for individual pollutants but not for the environment as a whole (Ekins, 2002), though even this is not always true. Grossman and Krueger (1991), analyzing the merits of NAFTA, show that there is a negative relationship between air quality and income up to a GDP per capita of about $5,000, whereas the relationship turns positive afterwards. Yet, for some pollutants the relationship looks more "N-shaped" than inverse U-shaped. In a later study, Grossman and Krueger (1995) refined their econometric analysis to a GLS model to correct for heteroskedasticity and autocorrelation and support their initial findings for most of the pollutants in their study. Cole et al. (1997) find similar findings, however, they stress that the EKC relationship only seems to hold for local pollution levels, and not global ones.

Other studies have questioned the relationship. Caviglia-Harris et al. (2009), instead of using one or more pollutants as a measure of environmental quality, use an aggregate index of environmental degradation called the Ecological Footprint and find no evidence of a EKC relationship. Reviews of the literature by Dasgupta et al. (2002) and Stern (2004) also suggest that there is no EKC relationship in the data. Stern

(2004) furthermore criticizes the robustness of some of the “pro EKC”-findings, pointing to heteroskedasticity, simultaneity, omitted variable bias, and cointegration issues.

3.5 Green Growth

Green growth supposes that the economy can keep growing while being environmentally friendly (“sustainable”) at the same time. For the purposes of this review, green growth is defined in the same way as sustainable growth. The appeal by economists to green growth falls into the concept of decoupling. Relative decoupling “refers to any decline in the material intensity (or the emission intensity) of economic output. It signals an improvement in the efficiency of the economy, but it doesn’t necessarily mean we’re using fewer materials overall. Absolute decoupling refers to the situation when resource use (or emission intensity) declines in absolute terms, even as economic output continues to rise” (Jackson, 2016).

A key question is whether natural and man-made capital are substitutes or complements. If substitutes, then environmental harm can be overcome by investments into physical and human capital and technological change; if complements, “then protecting the environment is necessary to maintain economic production” (Hallegatte et al., 2012). Classical economists like Solow (1997), Stiglitz (1997), or Nordhaus and Tobin (1972) tend to argue for the “substitute-camp”, while ecological economists like Daly (1997*b*) and Ayres (2007) argue for the “complement-camp.”

It seems reasonable that the idea that man-made capital and natural capital are perfect substitutes, a sentiment expressed in Solow (1974*a*), is not quite true. For example, there are clearly some services that only natural capital can provide, such as the creation and maintenance of fertile soil or the regulation of global climate (Cleveland and Ruth, 1997). Ecologists also argue that in production natural capital is being transformed while manufactured capital effects this transformation. Hence, they must be complements (Georgescu-Roegen, 1975). A pointed way to put it is that if natural and man-made capital were perfect substitutes, there would be no need for manufactured capital, since a perfect substitute would already exist (Costanza and Daly, 1992).

The complementarity between the two does not necessarily imply that they are not substitutes at all. The potential for substitution, however, depends on the type of substitution (direct vs. indirect and marginal vs. non-marginal); on where the boundaries are drawn (micro vs. macro economy); on the time scale (long vs. short-run); and on the spatial scale (local vs. global).[19] The true answer whether the two are complements or substitutes is therefore likely to be context specific.

When natural capital enters the production function of economists, this implies that production directly depends on natural capital. It is intuitively clear that accounting for “the environment” could result in a break down of the first-best scenario. For example, it could break down due to knowledge spill-overs and economies of scale that lead to under-investments in R&D (Aghion and Howitt, 1990), under-utilization of

[19] Cleveland and Ruth (1997) provide a very detailed analysis of this. For example, “elasticities of substitution between human-made and natural capital calculated for individual processes, firms, or industries may accurately reflect substitution possibilities at those scales. However, they may not accurately reflect possibilities for the economy as a whole because they do not account for the indirect natural capital costs of producing and maintaining manufactured capital.”

production factors in for temporary or structural reasons (Hallegatte et al., 2012), and behavioral biases (Tversky and Shafir, 1992). It follows that to analyze green growth, a second-best framework is needed.[20]

The production function for such a second-best scenario could be as follows (Hallegatte et al., 2012):

$$Y = \psi(P_E)f(A(P_E), K(P_E), L(P_E), E(P_E)) \tag{1}$$

where, A, K, and L, are productivity, capital, and labor, respectively; E represents the environment; ψ measures the efficiency of the production process and lies between 0 and 1. P_E can be thought of as the effort dedicated to environmental policies. There are possible negative and positive effects of policies on final output. Negative effects, for example, are a reduction in productivity which causes producers to use more expensive or less productive technologies. Positive effects can be direct via environmental quality and indirect via the other factors of production, such as labor (i.e. if policies increase worker health conditions, this can translate into increased productivity). Totally differentiating (1) identifies these direct and indirect positive effects:

$$\frac{dY}{dP_E} = \psi' f + \psi[f_A A' + f_K K' + f_L L' + f_E E'] \tag{2}$$

where f_X represent the derivative of $f(.)$ with respect to variable X and X' represents the derivative of X with respect to P_E. $\psi f_E E'$ is the direct benefit from the policy, while $\psi' f$, $\psi f_A A'$, $\psi f_K K'$, $\psi f_L L'$ are the indirect effects. There are thus five channels through which environmental policy positively affects output: its impacts on (1) capital stock ($\psi f_K K'$), (2) labor force ($\psi f_L L'$), (3) natural capital ($\psi f_E E'$), (4) efficiency and demand-led effects ($\psi' f$), and (5) technology and intellectual capital ($\psi f_A A'$).

Ultimately, economists care about welfare and not production. The classical utility maximizing framework can also be extended to include the environment, implying that people derive direct utility from preserving the environment. Assuming that individuals also receive direct utility from environmental policies, an agent then wants to maximize

$$max \int e^{-\rho t} u(C, E, P_E) \tag{3}$$

where C represents consumption, E and P_E are defined as above, and ρ is the discount rate. This equation thus maximizes the discounted utility an agent receives from C, E, and P_E. Once again, policies, P_E can have negative and positive impacts on utility.[21]

Many international institutions and researchers advocate the idea of green growth (EBRD, 2011; ADB, 2014; AfDB, 2013; OECD, 2011; UNEP, 2011; Fay, 2012; Hepburn et al., 2018; Hallegatte et al., 2012; Bowen and Hepburn, 2012; Perez, 2013) and suggest policies to achieve it (Sinn, 2008; Smulders et al., 2014), yet others are still critical (Scrieciu et al., 2013; Jackson, 2016).

[20] A second-best scenario takes into account that a real world economy is far from its optimal (first-best) state. In other words, the idea is to analyze how the framework changes when deviating away from the optimal state that classical economic theory predicts.

[21] Introducing uncertainty does not change the intuition but turns the utility and production function into partly stochastic functions, such as $Y = \psi(P_E)f(A(P_E), K(P_E), L(P_E), E(P_E), \zeta_1)$ and $U = u(C, E, P_E, \zeta_2)$, where ζ_1 and ζ_2 are random variables and $\frac{df}{d\zeta_1} > 0$ and $\frac{df}{d\zeta_2} > 0$. These random variables can represent any shock, including environmental uncertainty, that affects welfare and the economy. A green growth agenda can therefore help reduce the vulnerability of U to ζ_1 and ζ_2 by reducing $\frac{df}{d\zeta_1}$ and $\frac{df}{d\zeta_2}$.

Recent research has examined what countries are best placed to become the leaders of a green economy. Fankhauser et al. (2013) analyze 110 manufacturing sectors in eight countries from 2005 to 2007 and identify three success factors for green competitiveness at the sectoral level: the speed at which sectors convert to green products and processes, their ability to gain and maintain market share, and a favorable starting point. Their findings indicate that the "green race is likely to alter the present competitiveness landscape". Manufacturers in Japan and Germany appear to be best place to "win the green race", while Italy could easily fall behind. Mealy and Teytelboym (2017) construct a Green Complexity Index, confirm and complement the findings of Fankhauser et al. (2013) and suggest that countries that are currently exporting green products are best placed to diversify into more green products in the future.

3.6 The Weightless Economy

For a long time growth models have emphasized the importance of knowledge, for example in the form of R&D. Traditionally, models emphasize supply-side, or production-side, characteristics such as directed technological change. Quah (1999) suggests that it is possible that demand-side characteristics drive technological change and hence affect economic growth.

The intuition is based on the observation that in the last 20-30 years, knowledge-products, such as computer software, new media, electronic databases, and Internet delivery of goods and services, have captured an increasing share of GDP. These products are weightless in that they themselves have the properties of knowledge. Hence, these products reduce "the distance" between consumers and knowledge-based production. "As a result, demand-side factors - consumer attitudes on sophisticated goods, training, education, and skills for consumption (rather than production) - importantly influence patterns of technological development" and economic growth (Quah, 1999).

This suggests that traditional analyses might be missing the source, or at least one of the sources, of growth, which is of obvious importance to sustainable growth. It further emphasizes the importance of having educated consumers in the economy. Taken to the extreme this brings up the question whether it is possible to have growth without relying on natural resources at all. This is related to the feasibility question of decarbonizing our energy systems. Answers to this question are usually modeled in terms of the EKC. One issue is that most studies use domestic production-based greenhouse gas (GHG) emissions data to test whether the EKC holds. This is problematic because national emissions coming from domestic production hide GHG emissions coming from international trade. Mir and Storm (2016) therefore test whether the EKC relationship holds using consumption-based GHG emissions. They find that this is not the case, hence suggesting that there is no such thing as automatic decoupling. Decarbonizing, so they argue, must therefore rely on policy interventions.[22]

[22] Mazzucato et al. (2015) and Grubb (2014) provide examples of such policies. Grubb et al. (2017) point out some flaws in Mir and Storm (2016).

4 Growth from Various Angles

4.1 Macroeconomic Growth without Natural Resources

While growth theory has been on economists' minds for a long time, I here start in the 1950s with the Solow-Swan model (Solow, 1956; Swan, 1956).[23] The production function of the Solow-Swan model is of neoclassical form, usually Cobb-Douglas (Douglas and Cobb, 1928), and brings with it a few key assumptions: (1) constant returns to scale, (2) positive and diminishing marginal returns to each input, (3) positive and smooth elasticity of substitution between inputs. The function, combined with a constant savings rule, generates a general equilibrium model. A key prediction of the model is that, without exogenous technological shocks, economic growth will eventually halt, due to the diminishing returns to capital. Hence, the Solow-Swan model relies on exogenous technological improvements to achieve sustained growth.[24] Given that economies exhibit growth over long periods of time, the dependence on exogenous technical change to explain this is an obvious problem in this model. The Solow-Swan model, which includes labor and capital as its inputs into production, was augmented at various points in time. An important contribution here is Mankiw et al. (1992), who include human capital as a third factor into production and show that their augmented model accounts for about 80 percent of cross-country variation in income.

The classical economic growth model therefore relies on two crucial exogenous factors: the savings rate and technological change.[25] The former was addressed by Koopmans (1965) and Cass (1965), who, building on Ramsey (1928)'s analysis of consumer optimization, endogenize the savings rate. In its entirety, the Ramsey-Koopmans-Cass economy is a Pareto optimal decentralized competitive framework where (input) factors (labor and capital) are paid their marginal share. Crucially, however, the endogenous savings rate does not eliminate the need for exogenous technological change to sustain economic growth.

Endogenizing technological change is more complicated because technology is, at least partly, non-rival (Romer, 1990).[26] This creates issues with the standard constant returns to scale assumption. For example, it seems reasonable to assume that for a given level of technology, doubling the inputs into production doubles economic output. Yet, when technology is endogenized, this constant returns to scale turns into increasing returns to scale, which conflicts with perfect competition.

One way of endogenizing technological change is via the concept of learning by doing (Arrow, 1962; Sheshinski, 1967). The intuition behind learning by doing is that new ideas are an unintended by products of production or investment. These models assume that new ideas instantaneously spill over into the whole economy.[27]

[23]Classical economists like Smith (1776); Ricardo (1817); Malthus (1798) already discussed economic growth. Other early contributions are Ramsey (1928), Young (1928), Knight (1944), Schumpeter (1934), Harrod (1939), and Domar (1946). Solow (1956)'s motivation for writing this paper comes from a critique of the Harrod-Domar model. Barro and Sala-i Martin (2003) provide an in depth overview of economic growth.

[24]Another key prediction is conditional convergence.

[25]The population growth rate is also exogenous. There is a whole literature, which I do not summarize here, that endogenizes this also.

[26]A rival good is one that, when consumed by an agent, cannot be consumed by others. Technology is non-rival in that a new technological invention can, in theory, be used by others immediately as well. Patents, for example, can make technological improvements rival "goods", at least for some time.

[27]The use of the words "new ideas" warrants some clarification: in standard economic models, investments

It took around 20 years for endogenous growth theory to be developed further.[28] Building on the learning by doing models, Romer (1986) shows that the competitive framework can be retained to determine an equilibrium of technological advance. In general, this research (Romer, 1986; Lucas Jr, 1988) argues that some inputs into production, specifically versions of capital such as human capital, do not exhibit diminishing returns to scale. Burnside (1996), for example, argues that this increasing returns to scale assumption is rejected in the data.

The simplest endogenous growth model is the AK model. The AK model assumes that the capital exhibits constant, instead of diminishing, returns to scale.[29] In this model, the economy can sustain a positive growth rate without any technological progress. The simplest version of the model can be combined with optimizing behavior of households and firms to generate endogenous growth with Pareto optimal outcomes.

More fleshed out theories of endogenous growth incorporate R&D theories and imperfect competition into the growth framework. In short, technological progress can come from two sources: an increase in the number of varieties of products (Romer, 1990) or from an increase in quality or productivity of the products (Schumpeterian growth models) (Aghion and Howitt, 1990). The latter is related to a process called "creative destruction" (Schumpeter, 1934), which comes from the assumption that new and improved products replace old ones (i.e. they are perfect substitutes). More general, the idea is that investments into R&D, which exhibit constant returns to scale, result in technological advances. To combat the problem that technology is non-rival, producers investing in R&D are then rewarded with some monopoly power. Hence, as long as new ideas come up, the economy can sustain growth forever. In all these models, the growth rate is not Pareto optimal because of distortions in the creation of new ideas. In these endogenous growth models, the long-run growth rate depends on government policies such as taxation, property rights, regulations of trade and financial markets, and other aspects of the economy.[30]

How technological change, or innovation, comes about is generally very interesting. Schumpeter (1942), for example, sees three stages in the process of innovation: (1) invention, which represents the invention of a new idea, (2) innovation, which occurs when (or if) the new idea/product is commercialized, and (3) diffusion, which represents the stage where the innovation becomes widely available for use and applications for individuals and firms. In the growth models above, R&D refers to the first two stages of this process. Even earlier than that, Hicks (1932) stated his induced innovation hypothesis: "a change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind - directed to economizing the use of a factor which has become relatively expensive."

---

into R&D lead to new ideas and hence (endogenous) technological change. In reality, however, technological change can take other forms as well. For example, when framed more broadly as the evolution of the technological frontier, technological change also encompasses economies of scale. In that sense, building bigger factories to produce cheaper solar panels or batteries falls into technological change, but doesn't really correspond to "new ideas." There seems to be considerable confusion over "new ideas" in economic terms and "systems change" from a systems innovation perspective.

[28] In the 1970s, "growth theory effectively died as an active research field" (Barro and Sala-i Martin, 2003). During that time, macroeconomic research focused on short-term fluctuations, such as business cycles.

[29] Since the assumption of constant returns to scale for capital is quite unrealistic, Barro and Sala-i Martin (2003) suggest thinking of capital in this model to include human and physical capital.

[30] See Aghion and Howitt (1998) for a book on endogenous growth theory.

I here look at two aspects of technological innovation in more detail: directed and biased technological progress (Acemoglu, 1998, 2002) and the diffusion of technological progress (Grossman and Helpman, 1993; Connolly, 1999).[31] For the former, endogenous growth models are extended to show that there are two competing forces determining the relative profitability of types of technological progress: a price and a market size effect. The first creates incentives to develop technologies used in the production of more expensive goods while the latter encourages the development of technologies with larger markets. The two are competing because the prize effect implies that there will be more rapid technological improvements favoring scarce factors while the market size effect creates a force towards technological innovation complementing the abundant factor. The elasticity of substitution between the factors determines the strength of these effects. When the elasticity of substitution is low, scarce factors command higher prices, and the price effect is relatively more powerful. More recent work has analyzed experienced-biased technical change (Caselli, 2015).

The diffusion of new technologies is very hard to model. Classical models tend to model costs to adaption and costs to imitation. These two costs, at the very least, resemble abatement costs and inertia, two important terms in environmental economics. The idea in classical models is that the costs to imitate an innovation are lower than the cost to innovate itself, and that this cost is increasing as the number of innovations "free to imitate" decreases. This results in some form of diminishing returns to imitation, which, similar to the classical Solow-Swan model, creates a type of conditional convergence in income of countries across time. Empirically, Comin et al. (2006), for example, look at 115 technologies in 150 countries over 200 years and show that (a) 91% of technologies are eventually used by all countries, with an average speed of convergence of 3.9% per year and (b) technology appears to converge between OECD and non-OECD countries.[32]

So far, the theory seems to suggest that R&D positively affects the level of technology in an economy. Indeed, Hall et al. (2010) review the econometric literature on measuring the returns to R&D and find that social returns to R&D are higher than private returns, which themselves are already positive and higher than those for ordinal capital. If R&D positively affects the economy, a logical continuation of this is to ask what factors drive R&D. A simple answer to this could be that the high returns to R&D are incentive enough for people, businesses, and governments to invest in it.

Two other channels that the literature has emphasized are strong patent rights and competition. For the first, the idea is that strong patent rights incentivize R&D though the prospect of firms obtaining monopoly rights in the future (Romer, 1990; Aghion and Howitt, 1998). This arguably logical intuition has, however, been refuted empirically (Sakakibara and Branstetter, 1999; Qian, 2007; Lerner, 2009). For the second, standard economic intuition suggests that increased competition reduces monopoly rents, thus reducing innovation as R&D spending becomes less appealing. This is contrary to empirical studies on the link between competition increasing reforms and higher R&D spending (Griffith et al., 2010). Bridging theory and empirical evidence, Aghion et al.

[31] Grossman and Helpman (1993) (chapters 11 and 12) look at diffusion along the lines of an increase in the variety of the products whereas Connolly (1999) looks at diffusion along the lines of an increase in the quality of products.

[32] Another strand of the literature not mentioned here attempts to predict technological change. Famous "laws" for such predictions are Moore (1965) and Wright (1936). See Nagy et al. (2013), Magee et al. (2016) and Farmer and Lafond (2016) for an analysis of these, and other, laws.

(2005) show that in the UK there is an inverted U-shaped relationship between product market competition and innovation. Aghion, Akcigit and Howitt (2014) combine the two channels and suggest that competition increasing reforms and strong patent rights together can increase innovation.

More recent research suggests that new ideas are getting harder to find. Economic growth, as is now clear, results from technological progress, which can be equated to people finding new ideas. Bloom et al. (2017) find that the declining research productivity must be offset by an ever larger number of researchers to still sustain economic growth, thus implying that good ideas are getting harder to find. Other recent work has focused on artificial intelligence's effect on growth (Aghion et al., 2017) and the effect of the "fourth industrial revolution" (Schwab, 2017) on unemployment and economic growth (Acemoglu and Restrepo, 2018, 2017).[33]

Closely entangled with technological progress are studies of productivity, or the measurement of productivity (OECD, 2001; Feng and Serletis, 2008). There are four ways of measuring productivity: the growth accounting approach, the index number approach, the distance function approach, and the econometric approach.[34] The most popular approach is growth accounting, introduced by Solow (1957) and extended in Barro (1999).[35] Conceptually, the growth accounting framework divides income into two parts: the factors into production and a residual. Since income and the factors of production can be measured, the residual can be "backed out". This "measure of our ignorance" is usually attributed to technological change and is conventionally called total factor productivity (TFP). To see this, suppose the production function is

$$Y_t = A_t f(K_t, L_t) \tag{4}$$

where Y_t, A_t, K_t, and L_t are output, TFP, capital, and labor at time t. Differentiate (4) with respect to time and divide the result by Y:

$$\frac{\dot{Y}}{Y} = \frac{\dot{A}}{A} + A\frac{\partial f}{\partial K}\frac{\dot{K}}{Y} + A\frac{\partial f}{\partial L}\frac{\dot{L}}{Y} \tag{5}$$

where dots represent the partial derivative with respect to time. Noticing that $\frac{\dot{X}}{X}$, for any variable X, represents its growth rate, (5) can be re-written as

$$g_Y = g_A + \alpha_K g_K + \alpha_L g_L \tag{6}$$

where g represents the growth rates and α_K and α_L are the elasticity of output with respect to capital and labor. (6) can be solved for g_A and hence, with data for g_y, g_K, and g_L the residual can be backed out.

Recent growth accounting reviews (Caselli, 2005; Hulten, 2010) confirm the importance of technological progress as a major driver of economic growth. Similarly, Smets and Wouters (2007) and Anzoategui et al. (2016) suggest that technological change is an important driver of aggregate flucturations and long-run economic growth. Other

[33]More broadly, Jones (2016) presents a very good overview of the facts of economic growth. Also of importance in growth theory are stylized facts. See Kaldor (1961) for the "original" stylized facts and Jones and Romer (2010) for an "updated version".

[34]See Mawson et al. (2003) or Feng and Serletis (2008) for a description of each of these.

[35]For some early empirical assessments, see Basu and Fernald (1995); Bruno (1978); Jorgenson and Griliches (1967).

studies take this further and emphasize the importance of incentives structures in the adoption of new technologies (Crafts, 2010).

The growth accounting framework implicitly assumes that the residual (TFP) equals technological change, i.e. that the Solow residual "measures technology." This is problematic in that it is possible that the residual represents factors other than technology also. For example, research shows that labor hoarding is responsible for around half of the variance of exogenous technology shocks (Burnside et al., 1993) and that TFP includes variations in capacity utilization (Basu, 1995). Two other ways of "measuring technology" are in terms of technology diffusion (Comin and Mestieri, 2014) or in terms of learning curves (Nordhaus, 2009*b*; Lafond et al., 2018), though the latter approach has been criticized extensively.

The Lucas critique (Lucas, 1976) essentially argued that sound macroeconomic models should be based on microeconomic foundations. Shortly after, Kydland and Prescott (1982) introduced their real business cycle theory, which explains fluctuations around the growth trend based on technological shocks to productivity. Importantly, the model introduces uncertainty and is based on micro-foundations: individuals choose consumption and leisure and, in the model are represented by a representative agent.

This representative agent assumption was eventually relaxed and heterogenous agent models were introduced. Amongst many, heterogeneity can occur in age (OLG models), in preferences (risk sharing), in abilities (job market), and in policies (progressive marginal tax rates). Three seminal contributions here are Huggett (1993), Aiyagari (1994), and Krusell and Smith (1998). In all these models, agents are ex ante homogeneous and ex post heterogeneous and face some uninsurable (idiosyncratic) risk. In Huggett (1993) the risk comes from exogenous endowment shocks, whereas Aiyagari (1994) introduces production and "endogenizes" the idiosyncratic risk to labor shocks. Krusell and Smith (1998) introduce aggregate shocks. For our purposes, the main asset of these models is their ability to model heterogeneous agents while remaining in a dynamic stochastic general equilibrium (DSGE) framework.[36]

A drawback of DSGE models is that they "only" capture the log-linearized dynamics around the steady state. Furthermore, they are in discrete-time (contrary to early growth models, such as the Solow-model). In order to address this, continuous-time models have recently been introduced (Brunnermeier and Sannikov, 2016). The main asset of these models is their ability to capture the whole endogenous risk dynamics, as opposed to just studying individual adverse shocks.

Another class of models are agent-based models (ABMs). While these are no general equilibrium models, they simulate the economy as an interaction of heterogeneous, boundedly rational agents who act largely in their own interests. Typically, behaviors are solved numerically at the agent level, one behavior at a time. While DSGE models have been extended to the heterogeneous framework, ABMs take this heterogeneity one

[36]Some recent work creates heterogeneous agent New Keynesian DSGE models, in which more than one type of equilibrium is present (Ravn and Sterk, 2016). Heterogenous agent models have also been applied to inequality issues. Krueger and Perri (2006), for example, develop an incomplete markets model to show that an increase in the volatility of income leads to a smaller increase (and sometimes even a decrease) in consumption inequality. In regard to inequality, the most famous (empirical) contribution is probably Piketty (2014), who argues that a high growth rate, amongst other things, is a solution to the inequality issue. This, as I show below, is something non-economists disagree with. Other important work on inequality and intergenerational mobility is, for example, Chetty, Hendren, Kline and Saez (2014) and Chetty, Hendren, Kline, Saez and Turner (2014).

step further. This allows for some non-rational behavior for consumers. A downside of ABMs is that they are not in a general equilibrium framework.

While ABMs are widely used in the sciences, economics has not yet picked up on the trend even though some do advocate them (Tesfatsion, 2002; Haldane and Turrell, 2018). In general, DSGE models and ABMs complement one another nicely. DSGE models are well-suited to analyze equilibrium fluctuations and usually rely on linear approximations; ABMs are useful in situation where aggregate behavior is likely to be fat-tailed and can incorporate non-linearities. Both types of models can incorporate uncertainties, risks, and heterogeneity. Continuous-time models also model fat-tails of economic variables and also incorporate non-linearities. An advantage of these models over ABMs is that they are tractable and stay in a general equilibrium framework.

Alongside all of these developments, a separate literature investigating the role of institutions as a determinant of economic growth emerged. This literature shows that the quality of institutions, which are persistent over time, is of great importance in explaining a country's income and consumption level, for example (Acemoglu et al., 2001; Dell, 2010; Michalopoulos and Papaioannou, 2013). A more recent literature also emphasizes the role of cultural norms in economic development (Tabellini, 2008; Alesina and Giuliano, 2015). This suggests that a transition to a successful "sustainable" economy will to a large extent also be dependent upon how well its institutions function.

4.1.1 Microeconomic Foundations in Macroeconomic Models

Macroeconomic models include micro-foundations. Many assumptions of these micro-foundations are criticized. The aim here is to shortly address two criticisms: rationality and fixed preferences.[37]

The most criticized assumption is the rationality assumption. While there are situations where the rationality assumption serves as a good approximation, it is clear to most economists that it is at best incomplete. A whole field called behavioral economics has emerged to address this. One of the most famous contributions is *Prospect Theory* by Kahneman and Tversky (1979). This theory criticizes the classical expected utility framework and suggests that people make decisions based on the potential value of losses and gains. Further work, for example, emphasizes the use of "nudges" (Thaler and Sunstein, 2008) or analyzes bounded rationality (Spiegler, 2011).

Another criticism is that preferences of consumers are fixed. While this is again a fair criticism, recent work has also addressed this. Kőszegi and Rabin (2006) develop a model of reference-dependent preferences. Broadly speaking, this combines prospect theory with rational choice to allow for changes in people's preferences. This work has been used in job search models, empirically (DellaVigna et al., 2017) and theoretically (Eliaz and Spiegler, 2014). Other work, for example, has analyzed intergenerational preference transmission (Doepke and Zilibotti, 2008, 2017). Further criticism addresses that the "society" (social norms and beliefs) and policies are also likely to have an effect on people's preferences (Fehr and Hoff, 2011; Mattauch and Hepburn, 2016). Empirically this has been proven to be the case in various instances (Bowles, 1998; Sunstein, 2015), yet theoretically, this has not been looked at to my knowledge. Normative and welfare-theoretic aspects of preferences formation have rarely been explored too

[37]A complete review of microeconomic advances in recent years is out of the scope of this paper. The aim is to address some, albeit not even close to all, advances in regard to these two criticisms.

(exceptions are von Weizsäcker (2005); Bar-Gill and Fershtman (2005); Binder (2010)).

In terms of macroeconomics, all these advances are "useless" if they are not incorporated into macroeconomic models. Yet, even this has started to happen: for example, Woodford (2013), Farhi and Gabaix (2015), and Farhi and Werning (2017) introduce behavioral foundations into macro models.

Macroeconomics is often criticized for its use of homo economicus, complete markets, complete information, competitive behavior of all firms and consumers, and perfect foresight. While early models certainly did rely on these abstractions, I hope that this subsection has clarified that economics has moved onto much more realistic assumptions and provides useful tools for sustainable growth issues.

4.2 Macroeconomic Growth with Natural Resources

Hotelling (1931) creates a simple model where an agent decides whether to extract a finite resource or not in an economy with no technological progress. He establishes the "Hotelling rule", which states that the price of an exhaustible resource must grow at a rate equal to the rate of interest, both along an efficient extraction path and in a competitive resource industry equilibrium. Since the agent lives off of a finite resource, she is doomed to an eventual decline.

Dasgupta and Heal (1974), Solow (1974*a*), and Stiglitz (1974) extend the Hotelling model to incorporate labor supply and savings decisions as well as exogenous technological change. In general, these models identify three forces with the ability to offset the limitations imposed by natural resources: substitution possibilities with man-made capital, technological progress, and returns to scale. In all models, one conclusion is that output need not necessarily decline. This result depends either on a high elasticity of substitution between reproducible inputs and exhaustible resources (Dasgupta and Heal, 1974) or on two offsetting forces, namely technological progress and capital accumulation (Stiglitz, 1974). Stiglitz argues that even "with no technical change, capital accumulation can offset the effect of the declining inputs of natural resources, so long as capital is "more important" than natural resources, i.e. the share of capital is greater than that of natural resources." With technical change, the same result is even easier to find. Stiglitz further argues that under more stringent conditions on technological change[38], his model can sustain a constant per capita consumption path.

Dasgupta and Heal (1974) furthermore differentiate between essential and inessential exhaustible resources. They argue that a "resource is essential if output of final consumption goods is nil in the absence of the resource. Otherwise, it is called inessential." Whether a resource is essential or not depends on the elasticity of substitution between the two (a low elasticity of substitution implies that the resource is essential). An important point here is that an essential exhaustible resource may become inessential after the introduction of a new technology.[39]

The early endogenous growth model by Romer (1986) relies on the fact that learning by doing (i.e. technological process) immediately spills over into the economy. Introducing pollution into this model would result in negative externalities and hence would

[38]The condition is "that the ratio of the rate of technical change to the rate of population growth [be] greater than or equal to the share of natural resources" (Proposition 4).

[39]Two other useful references for "early" growth theory and natural resources or the climate are Dasgupta and Heal (1979) and Nordhaus (1977).

rival the positive externalities from learning by doing. Michel and Rotillon (1995), asking which of the two effects is stronger, show that unlimited growth is possible, but that this implies unlimited pollution since pollution is taken to be proportional to production. When looking at the social optimum, however, they show that the social optimum "consists in a trajectory towards a steady state with finite levels in consumption and pollution and a zero long-run growth rate." This is because taking into account both types of externalities strongly depresses economic growth.

Further work by Stokey (1998) analyzes pollution in an AK model, provides, as I have shown, a theoretical basis for the EKC, asks whether growth will eventually cease, and investigates the problem of implementing the optimal path in a decentralized economy. Sustained growth in the AK model, she shows, is not optimal in the presence of pollution because as the capital stock grows, society imposes ever stricter emissions standards, reducing the rate of return on capital. When the rate of return gets low enough, there is no incentive for further accumulation.[40] She finds that tax and voucher schemes can implement the optimal path in a decentralized setting, while direct regulation cannot.[41] Aghion and Howitt (1998) transpose Stokey's analysis of (un)limited growth to a Schumpeterian model and show that her conclusion may not hold when environmentally friendly innovations are possible. Grimaud (1999) extends this to include her analysis of the optimal path in a decentralized setting and describes a trade-off between the stringency of environmental policies and economic growth. More recently, Jones (2009), in a simple OLG and a more complex endogenous growth model, shows that incorporating environmental issues into the growth framework has first order consequences.[42]

The literature on the effect of environmental policies on technological progress can be grouped into two broad categories: 'equilibrium-optimization' theories and 'non-equilibrium-simulation' theories (Mercure et al., 2016). In the first, rational innovators adopt rent maximizing behaviors under specific institutional and policy frameworks. A policy, which corrects some market failure, is always costly as long as the externality has not been internalized into the agent's decision. The latter theories emphasize that economies are dynamic systems in constant change shaped by institutions and history. They do not have an 'ideal' equilibrium and the role of policy is to "intervene in processes to promote a better outcome or new economic trajectory" (Mercure et al., 2016). Economists, of course, have focused on the first. Generally, the effect of environmental policies on technological change can be analyzed by looking at the effect of alternative instruments on the rate and direction of relevant technological change and by looking at whether such policies result in economic efficiency (Jaffe et al., 2002). The obvi-

[40] She also analyzes this question in two models with exogenous technological change and finds that sustained growth is optimal there.

[41] The intuition is as follows: "The production technology can be written with capital and the total level of pollution as inputs. If pollution is regulated using a tax or a voucher system, then these two inputs are priced separately: the right to pollute has a market price that is entirely distinct from the rental rate for capital. Thus, the market return to capital measures the return on that input alone, and this price correctly guides savings decisions. By contrast, under direct regulation, ownership of a unit of capital confers the right to emit some pollution. Thus, the rental price of capital is the sum of the return to the capital itself and the implicit price of the pollution rights that accompany it. The bundled price, which exceeds the true return to capital, leads to excessive saving."

[42] Sustained growth is still possible as long as the preference parameter is between 0 and 1. The evidence on this is mixed.

ous market failure that policies are supposed to correct for are externalities associated with environmental pollution, however, research also emphasizes a second market failure, namely the failure associated with the invention, innovation, and diffusion of new technologies (Jaffe et al., 2005).

Endogenous growth models have been used to analyze the link between economic growth and environmental policies (Bovenberg and Smulders, 1995, 1996). Findings indicate that the effects of a tighter environmental policy depend on whether the environmental benefits accrue in the form of a public consumption good (i.e. in the form of amenities) or in the form of a public production factor (i.e. in the form of increase productivity in production). If the former, a tighter environmental policy reduces growth in the short- and the long-run (i.e. society faces a trade-off between more consumption goods and the quality of the environment); if the latter, a tighter environmental policy decreases short-run growth but increases long-run growth. Recent work indicates that public R&D is not synonymous with innovation and that there is no "silver bullet" technology that will solve all environmental issues we face (Grubb, 2004). Gerlagh et al. (2009) furthermore emphasize that the timing of the optimal emission reduction policy depends on the set of policy instruments available.

While both, energy prices and government regulation affect energy efficiency, other forces are also important (Newell et al., 1999). Popp (2002) shows that energy prices have a strong positive impact on new innovations in energy technology and that the reaction time to energy prices is short. Aghion et al. (2016) extend this by showing that higher fuel prices induce firms to redirect technical change away from "dirty" innovations towards "green" innovations. These findings are suggestive evidence for directed technical change, a finding confirmed by Hassler et al. (2012) who argue that the "economy directs its R&D efforts to save on inputs that are scarce, or expensive, and away from others." Furthermore, Bettencourt et al. (2013) show that global patenting trends in energy technologies are a function of R&D funding and market scales.[43]

The importance of directed technological change is further emphasized by Acemoglu et al. (2012). This work, emphasizing the price effect and the market size (see Acemoglu (1998, 2002)), suggests that sustained growth is possible as long as government policies redirect technical change away from "dirty" industries towards "cleaner" ones.[44] Hassler et al. (2012) suggest that not only sustained growth is possible, but even positive consumption growth over time.[45] Empirically, Calel and Dechezlepretre (2016) test whether the introduction of the EU Emissions Trading System (ETS) has induced incentives for technological change. They do so by exploiting the fact that the EU ETS only covers large installations, thus providing a nice discontinuity in installation-level inclusion among firms of similar sizes. Their estimates suggest that, while low-carbon patenting has increased substantially amongst EU ETS firms since 2005 (almost 10%), the overall effect is modest: only 2% of the post-2005 surge in low-carbon patenting can be attributed to the EU ETS.

Intertwined with directed technological change is the fact that technological progress is path dependent (Aghion, Hepburn, Teytelboym and Zenghelis, 2014). Path dependence in clean technology arises because of network effects and high switching costs.

[43] Popp et al. (2010) provide a good overview of the literature of energy induced technological change.

[44] Pottier et al. (2014) argue that the model, when calibrated more realistically, leads to opposite policy recommendations.

[45] Another interesting reference is Hassler et al. (2010), who investigate the oil market in detail.

An important implication of this path dependency is that, coupled with system inertia, the costs of delaying policies that redirect policies towards environmentally friendly technologies increase in the future. Aghion et al. (2016) show that a “firm’s propensity to innovate in clean technologies [is] stimulated by its own past history of clean innovations (and vice versa for dirty technologies).” More recently, Van der Meijden and Smulders (2017) show that in a model with two equilibria (based on observation that expectations about future energy supply technologies may not only affect the time path of fossil fuel supply but also the direction of technical progress), expectations about future energy use determine which equilibrium arises and hence can influence the transition to a low carbon economy. This suggests a possible “carbon lock-in”.

A paradox in regard to energy policies is that the diffusion of apparently cost-effective energy-conserving technologies is very slow (Jaffe and Stavins, 1994). The paradox, it turns out, can be explained by market failures, such as information problems, as well as explanations that do not represent market failures, such as high discount rates and heterogeneity amongst future adopters. This plays into issues of inertia and abatement costs. Ideas about inertia and abatement costs come out of criticisms of growth models with autonomous (exogenous) technological change that emphasize the importance of induced technical change (Grubb et al., 1995). Two early contributions are Grubb et al. (1994) and Goulder and Schneider (1999). Grubb et al. apply a simple model that solves for the optimal degree of GHG abatement under alternative specifications regarding induced technical change. Goulders and Schneider extend this by explicitly considering the connection between policy initiatives, the demand for and supply of R&D, and the rate of technological change and employing “a disaggregated general equilibrium framework in which the production decisions of various industries are identified and linked through market interactions.” This set-up allows them to analyze whether policies oriented towards one industry affect R&D incentives in other industries. They find that this is indeed the case. More recently, Vogt-Schilb et al. (2018) study the optimal timing, cost, and sectoral allocation of abatement investment. In their model, abatement “investment reduces emissions and transmits abatement capital to the future.” The value of abatement therefore depends on the carbon price and the value of abatement capital in the future. The former is the same in all sectors while the latter is greater in sectors facing higher emissions or higher adjustment costs. This results in a bell-shaped optimal abatement profile. Grubb, Mercure, Salas, Lange and Sognnaes (2018) build a model attempting to characterize learning associated with investment together with inertia. Their model models pliability, which they define as the tension between the adaptability and inertia of the system. They show that an adaptive emitting system, “in which costs decline in response to learning and infrastructure investments, can greatly lower the overall costs associated with climate change.”

If growth is to be sustainable, it is important to understand the relationship between natural resources and productivity. The first oil crisis in the early 1970s incentivized scholars to analyze the relationship between energy prices, efficiency and consumption, productivity (TFP) and economic growth (Berndt, 1980; Schurr and Netschert, 1960; Schurr, 1984*a*,*b*; Jorgenson, 1984; Beaudreau, 1995; Berndt and Wood, 1975) via the “classical” (Solow-like) growth accounting framework, but also by calculating energy intensities via input-output matrices (Hannon et al., 1983). Soon researchers attempted to extend this framework to directly account for raw materials, in addition to energy and other inputs. This led to the use of capital, labor, energy, and materials (KLEM) and capital, labor, energy, materials, and services (KLEMS) production functions (Berndt and Khaled, 1979). More recently, Baptist and Hepburn (2013) investigate the relationship between intermediate inputs and productivity more thoroughly.[46] Using a gross-output production function approach as opposed to a value-added approach[47], they show that low intermediate input intensity is associated with high productivity (TFP) measurements across sub-sectors in the US from 1958 to 2005. This suggests that sectors using more labor and capital and less intermediate inputs, and with this less raw materials, have higher measurements of productivity.

Alongside all of these developments, a literature countering the "institutions"-literature emerged that argues that trade, health, and soil productivity are important characteristics in explaining economic development and growth (Sachs et al., 2001; Sachs and Malaney, 2002). Underlying these claims is the argument that geography, in addition to institutional quality, is an important determinant for growth. Chichilnisky (1994) shows how ill-defined property rights on environmental resources affect trade.

4.2.1 Modeling the Climate: From IAMs to DSGE Models and ABMs

To integrate climate change into economic models and estimate, for example, the optimal price of carbon, economists make use of Integrated Assessment Models (IAMs). The most famous IAM is the dynamic integrate climate-economy (DICE) model, introduced by Nordhaus (1993), which extends the static first attempt at a cost-benefit analysis of policies to abate GHG emissions (Nordhaus, 1991). The model was updated at various points in time (Nordhaus and Boyer, 2000; Nordhaus, 2014), but at its core has remained the same: a Ramsey-Koopmans-Cass model of economic growth with an optimal steady state as well as an optimal transition path, extended to include a carbon cycle, a set of climate equations mapping atmospheric carbon into the atmosphere, and an energy sector. Importantly, technological change is assumed to be exogenous. The policy recommendation from the DICE model is a "climate policy ramp", indicating that emissions controls should increase over time.

The DICE model has been extended at various points in time: for example Nordhaus and Yang (1996) introduce RICE, a regionally disaggregated version of DICE. The main purpose behind the DICE and RICE models is to provide a transparent mechanism that links the climate and the economy, hence, providing useful theoretical insights relevant for policy design (Nordhaus and Boyer, 2000).

Dennig et al. (2015) extend the RICE model to incorporate within region and country inequality and call their Nested Inequalities Climate-Economy model NICE. The model shows that net consumption of the poor indeed declines, exhibiting a different pattern than that of average consumption in some regions; and that is despite adopting the model's suggestion of the optimal policy. Moreover, Popp (2004) endogenizes technological change in the DICE model in a new model called ENTICE. More recently,

[46]Intermediate inputs are defined as the sum of the real value of physical intermediate inputs, energy and purchased services. They focus on intermediate inputs instead of raw materials because of data limitations.

[47]The value-added approach is the traditional way of measuring total output. It is defined as total output minus the cost of raw materials, energy, and other intermediate inputs. Gross output is total output where the cost of raw materials (etc.) is not subtracted. Value-added calculations are useful for economy-wide analyses whereas gross-output calculations allow researchers to account for heterogeneity in intermediate input intensity and productivity across economic sectors. See Baptist and Hepburn (2013) for a more detailed discussion of this.

Dietz and Stern (2015) show that when changing three assumptions of the DICE model - endogenizing technological change, assuming convexity of damage and climate risk - the policy recommendations change drastically.

IAMs can be grouped into two broad categories: policy optimization models (POMs) and policy evaluation models (PEMs). The former conduct an economy-wide analysis of mitigation policies while the latter analyzes a specific mitigation target with a given policy. More generally, all IAMs have two components: an economic component and a physical component. The economic component is modeled as a representative agent making investment decisions while the physical component is modeled as a temperature increase as emissions accumulate in the atmosphere. "POMs have a third important component that PEMs lack: the damage function" (Farmer et al., 2015).[48]

IAMs are heavily criticized (Weitzman, 2013; Stern, 2013; Pindyck, 2013). Four main shortcomings of IAMs concern micro-founded neoclassical models, uncertainty, aggregation and distributional issues, technological change, and the damage function (Farmer et al., 2015).

Uncertainty and the damage function, along with issues of discounting, are of such importance that they are discussed separately in section 4.2.2. Aggregation issues mainly concern issues with the representative agent framework, which are documented elsewhere in more detail (see, for example, Kirman (1992)). For example, it is a well-known fact that individual rationality does not imply aggregate rationality. In regard to technology, an obvious shortcoming of early IAMs is the assumption of exogenous technological change. While this assumption has been relaxed in some models, the complexities governing the relationship between technological change and environmental policies have yet to be modeled in more detail.

Tackling the problem of climate change requires a global, dynamic, and equilibrium perspective. Hassler and Krusell (2012) elaborate on the need to integrate the climate into a modern macroeconomic setting - one that involves a fully micro-founded model. As such, DSGE models seem well equipped to contribute to the debate on how to best tackle the problem. Golosov et al. (2014) develop such an analytically tractable DSGE model that models the energy sector with a linear impulse response function of economic production to carbon emissions. Relying on four assumptions[49], their model provides an analytical solution to the optimal carbon tax problem that shows that only the discounting, damages, and carbon depreciation parameters matter for the externality costs of carbon emissions. The optimal per-unit tax on emissions is therefore equal to the marginal externality cost of emissions. This outcome implies that there is no use for very high tax rates until we know that damages will be very high. They find that the marginal externality damage cost is \$56.90 per ton of carbon with a discount rate of 1.5% (à la Nordhaus (1993)), but \$496 per ton of carbon with a discount rate of 0.1% (à la Stern (2007)). Nevertheless, the authors confirm the effectiveness of carbon taxes in mitigating climate change as coal use is twice as large in the laissez-faire market scenario (i.e. scenario with no carbon taxes introduced) as in the optimal outcome scenario (i.e. scenario with optimal carbon tax introduced). Moreover, when analyzing the damage elasticity - the percentage loss in GDP with

[48] See Farmer et al. (2015) for a more detailed overview of this and the many more IAMs that exist.

[49] (1) Period utility is logarithmic in consumption; (2) current climate damages are proportional to output and are a function of the current atmospheric carbon concentration with a constant elasticity; (3) the stock of carbon in the atmosphere is linear in the past and current energy use; and (4) the savings rate is constant.

every extra unit of carbon in the atmosphere - economic damages are estimated at 10% of GDP in 2200 in the laissez-faire scenario. The magnitude of the economic damages, however, significantly slows down to an estimated 1.4% of GDP by 2200 in the optimally-taxed scenario.

The model was extended twice. First, Hassler and Krusell (2012) expand the model to include regional heterogeneity by lumping the world into four regions (US, China, Europe and Africa) and show that there are big differences between the four regions (the US and China want to subsidize oil production while Europe and Africa want taxes on oil) and that the effect of carbon leakage is strong (one region self-imposing taxes on its oil use has only redistributive effects and zero aggregate effects). Second, Traeger (2015) extends the model to a "full" climate model (including temperature dynamics and the "greenhouse effect" on top of the carbon cycle) called GAUVAL. The carbon tax in his model is also independent of the stock of carbon in the atmosphere. He finds the social cost of carbon to be $57per ton of carbon.

While DSGE models account for stochastic uncertainty, ABMs are perhaps better suited to understand the non-deterministic nature of complex socio-technical transitions. Indeed, ABMs have been applied to the climate change problem. The issue with these applications is, however, that the focus of many of these models is too narrow.[50] Three exceptions are the ENGAGE model (Gerst et al., 2013), which combines level 1 ABMs with other levels (see footnote 50), the Lagom regiO model (Wolf et al., 2013), which models the interaction between various economic regions, and the Lamperti et al. (2016) model, which introduces the first agent-based integrated assessment model with feedbacks to the macroeconomy. Hence, while ABMs are intuitively well-suited to model important aspects of the climate change problem within an economics framework, much work remains to be done.[51]

It is no surprise that DSGE models and ABMs present an opportunity to address at least some of these issues. DSGE models, being general equilibrium models, are of course still subject to some assumptions (market clearing, optimality, and agent representativeness), yet, they can incorporate uncertainty into the agent's decision-making problem and can handle more complex technological dynamics. While heterogenous agent DSGE models have been introduced, they have yet to find an application in regard to climate change/sustainable growth. ABMs, being much more flexible, can address all four main issues of IAMs, however, this comes at the cost of tractability and the fact that they are not in a general equilibrium framework. Continuous-time models promise to be able to address many of the issues that ABMs seem well suited to tackle while staying in a general equilibrium framework. They have yet to be applied to the problem of climate change, however.

[50] Gerst et al. (2013) group these models into four categories: level 4 ABMs focus on the diffusion of technologies in a single market with (almost) no feedback to the economy (de Haan et al., 2009; Eppstein et al., 2011; Faber et al., 2010; Mueller and de Haan, 2009; Schwoon, 2006; Sopha et al., 2011; Van Vliet et al., 2010); level 3 ABMs focus on energy use and the electricity market with no macroeconomic feedback (Batten and Grozev, 2006; Conzelmann et al., 2005; Wittmann, 2008; Xu et al., 2008); level 2 ABMs focus on whole economies but neglect technological details (Beckenbach and Briegel, 2011; Janssen and De Vries, 1998; Nannen and van den Bergh, 2010; Robalino and Lempert, 2000); and level 1 ABMs look at interactions between countries and regions, with (almost) no feedback between domestic actors and international policy (Voudouris et al., 2011).

[51] Balint et al. (2017) provides a good and recent overview over climate ABMs.

4.2.2 Discounting, Uncertainties, and the Damage Function

The problem of climate change is a long-term problem. Decisions made today affect not only us but future generations centuries down the line. As such, the discount rate is of obvious importance. In general, economists think about discounting in a utilitarian framework, based on the Ramsey rule (Ramsey, 1928):

$$r = \rho + \sigma g \tag{7}$$

where r is the social rate of discount or the consumption discount rate, ρ the pure rate of time preference, σ the elasticity of marginal utility, and g the rate of growth of consumption. The debate about the discount rate focuses on ρ.

Nowhere has the issue of the discount rate been more clear than in the *Stern Review* (Stern, 2007) and the resulting answer by Nordhaus (2007). Simply put, the same problem with a low (à la Stern) or high (à la Nordhaus) discount rate leads to drastically different policy recommendations. Advocates of a low discount rate generally invoke ethical arguments, saying that the discount rate reflects judgements about the relative values of present and future people (Stern, 2007). Contrary to this, Nordhaus (2007) argues that ρ in (7) can be backed out by observing g, guessing σ, and observing r as the return on capital.

Climate science involves many obvious uncertainties and risks. Modeling these low-probability high-impact events is very difficult. This is exemplified by another answer to the *Stern Review* (Weitzman, 2007) (see also Weitzman (2009)). Weitzman argues that Stern's dire predictions are correct, but for the wrong reason. He argues that standard approaches to climate change fail to account for the "true" consequences of low-probability high-impact events. According to Weitzman the problem of climate change comes down to two questions: how humans cope with severe climate disruptions and whether the risk of such events decline in a thin tail (faster than costs rise) or in a thick tail (slower than costs rise). Arguing for the latter, Weitzman then shows that in such a set-up, cost-benefit analysis fails. He dubbs this the *Dismal Theorem*.[52]

Hassler et al. (2018) focus on uncertainty in an IAM with multiple energy sources. In addition to uncertainty, they look at extreme scenarios defined by the upper and lower bounds of the range of estimates of climate sensitivity and sensitivity of the economy presented in the literature as they claim that uncertainty is likely to be driven by extreme outcomes instead of random fluctuations within the range defined by the upper and lower bounds to evaluate policy errors. The authors conclude that adopting a high tax when climate and economic sensitivities are high does not have immense adverse effects, owing to an effective energy substitution mechanism. However, policy errors from adopting an overly passive carbon policy (i.e. implementing a low tax rate when in fact climate and economic sensitivities are both high) inflicts severe adverse effects on consumption and welfare by not promoting the substitution of coal with green energy.

More generally, this uncertainty is usually represented in economic models via the damage function. Weitzman (2012), for example, defines the damage function as a "reduced form representing global welfare losses from global average temperatures,

[52] Nordhaus (2009*a*) shows that the *Dismal Theorem* does not hold without two assumptions: the use of a CRRA utility function which leads to unbounded negative utility as consumption goes towards zero and the lognormal distribution of the policy multipliers.

which subsumes a staggering amount of regional, seasonal, and even daily weather heterogeneity." A classical damage function is of quadratic form:

$$D(T) = \frac{1}{[1 + \beta_1 T + \beta_2 T^2]} \tag{8}$$

where T denotes the change in (future) temperature and β_1 and β_2 are some temperature parameters. Such a quadratic function is found in the DICE model, for example. Output is then modeled as the product of the neoclassical production function and $D(T)$.

Amongst many, one issue with the damage function is that the parameters are basically guess-work. This is because no one knows what the damage function looks like for very high changes in temperature.[53] Weitzman (2012) shows how this quadratic form of the damage function yields very unrealistic results for changes in temperature of 12 degrees Celsius. To defend the quadratic form approach, scholars there usually assume a more modest increase in temperatures, such as 2 to 4 degrees Celsius. While still no one knows what the damages for such an increase look like, the quadratic form yields somewhat plausible results in these cases. Additionally, there is an established empirical "micro-literature" of the damages coming from climate change. These estimates are virtually ignored in calibrating the damage function (Dell et al., 2014). More recently, Llavador et al. (2015), in their IAM, do not use a damage function but instead incorporate the "damages" into the constraint of their problem. Intuitively, this is similar to introducing a damage function with a strong trade-off between economic activity and the climate at a temperature increase of 2 degrees Celsius (see Heal (2017) for a more detailed discussion).[54]

The Social Cost of Carbon (SCC) "is a measure, in dollars, of the long-term damage done by a ton of carbon dioxide (CO2) emissions in a given year."[55] It is therefore obvious that rigorous SCC estimates, which influence policy, depend on the shape of the damage function and on how these fat-tailed risks are incorporated into models. The sheer hopelessness of getting this right has led some to argue that there will never be an agreement on estimates for the SCC (Pezzey et al., 2018).

4.3 Alternative Approaches to Growth

Pollitt et al. (2010) examine 60 of the most widely used macroeconomic models and find that they fail to provide satisfactory coverage of sustainability policies. What if macroeconomics is ill-equipped to deal with issues of sustainability? Ecologists argue that this is the case and have come up with their own methods of addressing sustainability concerns.[56] A caveat is that my definition of sustainable growth now becomes problematic: ecologists argue that pursuing a one-dimensional concept like income is

[53] Weitzman (2012); Stern (2013); Pindyck (2013) all argue that climate models such as IAMs fail to model damages and risks correctly. Pindyck is especially critical of IAMs, calling them "close to useless."

[54] An examination of damage functions specific to certain models can, for example, be found in Ackerman and Munitz (2012)'s analysis of damages in the FUND model.

[55] Definition taken from an EPA Factsheet about the SCC.

[56] Ecologists are not the only social scientists and non-economists that think that way. However, given the focus on the environment of sustainable growth, they are the biggest field. For simplicity and brevity, and with no disrespect intended, I refer to all non-economists representing this view as ecologists.

"useless" and advocate focusing on multi-dimensional concepts like prosperity. A possibility to keep in mind is therefore that classical macroeconomic models may fail to deliver satisfactory results for sustainable development as a whole but may still provide useful tools for sustainable growth issues.

Ecologists start with the laws of thermodynamics. These, together with the conservation of matter, provide the boundaries within which the economy operates. Energy, they argue, is required in all economic activity and builds a non-reproducible factor of production. It follows that energy is a primary factor into production.

Early models of the production process are based on input-output matrices where the flow of energy is the only primary input into production (Hannon, 1973). An issue with these early models is that they abstract from information. Information about the quality of resources (and the associated energy required to extract the resource) are crucial. Costanza (1980) therefore extends the basic input-output approach to include solar energy and the energy embodied in fuels and other natural resources as net inputs ("embodied energy"). Information about the quality of resources is now embodied in total embodied energy. Yet, if information matters, so should other services provided by nature.

Georgescu-Roegen's fund flow model (Roegen, 1976) comes out of a criticism of the input-output approach (Georgescu-Roegen, 1971, 1986). In the fund-flow model, a flow of primary factors into production (materials, energy, and information - the material cause) is transformed by "funds" (labor and capital - the efficient cause). This, at the very least, implies a limit to substitution possibilities between energy, other materials, and man-made capital. For Daly (1991*a*) this implies that the two are complements.

Insights from ecology have also been incorporated into standard economic growth models. Ayres and Warr (2005) derive a model of endogenous technological change with a production function augmented to include "exergy services".[57] The model, called resource-exergy service (REXS), calculates exergy services from primary energy inputs multiplied by an empirically estimated average energy conversion efficiency, which is a function of technology and time. They then predict output growth and find that their model performs reasonably well until 1975 but diverges with real GDP thereafter. Warr and Ayres (2012) hypothesize and show that information and communications technologies can explain the gap between real GDP growth and the predicted values from the model post 1975. In other words, they confirm the importance of information and communications technologies as drivers of economic growth.

How technological transitions come about is also of great interest to ecologists. There are two views on how technology evolves: (1) evolution is a process of variation, selection, and retention and (2) evolution is a process of unfolding, resulting in paths and trajectories (Geels, 2002). In both views technological transitions are viewed as multi-dimensional processes, as a change from one socio-technical configuration to another. For example, Geels (2002, 2005) identify three levels within such a transition: technical niches, socio-technical regimes, and socio-technical landscapes. Path dependence and inertia also play an very important role in these transitions.

[57] "Exergy is the correct thermodynamic term for available energy or useful energy, or energy capable of performing mechanical, chemical or thermal work. [...] The formal definition of exergy is the maximum work that could theoretically be done by a system as it approaches thermodynamic equilibrium with its surroundings, reversibly. Thus, exergy is effectively equivalent to potential work. There is an important distinction between potential work and actual work [defined as exergy services] done by animals or machines" (Ayres and Warr, 2005).

Furthermore, from a modeling point of view, ecologists view a possible win-win situation (Jaffe et al., 2002). Given the uncertainty of the outcome of R&D investments, a firm will display a satisficing rather than a optimizing behavior (Barnard and Simon, 1947). Firms therefore behave based on rules of thumbs and routines. It is thus possible that a satisficing firm, when deciding whether/how to invest into R&D, rethinks its strategy and finds a more profitable way of operating, creating a situation where pollution is reduced and profits are increased.

Since the financial crisis, a field called ecological macroeconomics has received renewed attention. The aims of ecological macroeconomics can be viewed in terms of the three categories of ecological economics described in section 3.3. In other words, the aim is not to sustain economic growth, but rather to understand how macroeconomics can contribute to a sustainable economy. Recent work has focused on the income distribution and on financial markets (Rezai and Stagl, 2016). In regard to the former, Jackson and Victor (2016), for example, simulate the SIGMA model (a stock-flow consistent model of savings, inequality, and growth in a macro framework) with exogenous growth and savings rates to test Piketty (2014)'s hypothesis that low growth rates lead to rising inequality. Contrary to Piketty's claim they find conditions where declining growth rates actually reduce inequality. In regard to the latter, Jackson and Victor (2015) model financial assets and liabilities into a stock-flow consistent framework and prove that a capitalist economy can sustain a non-growing (stationary) state. Fontana and Sawyer (2016) present a model of endogenous money creation[58] and demand-led growth theory to offer a framework to reconcile the paradox of growth: de-growth is needed for a sustainable economy but de-growth also leads to unemployment and other issues. In general, the importance of finance for a transition to a sustainable economy is emphasized by Jackson (2016).

Other work has used stock-flow consistent modeling to model how multiple sectors, households, government, and financial markets interact with the environment under different policies such as carbon taxes (Naqvi, 2015). Taylor et al. (2016), furthermore present a model that combines biophysical limits in form of GHGs with Post-Keynesian growth theory. Their model suggests that aggregate demand, which in the short-term is an important determinant of economic growth, is itself determined by the distribution of income between profits and wages.

Stock-flow consistent modeling relies on a post-Keynesian theory of growth.[59] It emphasizes the need to account for all monetary stocks and flows as well as financial assets and liabilities (Godley and Lavoie, 2016) and therefore lends itself well to model the multi-dimensional dynamic interactions required for a transition to a sustainable economy (Hardt and O'Neill, 2017). Nonetheless, two important short-comings remain: it is hard to model a comprehensive description of environmental impacts via aggregate physical flows and it is difficult to incorporate feedback channels into the models through which the environment is affected by economic activity.

On the sidelines of these developments, some ecologists have advocated looking at "resilience." Introduced by Holling (1973), the concept, like the word suggests, is the capability of a system to resist or handle disturbances. This is in contradiction with neoclassical macroeconomics, where describing an optimal path is the objective. Rather, resilience advocates emphasize the importance of analyzing (or predicting)

[58]Whether money is supplied endogenously or exogenously is a big debate. See Taylor (2009).

[59]In post-Keynesian theories of growth demand is the main driver of growth.

behavior that slightly deviates from "the optimal path." More recently, the importance of resilience has been stressed by Scheffer et al. (2001) and Folke (2006).

5 The Environment and Economic Growth

5.1 Environmental Shocks and Macroeconomic Outcomes

While it is clear that economic growth affects the environment (for example, by increasing pollution), it is less clear whether environmental shocks also affect economic growth. Environmental shocks can represent almost anything, but I here focus on cyclones (e.g. typhoons, hurricanes). While some studies have found a significant negative effect of cyclones on economic growth (Hsiang and Jina, 2014), others have found the opposite effect (Skidmore and Toya, 2002) (see Kousky (2014) for a recent review). Apart from these contradictory findings, a further issue is that there is a lack of theoretical models trying to reconcile these empirical findings. As already mentioned, the impacts of such environmental shocks are also yet to be included into the damage functions of IAMs.

A recent paper by Bakkensen et al. (2018) (a) presents a framework to address the seemingly disparate empirical evidence, (b) presents an estimation approach to estimate the effect of cyclones on economic growth, and (c) includes the "cyclones effect" into the damage function of the IAM DICE by Nordhaus. To address the first point they develop a stochastic endogenous growth model. They show that the risk of an incoming cyclone can have positive and negative effects: on the one hand, cyclones destroy capital and hence decrease growth, while, on the other hand, higher risk may induce higher precautionary savings, which, all else equal, can increase growth. To facilitate the empirical estimation, they suggest to quantify the effects of cyclones on the structural determinants of economic growth. The implementation of their findings into DICE proceeds in three steps: (i) they estimate cyclone damage functions for TFP, depreciation, and fatalities for each country in their dataset, (ii) they compute PDFs of future cyclone realizations, and (iii) they compute the expected future impacts of cyclones. They find that including the "cyclone effect" in the damage function of the DICE model increases the social cost of carbon by 10-15 percent.

5.2 Energy and Macroeconomic Outcomes

There are four possible causal relationships between energy (use) and economic growth: (1) energy affects economic growth, (2) economic growth affects energy, (3) the relationship goes both ways, and (4) there is no relationship at all between the two. Knowing which way the relationship goes is crucial: for example, in terms of the LtG debate, if relationship (2) and/or (4) hold, then there is a potential for substantial future growth, whereas if relationships (1) and/or (3) hold, then limited energy resources can impose limits to growth. To complicate things, there is evidence for all four of these relationships.[60] It turns out that research on energy is full of stylized facts with very little hard empirical evidence. In order to attempt to clarify at least one of the four possible

[60] In their meta-analysis Kalimeris et al. (2014) cite about 20 papers as evidence for each of these relationships. Fizaine et al. (2016) further suggest that the effects differ when looking at energy consumption (use) or energy prices.

relationships, I provide a small framework for thinking about how energy can affect growth.

The classical Solow-Swan model can be extended to the following (Stern, 2011):

$$Y = \left[(1-\gamma)(A_L^{\beta} L^{\beta} K^{1-\beta})^{\phi} + \gamma (A_E E)^{\phi}\right]^{\frac{1}{\phi}} \tag{9}$$

$$\Delta K = s(Y - p_E E) - \delta K \tag{10}$$

where Y, K, L, and E are output, capital, labor, and energy, respectively; $\phi = \frac{\sigma-1}{\sigma}$, where σ is the elasticity of substitution between energy and the value-added aggregate; p_E is the exogenously given price of energy; s is an exogenously given savings rate; δ is the depreciation rate of capital; and γ is a parameter reflecting the relative importance of energy and value added. A_i, for $i = \{L, E\}$, is the labor and energy augmenting technology. (9) is the CES production function and (10) is the capital accumulation equation.

Assuming that the elasticity of substitution between energy and capital-labor is less than unity, energy supply in the long-run must increase and hence energy eventually constrains economic growth, even if there is labor augmenting technological change. More importantly, however, this set-up allows me to identify four factors affecting the relationship between energy and growth: (i) the substitution between energy and other inputs; (ii) technological change (a change in A) and a change in energy efficiency ($= \frac{E}{GDP}$); (iii) shifts in the composition of the energy input; and (iv) shifts in the composition of output.

5.3 Energy Issues Analyzed in more Detail

Energy expenditures as a fraction of GDP tell us whether we, as a people, on average, spend more or less on energy over time. Research, surprisingly, suggests that this fraction has remained (approximately) constant over time (Newbery, 2003; Bashmakov, 2007; Grubb, Bashmakov, Drummond, Myshak, Hughes, Biancardi, Agnolucci and Lowe, 2018). The most recent finding by Grubb et al. suggests that energy expenditures represent about 8 percent (plus minus 2 percent) of GDP. Interestingly, the studies also find a price elasticity of energy intensity of (minus) 1.

To make sense of this, suppose the ratio of energy expenditures to GDP can be expressed as follows (Grubb, Bashmakov, Drummond, Myshak, Hughes, Biancardi, Agnolucci and Lowe, 2018):

$$ratio = \frac{E \times P_E}{GDP \times D_{GDP}} = EI \times P_{ER} \tag{11}$$

where E is energy consumption; P_E is the price of energy; GDP is GDP in constant prices; D_{GDP} is the GDP deflator; EI is the GDP energy intensity; and P_{ER} is the real price of energy. By definition, $EI = \frac{E}{GDP}$ and $P_{ER} = \frac{P_E}{D_{GDP}}$.

The two factors affecting the fraction of energy expenditure to GDP are therefore energy intensity and the real price of energy. Clearly, for the fraction of energy expenditures of GDP to remain constant over time, and increase (decrease) in the energy intensity must be offset by a proportional decrease (increase) in the real price of energy. The relationship between energy intensity and real energy prices must therefore be (approximately) -1. Intuitive at least, this is reminiscent of the price elasticity of energy intensity.[61]

An issue with the three studies mentioned above is that they are descriptive and lack a rigorous empirical analysis. While the result of constant energy expenditure as a fraction of GDP can quite easily be seen in the data (though there is significant heterogeneity across countries), the result of a -1 price elasticity of energy intensity could be false. In this spirit, Labandeira et al. (2017) conduct a meta-analysis of 416 papers produced between 1990 and 2014, providing 951 short-term price elasticities and 991 long-term price elasticities of energy demand (see footnote 61). They find an average short-term price elasticity of -0.186 and an average long-term price elasticity of -0.524, both suggesting that energy demand is inelastic. Their analysis thus suggests heterogeneity in short-term vs. long-term price elasticities. Furthermore, they also show considerable heterogeneity in price elasticities depending on the type of energy product, the type of consumer, the country, the data and sample period, and the type of the model (see table 3).

Gerarden et al. (2017) define the "energy paradox" as "the apparent reality that some energy-efficiency technologies that would pay off for adopters are nevertheless not adopted" and the "energy-efficiency gap" as "the apparent reality that some energy-efficiency technologies that would be socially efficient are not adopted." In other words, at the individual and aggregate level, we do not consumer the optimal amount of energy. Given that energy consumption over the next 30-50 years is expected to rise significantly, this can cause unnecessary environmental damages.

To simplify the exposition, the diffusion/adoption of a new energy technology can be expressed as a stylized cost minimization problem (Gerarden et al., 2017):

$$\min TotalCost = K(E) + O(E, P_E) \times D(r, T) + OtherCosts \tag{12}$$

where $K(E)$ is the equipment purchase cost, E is the annual energy use, $O(C, P_E)$ is the annual operating cost, P_E is the price of energy, $D(r, T)$ is the present value factor, r is the discount rate, and T is the time horizon.

The equation suggests various possible explanations for the energy paradox or the energy-efficiency gap: (1) it is possible that new products are priced economically inefficient; (2) it is possible that operating costs are priced inefficiently; (3) it is possible that product choices are not actually cost minimizing in present value terms; and (4) it is possible that other costs inhibit energy-efficient decisions. These all fall into two categories: (i) market failures, such as information problems, energy, capital, and innovation market failures; and (ii) behavioral issues, such as inattentiveness and salience, myopia and short-sightedness, bounded rationality and heuristic decision-making, prospect theory and reference-point phenomena, and systematically biased beliefs (Gerarden et al., 2017).[62] The latter category, especially, suggests that advances in behavioral economics can and should be used to attempt to understand the energy paradox and the energy-efficiency gap better. Rasul and Hollywood (2012), for example, advocate the use of nudges.

[61] The price elasticity of energy intensity and the price elasticity of energy demand are not necessarily the same. They are the same with an elasticity of -1, however.

[62] For a short review on the barriers to energy efficiency, see Staub-Kaminski et al. (2014).

6 Frameworks for Sustainable Growth

6.1 Scientific Approaches

Scientific approaches are scientific frameworks establishing certain thresholds at which point life as we know it changes drastically. The most famous one is the planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2015). The aim of this framework is to establish a safe operating space within the Earth System for humans to operate in. To do so, they establish nine boundaries, one in each of the following: climate change, ocean acidification, stratospheric ozone, global phosphorus and nitrogen cycles, atmospheric aerosol loading, freshwater use, land use change, biodiversity loss, and chemical pollution. Given the high level of uncertainty around each of those boundaries, they create a "zone of uncertainty" around each boundary. The 2009 study argues that humanity already transgressed the planetary boundaries to climate change, the rate of biodiversity loss, and nitrogen cycles. The 2015 update to the framework introduces a multi-layered approach, reflecting regional heterogeneity and interactions among various processes underlying the planetary boundaries. Furthermore, the 2015 study identifies two core boundaries (climate change and biodiversity loss), each of which can alter the state of the Earth System should we substantially transgress their boundary. Lastly, the study adds a fourth boundary to the three transgressed boundaries from the 2009 study: land use change. O'Neill et al. (2018) quantify the resource use associated with humanity living within these planetary boundaries and show that, while physical needs like nutrition and sanitation can be met within planetary boundaries, achieving qualitative goals like life satisfaction or prosperity requires a level of resource use that is 2-6 times the sustainable level.

Closely related to the idea of boundaries is the concept of tipping points (Lenton et al., 2008). The intuition behind tipping points is that a small change can have large and long-term consequences for a system. In models, these tipping points correspond to bifurcations. In terms of climate change, scholars speak of catastrophic bifurcations since these have the properties that "once a threshold is exceeded, a positive feedback propels the system through a phase of directional change towards a contrasting state" (Scheffer et al., 2009). In general, systems near a bifurcation exhibit certain common traits, the most important of which is the critical slow down. This describes the fact that as a system closes in on its tipping point it becomes increasingly slow in recovering from small perturbations. In reality, and in regard to climate change, it is very difficult to know how far or close we are to a tipping point. Much research has been done on tipping points (Lenton et al., 2008; Lenton, 2011, 2013; Cai et al., 2015; Lontzek et al., 2015; Lenton and Livina, 2016; Cai et al., 2016): while early research attempted to characterize the critical thresholds in, for example, the Arctic sea-ice or the Greenland ice sheet, more recent research has incorporated tipping points into policy analysis, for example, by including tipping points into a stochastic dynamic IAM.[63]

A recent extension of the tipping points approach is a systems approach including feedback, tipping points and nonlinear dynamics (Steffen et al., 2018). A finding of this framework is that we may be close to a threshold, at which we will be "locked in a path", implying that there is a point at which the Earth System will be on a pathway

[63]The notion of tipping points has also been mentioned in regard to international climate change agreements (Hale, 2017).

with biogeophysical feedbacks that can no longer be influenced by human action.

6.2 Social Science Approaches

While scientific approaches create "clear" thresholds that humanity shouldn't transgress, the aim of social sciences approaches differs in that they attempt to provide policy makers as well as scholars with a framework of structuring the relevant information.

One such framework are "wedges" introduced to solve the carbon and climate problem (Pacala and Socolow, 2004). The intuition behind this framework is that current technologies can be deployed and applied more efficiently to partly offset carbon emissions. As such, the authors define 15 options, such as pursuing known approaches to energy-efficient space heating and cooling in residential and commercial buildings, where directed technological intervention could help lower emissions. All these contribute "one wedge" to solving the problem overall. Seven wedges are required to half GHG emissions by 2050.

A much more comprehensive framework is the Three Domains framework (Grubb, 2014; Grubb et al., 2015). In it, the authors relate the satisficing behavior by households and firms (the first domain) to the optimizing and efficiency frontier suggested by economics (the second domain) and analyze how this frontier shifts over time (the third domain). In other words, they acknowledge insights from psychology and behavioral economics that suggest that agents don't always behave according to the first-best outcome (the first domain), combine this with insights from economics suggesting that "better" outcomes can be achieved by moving towards the first-best outcome (the second domain), and incorporate various theories from economics and other social sciences analyzing how this first-best outcome/the efficiency frontier moves over time (the third domain). An important insight from their work is that the three domains are complements, emphasizing the cross-disciplinary nature of sustainability and the climate change problem.

7 Philosophical Issues

This section is not about philosophical issues in economics or climate change in general (see Hausman (2003) and Shue et al. (2010) or Kolstad et al. (2014) for overviews of philosophical issues in economics and climate change, respectively). Rather, this section aims to sketch some, but not all, ethical concerns in the context of sustainable growth.[64]

Section 2.2 already mentioned that the objective of sustainable growth is not clear and showed how this questions very fundamental questions such as "how do we measure the standard of living" and, more extreme, "what are our theories of value".[65] Such

[64]In addition to ethical aspects of growth, there is also a scientific aspect to it. This field, which I do not cover here, is connected to the philosophy of social sciences and covers questions about the use and role of theories and models as well as issues of causation and uncertainty. See Cartwright and Montuschi (2014) for a broad introduction.

[65]Two references not mentioned in section 2.2 are Sen et al. (1999), who argue that that we should not only focus on individuals well-being since it is possible that individuals voluntarily devote efforts towards maximizing objectives other than their own well-being and Sayer (2011), who argues that people care about the world (and with it, "things") and their relationship to it. This ties into the paradox established by

questions, however, presume that it is possible to measure well-being, or whatever the measurement in question is. Hausman (2015), for example, argues that well-being, which he equates to flourishing (Kraut, 2009), cannot be measured for policy purposes. The intuition behind this claim is that well-being is a inclusive good with much heterogeneity "within". The concept of well-being hinges on the aggregation of a variety of goods in each person's life and this aggregation depends on individual characteristics, values, cultures, talents, and histories of this person. Existing measurements of well-being fail to take this heterogeneity into account and hence well-being is not measurable. If true, this is very consequential for science and policy purposes. While the conception of well-being à la Hausman in theory makes sense it is rather obvious that in practice such a measurement doesn't exist. Recent research suggests that while it may be impossible to measure well-being in general, it is possible to measure well-being of a particular kind of people in specific circumstances ("contextual well-being"). "If it makes sense to predicate well-being to kinds and not merely of individuals, then general claims about what is good for a given kind will be possible too" (Alexandrova, 2016).

Sustainable growth, by definition, suggests that we must actively attempt to reduce our environmental impact. Given that this requires some sort of behavioral change, it raises questions of international equity, which, simply put, questions what is fair and just. There are two dimensions to this: the fairness between generations and the fairness between countries (Grubb, 1995; Caney, 2014). In other words, the first asks whether we have some ethical responsibilities towards future generations while the latter asks who is responsible for the environmental challenges we face and who the leaders should be in solving the problem.

Whether we have responsibilities towards future generations is related to the discount rate debate in section 4.2.2. The argument for a low discount rate, which the Stern review argues for, comes from British utilitarian tradition. Yet, there are other ways of looking at this: it could be that societies should maximize the well-being of the poorest generations (Rawls, 1971) or that every generation should leave at least as much capital (including natural capital) as it inherits (Nordhaus, 2007). While this is an interesting but never-ending debate, a slightly more practical point is that the problem of climate change will affect us also, and not only future generations.

In regard to equity between countries, there are three possibilities: (a) causal responsibility (those who have caused the build-up of emissions in the atmosphere should pay - "polluter pays"), (b) beneficiary pays (those who have benefited from excess emissions should pay), and (c) ability to pay (those who are able to pay should pay) (Hayward, 2012). First, while (a) seems like a "fair" argument, past polluters may not have been aware that they were doing something wrong. Hence, while it seems fair to make future polluters pay, applying the causal responsibility principle to past polluters seems unjust. Second, for (b) it also seems just to argue that beneficiaries from emissions should pay their share. However, since these benefits were bequeathed to them in the past, present beneficiaries might see this as unfair. Third, if past emis-

Jackson (2016) which states that, on the one hand, we are able to flourish more with fewer material things while, on the other hand, "material goods provide a vital language through which we communicate with each other about the things that really matter," such as family or identity. Further related to Jackson (2016)'s idea of flourishing is the notion of alternative hedonism (Soper, 2014), a criticism of consumerism suggesting a "non-consumerist"-version of the notion of a "good life." This idea can also be found in the popular book Klein (2009).

sions harmed, instead of benefited, countries, (c) places the burden into the hands of countries that were least harmed. However, this principle disconnects responsibility from causation, which can lead to many issues.

Lastly, many proposed solutions to the climate change problem that affect sustainable growth, such as carbon taxes or carbon trading, are market-based mechanisms. Michael Sandel argues that "turning pollution into a commodity to be bought and sold removes the moral stigma that is properly associated with it...[and] may undermine the sense of shared responsibility that increased global cooperation requires" (Sandel, 2005).[66]

8 Conclusion

The aim of this review was to review the relevant sustainable growth literature from different fields of the social sciences and inform future research about what the contributions from various fields are. Especially in regard to economics, there is a misconception in the world that everything economists do is connected to perfectly rational individuals with perfect foresight and full information in complete markets exhibiting optimizing behavior. I hope to have shown that economics is much more than that and that it provides useful tools for research on sustainable growth. That said, climate change, and with it sustainable growth, is a multi-disciplinary problem and as such a plausible solution requires insights from all the social sciences.

I end by emphasizing some open research questions in three areas: (1) modeling, (2) technological change, (3) energy issues.

- Modeling
  - Damage Function: this issue concerns the disconnect between micro-studies of environmental impacts on economic indicators and their omission in macro-models, such as IAMs. Improvements of damage functions, for example, must be based on rigorous empirical evidence and hence, new methods for incorporating these micro-findings into macro-models such as IAMs, DSGE models, ABMs and continuous-time models are urgently needed.
  - Risks: new methods and models are needed to convincingly model the fat-tailed risks that climate change poses. Continuous-time models and ABMs seem promising in this regard.
  - Finance: finance will undoubtedly play an important role in the transition to a sustainable economy. IAMs, DSGE models, ABMs, and continuous-time models should be extended to look at role of finance in such a transition in more detail. A positive aspect of stock-flow consistent models is their inclusion of the financial sector.
  - Overall: the most promising area for future research in regard to modeling techniques for questions of sustainable growth are clearly the recent advancement in DSGE models and ABMs. Their flexibility and structure allow each to investigate a clear set of distinct questions. Combined they can bring about many useful policy recommendations. Continuous-time models have

[66] The issue of whether carbon trading is ethical or not is analyzed in Caney and Hepburn (2011). See also O'Neill (2013).

yet to be applied to environmental issues, but promise to be very useful as well. Stock-flow consistent modeling still has a further way to go.

- Technological Change
  - R&D Investment Decisions: it is important to gain a deeper understanding of why firms invest in R&D in the first place.
  - Directed Technological Change: we need more rigorous empirical evidence of the effects of directed technological change in order to advance the understanding of how R&D investment decisions affect actual innovation.
  - Diffusion: the diffusion of new technologies, and with it issues of inertia and abatement costs, must be analyzed in more detail, empirically and theoretically. Of further interest here are the effects of path dependency.
- Energy Issues
  - Energy Elasticities: understanding how energy demand changes in response to price changes is crucial. Further and more rigorous empirical research is needed to analyze this relationship.
  - Energy and Growth: it is likely that this is a two-way relationship. New methods and more rigorous empirical research is needed to analyze this joint relationship.
  - Overall: the energy issues surveyed here are full of stylized facts and descriptive studies. Few actual causal relationships have been established. This needs to change. Recent advances taking lessons from behavioral economic to study the energy-efficiency gap seem promising.

9 Bibliography

Acemoglu, D. (1998), 'Why do New Technologies Complement Skills? Directed Technical Change and Wage Inequality', *The Quarterly Journal of Economics* **113**(4), 1055–1089.

Acemoglu, D. (2002), 'Directed Technical Change', *The Review of Economic Studies* **69**(4), 781–809.

Acemoglu, D., Aghion, P., Bursztyn, L. and Hemous, D. (2012), 'The Environment and Directed Technical Change', *American Economic Review* **102**(1), 131–66.

Acemoglu, D., Johnson, S. and Robinson, J. A. (2001), 'The Colonial Origins of Comparative Development: An Empirical Investigation', *American Economic Review* **91**(5), 1369–1401.

Acemoglu, D. and Restrepo, P. (2017), 'Robots and Jobs: Evidence from US Labor Markets'.

Acemoglu, D. and Restrepo, P. (2018), 'The Race Between Man and Machine: Implications of Technology for Growth, Factor Shares, and Employment', *American Economic Review* **108**(6), 1488–1542.

Ackerman, F. and Munitz, C. (2012), 'Climate Damages in the FUND Model: A Disaggregated Analysis', *Ecological Economics* **77**, 219–224.

ADB (2014), *Low-Carbon Green Growth in Asia: Policies and Practices*, Asian Development Bank.

AfDB (2013), 'African Development Report: Towards Green Growth in Africa'.

Aghion, P., Akcigit, U. and Howitt, P. (2014), What do we Learn from Schumpeterian Growth Theory?, *in* 'Handbook of Economic Growth', Vol. 2, Elsevier, pp. 515–563.

Aghion, P., Bloom, N., Blundell, R., Griffith, R. and Howitt, P. (2005), 'Competition and Innovation: An Inverted-U Relationship', *The Quarterly Journal of Economics* **120**(2), 701–728.

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R. and Van Reenen, J. (2016), 'Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry', *Journal of Political Economy* **124**(1), 1–51.

Aghion, P., Hepburn, C., Teytelboym, A. and Zenghelis, D. (2014), 'Path Dependence, Innovation and the Economics of Climate Change', *Policy Paper. Centre for Climate Change Economics and Policy and Grantham Research Institute on Climate Change and the Environment. A contributing paper to: The New Climate Economy. See http://newclimateeconomy.report/misc/working-papers* .

Aghion, P. and Howitt, P. (1990), A Model of Growth Through Creative Destruction, Technical report, National Bureau of Economic Research.

Aghion, P. and Howitt, P. (1998), *Endogenous Growth Theory*, MIT Press.

Aghion, P., Jones, B. F. and Jones, C. I. (2017), Artificial Intelligence and Economic Growth, Technical report, National Bureau of Economic Research.

Aiyagari, S. R. (1994), 'Uninsured Idiosyncratic Risk and Aggregate Saving', *The Quarterly Journal of Economics* **109**(3), 659–684.

Alesina, A. and Giuliano, P. (2015), 'Culture and Institutions', *Journal of Economic Literature* **53**(4), 898–944.

Alexandrova, A. (2016), 'Is Well-Being Measurable After All?', *Public Health Ethics* **10**(2), 129–137.

Anzoategui, D., Comin, D., Gertler, M. and Martinez, J. (2016), Endogenous Technology Adoption and R&D as Sources of Business Cycle Persistence, Technical report, National Bureau of Economic Research.

Arrow, K., Dasgupta, P., Goulder, L., Daily, G., Ehrlich, P., Heal, G., Levin, S., Mäler, K.-G., Schneider, S., Starrett, D. et al. (2004), 'Are we Consuming too Much?', *Journal of Economic Perspectives* **18**(3), 147–172.

Arrow, K. J. (1962), 'The Economic Implications of Learning by Doing', *The Review of Economic Studies* **29**(3), 155–173.

Arrow, K. J., Dasgupta, P., Goulder, L. H., Mumford, K. J. and Oleson, K. (2012), 'Sustainability and the Measurement of Wealth', *Environment and Development Economics* **17**(3), 317–353.

Ayres, R. U. (2007), 'On the Practical Limits to Substitution', *Ecological Economics* **61**(1), 115–128.

Ayres, R. U. and Warr, B. (2005), 'Accounting for Growth: The Role of Physical Work', *Structural Change and Economic Dynamics* **16**(2), 181–209.

Bakkensen, L., Barrage, L. et al. (2018), Climate Shocks and Economic Growth: Bridging the Micro-Macro Gap, *in* '2018 Meeting Papers', number 1198, Society for Economic Dynamics.

Balint, T., Lamperti, F., Mandel, A., Napoletano, M., Roventini, A. and Sapio, A. (2017), 'Complexity and the Economics of Climate Change: A Survey and a Look Forward', *Ecological Economics* **138**, 252–265.

Baptist, S. and Hepburn, C. (2013), 'Intermediate Inputs and Economic Productivity', *Phil. Trans. R. Soc. A* **371**(1986), 20110565.

Bar-Gill, O. and Fershtman, C. (2005), 'Public Policy with Endogenous Preferences', *Journal of Public Economic Theory* **7**(5), 841–857.

Bardi, U. (2014), *Extracted: How the Quest for Mineral Wealth is Plundering the Planet*, Chelsea Green Publishing.

Barnard, C. and Simon, H. A. (1947), 'Administrative Behavior. A Study of Decision-Making Processes in Administrative Organization', *New York: Free Press* .

Barrett, S. (1994), 'Self-Enforcing International Environmental Agreements', *Oxford Economic Papers* pp. 878–894.

Barro, R. J. (1999), 'Notes on Growth Accounting', *Journal of Economic Growth* **4**(2), 119–137.

Barro, R. J. and Sala-i Martin, X. (2003), *Economic Growth*, MIT Press.

Bashmakov, I. (2007), 'Three Laws of Energy Transitions', *Energy Policy* **35**(7), 3583–3594.

Basu, S. (1995), 'Intermediate Goods and Business Cycles: Implications for Productivity and Welfare', *The American Economic Review* pp. 512–531.

Basu, S. and Fernald, J. G. (1995), Are Apparent Productive Spillovers a Figment of Specification Error?, Technical report, National Bureau of Economic Research.

Batten, D. and Grozev, G. (2006), 'NEMSIM: Finding Ways to Reduce Greenhouse Gas Emissions Using Multi-Agent Electricity Modelling', *Complex Science for a Complex World: Exploring Human Ecosystems with Agents, P. Perez and D. Batten, Eds* p. 227.

Batten, S. (2018), 'Climate Change and the Macro-Economy: A critical Review'.

Batten, S., Sowerbutts, R. and Tanaka, M. (2016), 'Let's Talk About the Weather: The Impact of Climate Change on Central Banks'.

Beaudreau, B. C. (1995), 'The Impact of Electric Power on Productivity: A Study of US Manufacturing 1950–1984', *Energy Economics* **17**(3), 231–236.

Beckenbach, F. and Briegel, R. (2011), Multi-Agent Modeling of Economic Innovation Dynamics and its Implications for Analyzing Emission Impacts, *in* 'International Economics of Resource Efficiency', Springer, pp. 289–315.

Beckerman, W. (1994), '"sustainable Development": Is it a Iseful Concept?', *Environmental Values* **3**(3), 191–209.

Berndt, E. R. (1980), *Energy Price Increases and the Productivity Slowdown in United States Manufacturing*, University of British Columbia, Department of Economics.

Berndt, E. R. and Khaled, M. S. (1979), 'Parametric Productivity Measurement and Choice Among Flexible Functional Forms', *Journal of Political Economy* **87**(6), 1220–1245.

Berndt, E. R. and Wood, D. O. (1975), 'Technology, Prices, and the Derived Demand for Energy', *The Review of Economics and Statistics* pp. 259–268.

Bettencourt, L. M., Trancik, J. E. and Kaur, J. (2013), 'Determinants of the Pace of Global Innovation in Energy Technologies', *PloS one* **8**(10), e67864.

Binder, M. (2010), *Elements of an Evolutionary Theory of Welfare: Assessing Welfare when Preferences Change*, Routledge.

Bloom, N., Jones, C. I., Van Reenen, J. and Webb, M. (2017), Are Ideas Getting Harder to Find?, Technical report, National Bureau of Economic Research.

Bovenberg, A. L. and Smulders, S. (1995), 'Environmental Quality and Pollution-Augmenting Technological Change in a Two-Sector Endogenous Growth Model', *Journal of Public Economics* **57**(3), 369–391.

Bovenberg, A. L. and Smulders, S. A. (1996), 'Transitional Impacts of Environmental Policy in an Endogenous Growth Model', *International Economic Review* pp. 861–893.

Bowen, A. and Hepburn, C. (2012), 'Prosperity with Growth: Economic Growth, Climate Change and Environmental Limits'.

Bowles, S. (1998), 'Endogenous Preferences: The Cultural Consequences of Markets and Other Economic Institutions', *Journal of Economic literature* **36**(1), 75–111.

Brundtland, G., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., Fadika, L., Hauff, V., Lang, I., Shijun, M., de Botero, M. M. et al. (1987), 'Our Common Future ('Brundtland Report')'.

Brunnermeier, M. K. and Sannikov, Y. (2016), Macro, Money, and Finance: A Continuous-Time Approach, *in* 'Handbook of Macroeconomics', Vol. 2, Elsevier, pp. 1497–1545.

Bruno, M. (1978), Duality, Intermediate Inputs and Value-Added, *in* 'Contributions to Economic Analysis', Vol. 2, Elsevier, pp. 3–16.

Bruvoll, A., Glomsrød, S. and Vennemo, H. (1999), 'Environmental Drag: Evidence from Norway', *Ecological Economics* **30**(2), 235–249.

Burnside, C. (1996), 'Production Function Regressions, Returns to Scale, and Externalities', *Journal of Monetary Economics* .

Burnside, C., Eichenbaum, M. and Rebelo, S. (1993), 'Labor Hoarding and the Business Cycle', *Journal of Political Economy* **101**(2), 245–273.

Cai, Y., Judd, K. L., Lenton, T. M., Lontzek, T. S. and Narita, D. (2015), 'Environmental Tipping Points Significantly Affect the Cost- Benefit Assessment of Climate Policies', *Proceedings of the National Academy of Sciences* p. 201503890.

Cai, Y., Lenton, T. M. and Lontzek, T. S. (2016), 'Risk of Multiple Interacting Tipping Points Should Encourage Rapid CO2 Emission Reduction', *Nature Climate Change* **6**(5), 520.

Calel, R. and Dechezlepretre, A. (2016), 'Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market', *Review of Economics and Statistics* **98**(1), 173–191.

Caney, S. (2014), 'Two Kinds of Climate Justice: Avoiding Harm and Sharing Burdens', *Journal of Political Philosophy* **22**(2), 125–149.

Caney, S. and Hepburn, C. (2011), 'Carbon Trading: Unethical, Unjust and Ineffective?', *Royal Institute of Philosophy Supplements* **69**, 201–234.

Carleton, T. A. and Hsiang, S. M. (2016), 'Social and Economic Impacts of Climate', *Science* **353**(6304), aad9837.

Carney, M. (2015), 'Breaking the Tragedy of the Horizon: Climate Change and Financial Stability', *Speech given at Lloyd's of London, September* **29**.

Cartwright, N. and Montuschi, E. (2014), *Philosophy of Social Science: A New Introduction*, OUP UK.

Caselli, F. (2005), 'Accounting for Cross-Country Income Differences', *Handbook of Economic Growth* **1**, 679–741.

Caselli, F. (2015), 'Experience-Biased Technical Change'.

Cass, D. (1965), 'Optimum Growth in an Aggregative Model of Capital Accumulation', *The Review of Economic Studies* **32**(3), 233–240.

Caviglia-Harris, J. L., Chambers, D. and Kahn, J. R. (2009), 'Taking the "U" out of Kuznets: A Comprehensive Analysis of the EKC and Environmental Degradation', *Ecological Economics* **68**(4), 1149–1159.

Chetty, R., Hendren, N., Kline, P. and Saez, E. (2014), 'Where is the Land of Opportunity? The Geography of Intergenerational Mobility in the United States', *The Quarterly Journal of Economics* **129**(4), 1553–1623.

Chetty, R., Hendren, N., Kline, P., Saez, E. and Turner, N. (2014), 'Is the United States still a Land of Opportunity? Recent Trends in Intergenerational Mobility', *American Economic Review* **104**(5), 141–47.

Chichilnisky, G. (1994), 'North-South Trade and the Global Environment', *The American Economic Review* pp. 851–874.

Cleveland, C. J. and Ruth, M. (1997), 'When, Where, and by How Much do Biophysical Limits Constrain the Economic Process? A Survey of Nicholas Georgescu-Roegen's Contribution to Ecological Economics', *Ecological Economics* **22**, 203–223.

Cole, M. A., Rayner, A. J. and Bates, J. M. (1997), 'The Environmental Kuznets Curve: An Empirical Analysis', *Environment and Development Economics* **2**(4), 401–416.

Comin, D., Hobijn, B. and Rovito, E. (2006), Five Facts You Need to Know About Technology Diffusion, Technical report, National Bureau of Economic Research.

Comin, D. and Mestieri, M. (2014), Technology Diffusion: Measurement, Causes, and Consequences, *in* 'Handbook of economic growth', Vol. 2, Elsevier, pp. 565–622.

Connolly, M. (1999), 'North-South Technological Diffusion: A New Case for Dynamic Gains from Trade'.

Conzelmann, G., Boyd, G., Koritarov, V. and Veselka, T. (2005), Multi-Agent Power Market Simulation using EMCAS, *in* 'Power Engineering Society General Meeting, 2005. IEEE', IEEE, pp. 2829–2834.

Copeland, B. R. and Taylor, M. S. (2013), *Trade and the Environment: Theory and Evidence*, Princeton University Press.

Costanza, R. (1980), 'Embodied Energy and Economic Valuation', *Science* **210**(4475), 1219–1224.

Costanza, R. and Daly, H. E. (1992), 'Natural Capital and Sustainable Development', *Conservation biology* **6**(1), 37–46.

Crafts, N. (2010), 'The Contribution of New Technology to Economic Growth: Lessons from Economic History', *Revista de Historia Económica-Journal of Iberian and Latin American Economic History* **28**(3), 409–440.

Daly, H. (2017), 'A new Economics for our full World', *Victor, P., Dolter, B., Handbook of Growth and Sustainability. Cheltenham: Edward Elgar* pp. 85–106.

Daly, H. E. (1973), 'Towards a Steady State Economy'.

Daly, H. E. (1991*a*), 'Elements of Environmental Macroeconomics', *Ecological economics: The science and Management of Sustainability* pp. 32–46.

Daly, H. E. (1991*b*), *Steady-State Economics Second Edition with New Essays.*

Daly, H. E. (1997*a*), *Beyond Growth: The Economics of Sustainable Development*, Beacon Press.

Daly, H. E. (1997*b*), 'Georgescu-Roegen versus Solow/Stiglitz', *Ecological Economics* **22**(3), 261–266.

Dasgupta, A. and Dasgupta, P. (2017), 'Socially Embedded Preferences, Environmental Externalities, and Reproductive Rights', *Population and Development Review* **43**(3), 405–441.

Dasgupta, P. and Heal, G. (1974), 'The Optimal Depletion of Exhaustible Resources', *The Review of Economic Studies* **41**, 3–28.

Dasgupta, P. and Mäler, K.-G. (2000), 'Net National Product, Wealth, and Social Well-Being', *Environment and Development Economics* **5**(1), 69–93.

Dasgupta, P. S. and Heal, G. M. (1979), *Economic Theory and Exhaustible Resources*, Cambridge University Press.

Dasgupta, S., Laplante, B., Wang, H. and Wheeler, D. (2002), 'Confronting the Environmental Kuznets Curve', *Journal of Economic Perspectives* **16**(1), 147–168.

de Haan, P., Mueller, M. G. and Scholz, R. W. (2009), 'How Much do Incentives Affect Car Purchase? Agent-Based Microsimulation of Consumer Choice of New Cars-Part II: Forecasting Effects of Feebates Based on Energy-Efficiency', *Energy Policy* **37**(3), 1083–1094.

Deaton, A. (2008), 'Income, Health, and Well-Being Around the World: Evidence from the Gallup World Poll', *Journal of Economic Perspectives* **22**(2), 53–72.

Dell, M. (2010), 'The Persistent Effects of Peru's Mining Mita', *Econometrica* **78**(6), 1863–1903.

Dell, M., Jones, B. F. and Olken, B. A. (2014), 'What do we Learn from the Weather? the New Climate-Economy Literature', *Journal of Economic Literature* **52**(3), 740–98.

DellaVigna, S., Lindner, A., Reizer, B. and Schmieder, J. F. (2017), 'Reference-Dependent Job Search: Evidence from Hungary', *The Quarterly Journal of Economics* **132**(4), 1969–2018.

Dennig, F., Budolfson, M. B., Fleurbaey, M., Siebert, A. and Socolow, R. H. (2015), 'Inequality, Climate Impacts on the Future Poor, and Carbon Prices', *Proceedings of the National Academy of Sciences* **112**(52), 15827–15832.

Dietz, S. and Stern, N. (2015), 'Endogenous Growth, Convexity of Damage and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions', *The Economic Journal* **125**(583), 574–620.

Doepke, M. and Zilibotti, F. (2008), ‘Occupational Choice and the Spirit of Capitalism’, *The Quarterly Journal of Economics* **123**(2), 747–793.

Doepke, M. and Zilibotti, F. (2017), ‘Parenting with Style: Altruism and Paternalism in Intergenerational Preference Transmission’, *Econometrica* **85**(5), 1331–1371.

Domar, E. D. (1946), ‘Capital Expansion, Rate of Growth, and Employment’, *Econometrica, Journal of the Econometric Society* pp. 137–147.

Douglas, P. and Cobb, C. W. (1928), ‘A Theory of Production’, *The American Economic Review* **18**(1), 139–165.

EBRD (2011), ‘Special Report on Climate Change. The Low-Carbon Transition’.

Ehrlich, P. R. (1978), *The Population Bomb.*, New York Ballantine 1978.

Ehrlich, P. R. and Holdren, J. P. (1971), ‘Impact of Population Growth’, *Science* **171**(3977), 1212–1217.

Ekins, P. (2002), *Economic Growth and Environmental Sustainability: The Prospects for Green Growth*, Routledge.

Eliaz, K. and Spiegler, R. (2014), ‘Reference Dependence and Labor Market Fluctuations’, *NBER Macroeconomics Annual* **28**(1), 159–200.

Eppstein, M. J., Grover, D. K., Marshall, J. S. and Rizzo, D. M. (2011), ‘An Agent-Based Model to Study Market Penetration of Plug-in Hybrid Electric Vehicles’, *Energy Policy* **39**(6), 3789–3802.

EU Commission (2017), ‘Study on the Review of the List of Critical Raw Metals’.

Faber, A., Valente, M. and Janssen, P. (2010), ‘Exploring Domestic Micro-Cogeneration in the Netherlands: An Agent-Based Demand Model for Technology Diffusion’, *Energy Policy* **38**(6), 2763–2775.

Fankhauser, S., Bowen, A., Calel, R., Dechezleprêtre, A., Grover, D., Rydge, J. and Sato, M. (2013), ‘Who Will Win the Green Race? In Search of Environmental Competitiveness and Innovation’, *Global Environmental Change* **23**(5), 902–913.

Farhi, E. and Gabaix, X. (2015), Optimal Taxation with Behavioral Agents, Technical report, National Bureau of Economic Research.

Farhi, E. and Werning, I. (2017), Monetary Policy, Bounded Rationality, and Incomplete Markets, Technical report, National Bureau of Economic Research.

Farmer, J. D. and Lafond, F. (2016), ‘How Predictable is Technological Progress?’, *Research Policy* **45**(3), 647–665.

Farmer, J., Hepburn, C., Mealy, P. and Teytelboym, A. (2015), ‘A Third Wave in the Economics of Climate Change’, *Environmental & Resource Economics* **62**(2), 329–357.

Fay, M. (2012), *Inclusive Green Growth: The Pathway to Sustainable Development*, World Bank Publications.

Fehr, E. and Hoff, K. (2011), *Tastes, Castes, and Culture: The Influence of Society on Preferences*, The World Bank.

Feng, G. and Serletis, A. (2008), 'Productivity Trends in US Manufacturing: Evidence from the NQ and AIM Cost Functions', *Journal of Econometrics* **142**(1), 281–311.

Fizaine, F. et al. (2016), 'Energy Expenditure, Economic Growth, and the Minimum EROI of Society', *Energy Policy* **95**, 172–186.

Folke, C. (2006), 'Resilience: The Emergence of a Perspective for Social-Ecological Systems Analyses', *Global Environmental Change* **16**(3), 253–267.

Fontana, G. and Sawyer, M. (2016), 'Towards Post-Keynesian Ecological Macroeconomics', *Ecological Economics* **121**, 186–195.

Geels, F. W. (2002), 'Technological Transitions as Evolutionary Reconfiguration Processes: A Multi-Level Perspective and a Case-Study', *Research Policy* **31**(8-9), 1257–1274.

Geels, F. W. (2005), 'Processes and Patterns in Transitions and System Innovations: Refining the Co-Evolutionary Multi-Level Perspective', *Technological Forecasting and Social Change* **72**(6), 681–696.

Georgescu-Roegen, N. (1971), The Entropy Law and the Economic Process, Technical report.

Georgescu-Roegen, N. (1975), 'Energy and Economic Myths', *Southern Economic Journal* pp. 347–381.

Georgescu-Roegen, N. (1986), 'The Entropy Law and the Economic Process in Retrospect', *Eastern Economic Journal* **12**(1), 3–25.

Gerarden, T. D., Newell, R. G. and Stavins, R. N. (2017), 'Assessing the Energy-Efficiency Gap', *Journal of Economic Literature* **55**(4), 1486–1525.

Gerlagh, R., Kverndokk, S. and Rosendahl, K. E. (2009), 'Optimal Timing of Climate Change Policy: Interaction Between Carbon Taxes and Innovation Externalities', *Environmental and resource Economics* **43**(3), 369–390.

Gerst, M., Wang, P., Roventini, A., Fagiolo, G., Dosi, G., Howarth, R. and Borsuk, M. (2013), 'Agent-Based Modeling of Climate Policy: An Introduction to the ENGAGE Multi-Level Model Framework', *Environmental Modelling & Software* **44**, 62 – 75.

Godley, W. and Lavoie, M. (2016), *Monetary Economics: An Integrated Approach to Credit, Money, Income, Production and Wealth*, Springer.

Golosov, M., Hassler, J., Krusell, P. and Tsyvinski, A. (2014), 'Optimal Taxes on Fossil Fuel in General Equilibrium', *Econometrica* **82**(1), 41–88.

Gordon, R. J. (2012), Is US Economic Growth Over? Faltering Innovation Confronts the Six Headwinds, Technical report, National Bureau of Economic Research.

Goulder, L. H. and Schneider, S. H. (1999), 'Induced Technological Change and the Attractiveness of CO2 Abatement Policies', *Resource and Energy Economics* **21**(3-4), 211–253.

Griffith, R., Harrison, R. and Simpson, H. (2010), 'Product Market Reform and Innovation in the EU', *Scandinavian Journal of economics* **112**(2), 389–415.

Grimaud, A. (1999), 'Pollution Permits and Sustainable Growth in a Schumpeterian Model', *Journal of Environmental Economics and Management* **38**(3), 249–266.

Grossman, G. M. and Helpman, E. (1993), *Innovation and Growth in the Global Economy*, MIT press.

Grossman, G. M. and Krueger, A. B. (1991), Environmental Impacts of a North American Free Trade Agreement, Technical report, National Bureau of Economic Research.

Grossman, G. M. and Krueger, A. B. (1995), 'Economic Growth and the Environment', *The Quarterly Journal of Economics* **110**(2), 353–377.

Grubb, M. (1995), 'Seeking Fair Weather: Ethics and the International Debate on Climate Change', *International Affairs* **71**(3), 463–496.

Grubb, M. (2004), 'Technology Innovation and Climate Change Policy: An Overview of Issues and Options', *Keio Economic Studies* **41**(2), 103.

Grubb, M. (2014), *Planetary Economics: Energy, Climate Change and the Three Domains of Sustainable Development*, Routledge.

Grubb, M., Anger-Kraavi, A., Bashmakov, I. and Wood, R. (2017), 'Carbon Decoupling?'.

Grubb, M., Bashmakov, I., Drummond, P., Myshak, A., Hughes, N., Biancardi, A., Agnolucci, P. and Lowe, R. (2018), 'An Exploration of Energy Cost, Ranges, Limits and Adjustment Process', *UCL-ISR* .

Grubb, M., Duong, M. and Chapuis, T. (1994), 'Optimizing Climate Change Abatement Responses: On Inertia and Induced Technology Development', *Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change* (009), 513–534.

Grubb, M., Hourcade, J.-C. and Neuhoff, K. (2015), 'The Three Domains Structure of Energy-Climate Transitions', *Technological Forecasting and Social Change* **98**, 290–302.

Grubb, M., Mercure, J.-F., Salas, P., Lange, R.-J. and Sognnaes, I. (2018), 'Systems Innovation, Inertia and Pliability: A Mathematical Exploration with Implications for Climate Change Abatement', *Cambridge EPRG* (1808).

Grubb, M., Thierry, C. and Ha-Duong, M. (1995), 'The Economics of Changing Course: Implications of Adaptability and Inertia for Optimal Climate Policy.', *Energy Policy* **23**(4/5), 417–432.

Haldane, A. G. and Turrell, A. E. (2018), 'An Interdisciplinary Model for Macroeconomics', *Oxford Review of Economic Policy* **34**(1-2), 219–251.

Hale, T. (2017), 'Tipping out of Tragedy? Catalytic Institutions for the Global Commons'.

Hall, B. H., Mairesse, J. and Mohnen, P. (2010), 'Measuring the Returns to R&D, in Handbook of the Economics of Innovation, Bronwyn H. Hall and Nathan Rosenberg (eds.), Vol. 2, Chapter 22'.

Hallegatte, S., Heal, G., Fay, M. and Treguer, D. (2012), From Growth to Green Growth: A Framework, Technical report, National Bureau of Economic Research.

Hamilton, K. and Hepburn, C. (2014), 'Wealth', *Oxford Review of Economic Policy* **30**(1), 1–20.

Hannon, B. (1973), 'The Structure of Ecosystems', *Journal of Theoretical Biology* **41**(3), 535–546.

Hannon, B., Blazeck, T., Kennedy, D. and Illyes, R. (1983), 'A Comparison of Energy Intensities: 1963, 1967 and 1972', *Resources and Energy* **5**(1), 83–102.

Hardt, L. and O'Neill, D. W. (2017), 'Ecological Macroeconomic Models: Assessing Current Developments', *Ecological Economics* **134**, 198–211.

Harrod, R. F. (1939), 'An Essay in Dynamic Theory', *The Economic Journal* **49**(193), 14–33.

Hassler, J. and Krusell, P. (2012), 'Economics and Climate Change: Integrated Assessment in a Multi-Region World', *Journal of the European Economic Association* **10**(5), 974–1000.

Hassler, J., Krusell, P. and Olovsson, C. (2010), 'Oil Monopoly and the Climate', *American Economic Review* **100**(2), 460–64.

Hassler, J., Krusell, P. and Olovsson, C. (2012), Energy-Saving Technical Change, Technical report, National Bureau of Economic Research.

Hassler, J., Krusell, P., Olovsson, C. and Reiter, M. (2018), 'Integrated Assessment in a Multi-Region World with Multiple Energy Sources and Endogenous Technical Change'.

Hausman, D. M. (2003), 'Philosophy of Economics'.

Hausman, D. M. (2015), *Valuing Health: Well-Being, Freedom, and Suffering*, Oxford University Press.

Hayward, T. (2012), 'Climate Change and Ethics', *Nature Climate Change* **2**(12), 843.

Heal, G. (2000), *Valuing the Future: Economic Theory and Sustainability*, Columbia University Press.

Heal, G. (2017), 'The Economics of the Climate', *Journal of Economic Literature* **55**(3), 1046–63.

Hepburn, C., Pfeiffer, A. and Teytelboym, A. (2018), Green Growth, *in* 'The New Oxford Handbook of Economic Geography'.

Hicks, J. R. (1932), 'The Wheory of Wages'.

Hicks, J. R. (1946), 'Value and Capital, 2nd'.

Holling, C. S. (1973), 'Resilience and Stability of Ecological Systems', *Annual Review of Ecology and Systematics* **4**(1), 1–23.

Hotelling, H. (1931), 'The Economics of Exhaustible Resources', *Journal of Political Economy* **39**(2), 137–175.

Houser, T., Hsiang, S., Kopp, R. and Larsen, K. (2015), *Economic Risks of Climate Change: An American Prospectus*, Columbia University Press.

Hsiang, S. (2016), 'Climate Econometrics', *Annual Review of Resource Economics* **8**, 43–75.

Hsiang, S. M. and Jina, A. S. (2014), The Causal Effect of Environmental Catastrophe on Long-Run Economic Growth: Evidence from 6,700 Cyclones, Technical report, National Bureau of Economic Research.

Huggett, M. (1993), 'The Risk-Free Rate in Heterogeneous-Agent Incomplete-Insurance Economies', *Journal of economic Dynamics and Control* **17**(5-6), 953–969.

Hulten, C. R. (2010), Growth Accounting, *in* 'Handbook of the Economics of Innovation', Vol. 2, Elsevier, pp. 987–1031.

Jackson, T. (2016), *Prosperity Without Growth: Foundations for the Economy of Tomorrow*, Routledge.

Jackson, T. and Victor, P. A. (2015), 'Does Credit Create a "Growth Imperative"? A Quasi-Stationary Economy with Interest-Bearing Debt', *Ecological Economics* **120**, 32–48.

Jackson, T. and Victor, P. A. (2016), 'Does Slow Growth Lead to Rising Inequality? Some Theoretical Reflections and Numerical Simulations', *Ecological Economics* **121**, 206–219.

Jaffe, A. B., Newell, R. G. and Stavins, R. N. (2002), 'Environmental Policy and Technological Change', *Environmental and Resource Economics* **22**(1-2), 41–70.

Jaffe, A. B., Newell, R. G. and Stavins, R. N. (2005), 'A Tale of Two Market Failures: Technology and Environmental Policy', *Ecological Economics* **54**(2-3), 164–174.

Jaffe, A. B. and Stavins, R. N. (1994), 'The Energy Paradox and the Diffusion of Conservation Technology', *Resource and Energy Economics* **16**(2), 91–122.

Janssen, M. and De Vries, B. (1998), 'The Battle of Perspectives: A Multi-Agent Model with Adaptive Responses to Climate Change', *Ecological Economics* **26**(1), 43–65.

Jones, C. (2009), The Costs of Economic Growth, Technical report, Mimeo, Stanford University.

Jones, C. I. (2016), The Facts of Economic Growth, *in* 'Handbook of Macroeconomics', Vol. 2, Elsevier, pp. 3–69.

Jones, C. I. and Romer, P. M. (2010), 'The New Kaldor Facts: Ideas, Institutions, Population, and Human Capital', *American Economic Journal: Macroeconomics* **2**(1), 224–45.

Jorgenson, D. W. (1984), 'The Role of Energy in Productivity Growth', *The Energy Journal* **5**(3), 11–26.

Jorgenson, D. W. and Griliches, Z. (1967), 'The Explanation of Productivity Change', *The Review of Economic Studies* **34**(3), 249–283.

Kahneman, D. and Tversky, A. (1979), 'Prospect Theory: An Analysis of Decision Under Risk', *Econometrica* **47**(2), 263–91.

Kaldor, N. (1961), Capital Accumulation and Economic Growth, *in* 'The theory of capital', Springer, pp. 177–222.

Kalimeris, P., Richardson, C. and Bithas, K. (2014), 'A Meta-Analysis Investigation of the Direction of the Energy-GDP Causal Relationship: Implications for the Growth-Degrowth Dialogue', *Journal of Cleaner Production* **67**, 1–13.

Kallis, G., Kerschner, C. and Martinez-Alier, J. (2012), 'The Economics of Degrowth'.

Kirman, A. P. (1992), 'Whom or What Does the Representative Individual Represent?', *Journal of Economic Perspectives* **6**(2), 117–136.

Klein, N. (2009), *No Logo*, Vintage Books Canada.

Knight, F. H. (1944), 'Diminishing Returns from Investment', *Journal of Political Economy* **52**(1), 26–47.

Kolstad, C., Urama, K., Broome, J., Bruvoll, A., Olvera, M. C., Fullerton, D., Gollier, C., Hanemann, W. M., Hassan, R., Jotzo, F. et al. (2014), 'Social, Economic and Ethical Concepts and Methods', *Climate Change* pp. 207–282.

Koopmans, T. C. (1965), 'On the Concept of Optimal Economic Growth'.

Kőszegi, B. and Rabin, M. (2006), 'A Model of Reference-Dependent Preferences', *The Quarterly Journal of Economics* **121**(4), 1133–1165.

Kousky, C. (2014), 'Informing Climate Adaptation: A Review of the Economic Costs of Natural Disasters', *Energy Economics* **46**, 576–592.

Kraut, R. (2009), *What is Good and Why: The Ethics of Well-Being*, Harvard University Press.

Krueger, D. and Perri, F. (2006), 'Does Income Inequality Lead to Consumption Inequality? Evidence and Theory', *The Review of Economic Studies* **73**(1), 163–193.

Krusell, P. and Smith, Jr, A. A. (1998), 'Income and Wealth Heterogeneity in the Macroeconomy', *Journal of Political Economy* **106**(5), 867–896.

Kuznets, S. (1955), 'Economic Growth and Income Inequality', *The American Economic Review* **45**(1), 1–28.

Kydland, F. E. and Prescott, E. C. (1982), 'Time to Build and Aggregate Fluctuations', *Econometrica: Journal of the Econometric Society* pp. 1345–1370.

Labandeira, X., Labeaga, J. M. and López-Otero, X. (2017), 'A Meta-Analysis on the Price Elasticity of Energy Demand', *Energy Policy* **102**, 549–568.

Lafond, F., Bailey, A. G., Bakker, J. D., Rebois, D., Zadourian, R., McSharry, P. and Farmer, J. D. (2018), 'How well do Experience Curves Predict Technological Progress? A Method for Making Distributional Forecasts', *Technological Forecasting and Social Change* **128**, 104–117.

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A. and Sapio, A. (2016), 'Faraway, So Close: An Agent Based Model for Climate, Energy and Macroeconomic Policy'.

Lange, G.-M., Wodon, Q. and Carey, K. (2018), *The Changing Wealth of Nations 2018: Building a Sustainable Future*, The World Bank.

Latouche, S. (2003), 'Pour une Société de Décroissance', *Le Monde Diplomatique* **11**, 18–19.

Latouche, S. (2009), 'Farewell to Growth Polity Press', *Cambridge, UK* .

Lenton, T. M. (2011), 'Early Warning of Climate Tipping Points', *Nature Climate Change* **1**(4), 201.

Lenton, T. M. (2013), 'Environmental Tipping Points', *Annual Review of Environment and Resources* **38**, 1–29.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S. and Schellnhuber, H. J. (2008), 'Tipping Elements in the Earth's Climate System', *Proceedings of the National Academy of Sciences* **105**(6), 1786–1793.

Lenton, T. M. and Livina, V. N. (2016), 'Detecting and Anticipating Climate Tipping Points', *Observations, Modeling, and Economics* p. 51.

Lerner, J. (2009), 'The Empirical Impact of Intellectual Property Rights on Innovation: Puzzles and Clues', *American Economic Review* **99**(2), 343–48.

Llavador, H., Roemer, J. E. and Silvestre, J. (2015), *Sustainability for a Warming Planet*, Harvard University Press.

Lontzek, T. S., Cai, Y., Judd, K. L. and Lenton, T. M. (2015), 'Stochastic Integrated Assessment of Climate Tipping Points Indicates the Need for Strict Climate Policy', *Nature Climate Change* **5**(5), 441.

Lucas Jr, R. E. (1988), 'On the Mechanics of Economic Development', *Journal of Monetary Economics* **22**(1), 3–42.

Lucas, R. (1976), 'Econometric Policy Evaluation: A Critique', *Carnegie-Rochester Conference Series on Public Policy* **1**(1), 19–46.

Magee, C. L., Basnet, S., Funk, J. L. and Benson, C. L. (2016), 'Quantitative Empirical Trends in Technical Performance', *Technological Forecasting and Social Change* **104**, 237–246.

Malthus, T. R. (1798), 'An Essay on the Principle of Population. London: W. Pickering, 1986', *English* .

Mankiw, N. G. and Reis, R. (2018), 'Friedman's Presidential Address in the Evolution of Macroeconomic Thought', *Journal of Economic Perspectives* **32**(1), 81–96.

Mankiw, N. G., Romer, D. and Weil, D. N. (1992), 'A Contribution to the Empirics of Economic Growth', *The Quarterly Journal of Economics* **107**(2), 407–437.

Martínez-Alier, J., Pascual, U., Vivien, F.-D. and Zaccai, E. (2010), 'Sustainable De-Growth: Mapping the Context, Criticisms and Future Prospects of an Emergent Paradigm', *Ecological Economics* **69**(9), 1741–1747.

Marx, K. (1867), *Capital: A Critique of Political Economy.*

Mattauch, L. and Hepburn, C. (2016), 'Climate Policy when Preferences are Endogenous - and Sometimes They Are', *Midwest Studies in Philosophy* **40**(1), 76–95.

Mawson, P., Carlaw, K. and McClellan, N. (2003), Productivity Measurement: Alternative Approaches and Estimates, Technical report, New Zealand Treasury Wellington.

Mazzucato, M., Perez, C., Fageburg, J., Laestadius, S. and Martin, B. (2015), 'Innovation as Growth Policy', *The Triple Challenge for Europe: Economic Development, Climate Change, and Governance. Oxford: OUP* pp. 229–264.

Meadows, D. H., Meadows, D. L., Randers, J. and Behrens, W. W. (1972), 'The Limits to Growth', *New York* **102**, 27.

Meadows, D. H., Meadows, D. L., Randers, J. et al. (1992), *Beyond the Limits: Global Collapse or a Sustainable Future.*, Earthscan Publications Ltd.

Meadows, D. and Randers, J. (2012), *The Limits to Growth: The 30-Year Update*, Routledge.

Mealy, P. and Teytelboym, A. (2017), 'Economic Complexity and the Green Economy'.

Mercure, J., Knobloch, F., Pollitt, H., Lewney, R., Rademakers, K., Eichler, L., van der Laan, J. and Paroussos, L. (2016), 'Policy-Induced Energy Technological Innovation and Finance for Low-Carbon Economic Growth. Study on the Macroeconomics of Energy and Climate Policies.'.

Michalopoulos, S. and Papaioannou, E. (2013), 'Pre-Colonial Ethnic Institutions and Contemporary African Development', *Econometrica* **81**(1), 113–152.

Michel, P. and Rotillon, G. (1995), 'Disutility of Pollution and Endogenous Growth', *Environmental and Resource Economics* **6**(3), 279–300.

Mir, G.-U.-R. and Storm, S. (2016), 'Carbon Emissions and Economic Growth: Production-Based versus Consumption-Based Evidence on Decoupling'.

Mishan, E. J. and Mishan, E. J. (1967), *The Costs of Economic Growth*, Staples Press London.

Moore, G. E. (1965), 'Cramming More Components onto Integrated Circuits', *Electronics* **38**, 8.

Mueller, M. G. and de Haan, P. (2009), 'How much do Incentives Affect Car Purchase? Agent-Based Microsimulation of Consumer Choice of New Cars - Part I: Model Structure, Simulation of Bounded Rationality, and Model Validation', *Energy Policy* **37**(3), 1072–1082.

Nagy, B., Farmer, J. D., Bui, Q. M. and Trancik, J. E. (2013), 'Statistical Basis for Predicting Technological Progress', *PloS One* **8**(2), e52669.

Nannen, V. and van den Bergh, J. C. (2010), 'Policy Instruments for Evolution of Bounded Rationality: Application to Climate–Energy Problems', *Technological Forecasting and Social Change* **77**(1), 76–93.

Naqvi, S. A. A. (2015), 'Modeling Growth, Distribution, and the Environment in a Stock-Flow Consistent Framework'.

Newbery, D. M. (2003), 'Sectoral Dimensions of Sustainable Development: Energy and Transport', *Economic Survey of Europe* pp. 73–100.

Newell, R. G., Jaffe, A. B. and Stavins, R. N. (1999), 'The Induced Innovation Hypothesis and Energy-Saving Technological Change', *The Quarterly Journal of Economics* **114**(3), 941–975.

Nordhaus, W. (2015), 'Climate Clubs: Overcoming Free-Riding in International Climate Policy', *American Economic Review* **105**(4), 1339–70.

Nordhaus, W. D. (1977), 'Economic Growth and Climate: The Carbon Dioxide Problem', *The American Economic Review* **67**(1), 341–346.

Nordhaus, W. D. (1991), 'To Slow or not to Slow: The Economics of the Greenhouse Effect', *The Economic Journal* **101**(407), 920–937.

Nordhaus, W. D. (1993), 'Rolling the "DICE": An Optimal Transition Path for Controlling Greenhouse Gases', *Resource and Energy Economics* **15**(1), 27–50.

Nordhaus, W. D. (2007), 'A Review of the Stern Review on the Economics of Climate Change', *Journal of Economic Literature* **45**(3), 686–702.

Nordhaus, W. D. (2009*a*), 'An Analysis of the Dismal Theorem'.

Nordhaus, W. D. (2009*b*), The Perils of the Learning Model for Modeling Endogenous Technological Change, Technical report, National Bureau of Economic Research.

Nordhaus, W. D. (2014), *A question of balance: Weighing the options on global warming policies*, Yale University Press.

Nordhaus, W. D. and Boyer, J. (2000), 'Warming the World'.

Nordhaus, W. D., Stavins, R. N. and Weitzman, M. L. (1992), 'Lethal Model 2: The Limits to Growth Revisited', *Brookings Papers on Economic Activity* **1992**(2), 1–59.

Nordhaus, W. D. and Tobin, J. (1972), Is Growth Obsolete?, *in* 'Economic Research: Retrospect and Prospect, Volume 5, Economic growth', Nber, pp. 1–80.

Nordhaus, W. D. and Yang, Z. (1996), 'A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies', *The American Economic Review* pp. 741–765.

OECD (2001), *Measuring Productivity - OECD Manual: Measurement of Aggregate and Industry-Level Productivity Growth*, Organisation for Economic Co-operation and Development.

OECD (2011), 'Towards Green Growth'.

O'Neill, D. W., Fanning, A. L., Lamb, W. F. and Steinberger, J. K. (2018), 'A Good Life for all Within Planetary Boundaries', *Nature Sustainability* **1**(2), 88.

O'Neill, J. (2013), *Markets, Deliberation and Environment*, Routledge.

Pacala, S. and Socolow, R. (2004), 'Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies', *Science* **305**(5686), 968–972.

Pearce, D., Barbier, E. and Markandya, A. (2013), *Sustainable Development: Economics and Environment in the Third World*, Routledge.

Perez, C. (2013), 'Unleashing a Golden Age after the Financial Collapse: Drawing Lessons from History', *Environmental Innovation and Societal Transitions* **6**, 9–23.

Pezzey, J. (1989), 'Economic Analysis of Sustainable Growth and Sustainable Development, Environment Department Working Paper 15, World Bank'.

Pezzey, J. C. and Toman, M. A. (2005), Sustainability and its Economic Interpretations, *in* 'Scarcity and Growth Revisited: Natural Resources and the Environment in the New Millenium', Resources for the Future Washington DC.

Pezzey, J. C. et al. (2018), High Unknowability of Climate Damage Valuation means the Social Cost of Carbon will Always be Disputed, Technical report, Centre for Climate Economics & Policy, Crawford School of Public Policy, The Australian National University.

Piketty, T. (2014), 'Capital in the 21st Century'.

Pindyck, R. S. (2013), 'Climate Change Policy: What do the Models tell us?', *Journal of Economic Literature* **51**(3), 860–72.

Pollitt, H., Barker, A., Barton, J., Pirgmaier, E., Polzin, C., Lutter, S., Hinterberger, F. and Stocker, A. (2010), 'A Scoping Study on the Macroeconomic View of Sustainability', *Final report for the European Commission, DG Enviornment, SERI (Sustainable Europe Research Institute), Cambridge Econometrics, http://seri.at/wp-content/uploads/2009/12/SERICE-2010_Macroeconomic-view-of-sustainability.pdf* .

Popp, D. (2002), 'Induced Innovation and Energy Prices', *American Economic Review* **92**(1), 160–180.

Popp, D. (2004), 'ENTICE: Endogenous Technological Change in the DICE Model of Global Warming', *Journal of Environmental Economics and management* **48**(1), 742–768.

Popp, D., Newell, R. G. and Jaffe, A. B. (2010), Energy, the Environment, and Technological Change, *in* 'Handbook of the Economics of Innovation', Vol. 2, Elsevier, pp. 873–937.

Pottier, A., Hourcade, J.-C. and Espagne, E. (2014), 'Modelling the Redirection of Technical Change: The Pitfalls of Incorporeal Visions of the Economy', *Energy Economics* **42**, 213–218.

Qian, Y. (2007), 'Do National Patent Laws Stimulate Domestic Innovation in a Global Patenting Environment? A Cross-Country Analysis of Pharmaceutical Patent Protection, 1978–2002', *The Review of Economics and Statistics* **89**(3), 436–453.

Quah, D. (1999), 'The Weightless Economy in Economic Development'.

Ramsey, F. P. (1928), 'A Mathematical Theory of Saving', *The Economic Journal* **38**(152), 543–559.

Rasul, I. and Hollywood, D. (2012), 'Behavior Change and Energy Use: Is a "Nudge" Enough?', *Carbon Management* **3**(4), 349–351.

Ravn, M. O. and Sterk, V. (2016), 'Macroeconomic Fluctuations with HANK & SAM: An Analytical Approach'.

Rawls, J. (1971), *A Theory of Justice*, Harvard university press.

Raworth, K. (2017), *Doughnut Economics: Seven Ways to Think like a 21st-Century Economist*, Chelsea Green Publishing.

Rezai, A. and Stagl, S. (2016), 'Ecological Macroeconomics: Introduction and Review', *Ecological Economics* **121**, 181–185.

Ricardo, D. (1817), *On the Principles of Political Economy and Taxation.*

Robalino, D. A. and Lempert, R. J. (2000), 'Carrots and Sticks for New Technology: Abating Greenhouse Gas Emissions in a Heterogeneous and Uncertain World', *Integrated Assessment* **1**(1), 1–19.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J. et al. (2009), 'Planetary Boundaries: Exploring the Safe Operating Space for Humanity', *Ecology and Society* **14**(2).

Roegen, N. G. (1976), *Energy and Economic Myths: Institutional and Analytical Economic Essays*, Pergamon Press.

Romer, P. (1990), 'Endogenous Technological Change', *Journal of Political Economy* **98**(5), S71–102.

Romer, P. M. (1986), 'Increasing Returns and Long-Run Growth', *Journal of Political Economy* **94**(5), 1002–1037.

Sachs, J. D. (2015), *The Age of Sustainable Development*, Columbia University Press.

Sachs, J. D., Mellinger, A. D. and Gallup, J. L. (2001), 'The Geography of Poverty and Wealth', *Scientific American* **284**(3), 70–75.

Sachs, J. and Malaney, P. (2002), 'The Economic and Social Burden of Malaria', *Nature* **415**(6872), 680.

Sakakibara, M. and Branstetter, L. (1999), Do Stronger Patents Induce More Innovation? Evidence From the 1988 Japanese Patent Law Reforms, Technical report, National Bureau of Economic Research.

Sandel, M. (2005), 'Should we Buy the Right to Pollute', *Public Philosophy: Essays on Morality in Politics* pp. 93–6.

Sayer, A. (2011), *Why Things Matter to People: Social Science, Values and Ethical Life*, Cambridge University Press.

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., Held, H., Van Nes, E. H., Rietkerk, M. and Sugihara, G. (2009), 'Early-Warning Signals for Critical Transitions', *Nature* **461**(7260), 53.

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C. and Walker, B. (2001), 'Catastrophic Shifts in Ecosystems', *Nature* **413**(6856), 591.

Schumacher, E. F. (1973), *Small is Beautiful: A Study of Economics as if People Mattered*, Random House.

Schumpeter, J. (1942), 'Capitalism, Socialism and Democracy, New York: Harper, 1975'.

Schumpeter, J. A. (1934), *Theory of Economic Development*, Routledge.

Schurr, S. H. (1984*a*), 'Energy Use, Technological Change, and Productive Efficiency: an Economic-Historical Interpretation', *Annual Review of Energy* **9**(1), 409–425.

Schurr, S. H. (1984*b*), 'Productive Efficiency and Energy Use: An Historical Perspective', *Annals of Operations Research* **2**(1), 229–238.

Schurr, S. H. and Netschert, B. C. (1960), 'Energy in the American Economy, 1850-1975'.

Schwab, K. (2017), *The Fourth Industrial Revolution*, Crown Business.

Schwoon, M. (2006), 'Simulating the Adoption of Fuel Cell Vehicles', *Journal of Evolutionary Economics* **16**(4), 435–472.

Scrieciu, S., Rezai, A. and Mechler, R. (2013), 'On the Economic Foundations of Green Growth Discourses: The Case of Climate Change Mitigation and Macroeconomic Dynamics in Economic Modeling', *Wiley Interdisciplinary Reviews: Energy and Environment* **2**(3), 251–268.

Sen, A. (1984), 'The Living Standard', *Oxford Economic Papers* **36**, 74–90.

Sen, A. et al. (1999), 'On Ethics and Economics', *OUP Catalogue* .

Sheshinski, E. (1967), 'Optimal Accumulation with Learning by Doing', *Essays on the Theory of Optimal Economic Growth* .

Shue, H., Gardiner, S. M., Caney, S. and Jamieson, D. (2010), 'Climate Ethics: Essential Readings'.

Simon, J. L. (1980), 'Resources, Population, Environment: An Oversupply of False Bad News', *Science* **208**(4451), 1431–1437.

Simon, J. L. (1981), 'The Ultimate Resource', *Printed on the United States of America by Princeton University Press, Princeton, New Jersey, 415p* .

Sinn, H.-W. (2008), 'Public Policies against Global Warming: A Supply Side Approach', *International Tax and Public Finance* **15**(4), 360–394.

Skidmore, M. and Toya, H. (2002), 'Do Natural Disasters Promote Long-Run Growth?', *Economic Inquiry* **40**(4), 664–687.

Smets, F. and Wouters, R. (2007), 'Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach', *American Economic Review* **97**(3), 586–606.

Smith, A. (1776), *An Inquiry Into the Nature and Causes of the Wealth of Nations*, London: Printed for W. Strahan; and T. Cadell, 1776.

Smulders, S., Toman, M. and Withagen, C. (2014), 'Growth Theory and "green growth"', *Oxford Review of Economic Policy* **30**(3), 423–446.

Solow, R. M. (1956), 'A Contribution to the Theory of Economic Growth', *The Quarterly Journal of Economics* **70**(1), 65–94.

Solow, R. M. (1957), 'Technical Change and the Aggregate Production Function', *The Review of Economics and Statistics* **39**(3), 312–320.

Solow, R. M. (1974*a*), The Economics of Resources or the Resources of Economics, *in* 'Classic Papers in Natural Resource Economics', Springer, pp. 257–276.

Solow, R. M. (1974*b*), 'Intergenerational Equity and Exhaustible Resources', *Review of Economic Studies* **41**(5), 29–45.

Solow, R. M. (1997), 'Georgescu-Roegen versus Solow-Stiglitz', *Ecological Economics* **22**(3), 267–268.

Soper, K. (2014), Alternative Hedonism, Cultural Theory and the Role of Aesthetic Revisioning, *in* 'Cultural Studies and Anti-Consumerism', Routledge, pp. 59–79.

Sopha, B. M., Klöckner, C. A. and Hertwich, E. G. (2011), 'Exploring Policy Options for a Transition to Sustainable Heating System Diffusion Using an Agent-Based Simulation', *Energy Policy* **39**(5), 2722–2729.

Spiegler, R. (2011), *Bounded Rationality and Industrial Organization*, Oxford University Press.

Staub-Kaminski, I., Zimmer, A., Jakob, M. and Marschinski, R. (2014), 'Climate Policy in Practice: A Typology of Obstacles and Implications for Integrated Assessment Modeling', *Climate Change Economics* **5**(01), 1440004.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., De Wit, C. A. et al. (2015), 'Planetary Boundaries: Guiding Human Development on a Changing Planet', *Science* **347**(6223), 1259855.

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M. et al. (2018), 'Trajectories of the Earth System in the Anthropocene', *Proceedings of the National Academy of Sciences* p. 201810141.

Stern, D. I. (2004), 'The Rise and Fall of the Environmental Kuznets Curve', *World Development* **32**(8), 1419–1439.

Stern, D. I. (2011), 'The Role of Energy in Economic Growth', *Annals of the New York Academy of Sciences* **1219**(1), 26–51.

Stern, N. (2007), 'The economics of Climate Change: The Stern Review. Cambridge Univ. Press, Cambridge, UK.', *The Economics of Climate Change: The Stern Review. Cambridge Univ. Press, Cambridge, UK.* .

Stern, N. (2013), 'The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models', *Journal of Economic Literature* **51**(3), 838–59.

Stiglitz, J. (1974), ‘Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths’, *The Review of Economic Studies* **41**, 123–137.

Stiglitz, J. E. (1997), ‘Georgescu-Roegen versus Solow/Stiglitz’, *Ecological Economics* **22**(3), 269–270.

Stokey, N. (1998), ‘Are There Limits to Growth?’, *International Economic Review* **39**(1), 1–31.

Sunstein, C. R. (2015), ‘The Ethics of Nudging’, *Yale J. on Reg.* **32**, 413.

Swan, T. W. (1956), ‘Economic Growth and Capital Accumulation’, *Economic Record* **32**(2), 334–361.

Tabellini, G. (2008), ‘Institutions and Culture’, *Journal of the European Economic Association* **6**(2-3), 255–294.

Taylor, L. (2009), *Reconstructing Macroeconomics: Structuralist Proposals and Critiques of the Mainstream*, Harvard University Press.

Taylor, L., Rezai, A. and Foley, D. K. (2016), ‘An Integrated Approach to Climate Change, Income Distribution, Employment, and Economic Growth’, *Ecological Economics* **121**, 196–205.

Tesfatsion, L. (2002), ‘Agent-Based Computational Economics: Growing Economies from the Bottom Up’, *Artificial Life* **8**(1), 55–82.

Thaler, R. and Sunstein, C. (2008), ‘Nudge: Improving Decisions About Health, Wealth, and Happiness’.

Traeger, C. (2015), Analytic iIntegrated Assessment and Uncertainty.

Turner, G. M. (2008), ‘A Comparison of The Limits to Growth with 30 Years of Reality’, *Global environmental change* **18**(3), 397–411.

Tversky, A. and Shafir, E. (1992), ‘Choice under Conflict: The Dynamics of Deferred Decision’, *Psychological Science* **3**(6), 358–361.

UNEP (2011), *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication*, United Nations Environment Programme.

Van der Meijden, G. and Smulders, S. (2017), ‘Carbon Lock-In: The Role of Expectations’, *International Economic Review* **58**(4), 1371–1415.

Van Vliet, O., De Vries, B., Faaij, A., Turkenburg, W. and Jager, W. (2010), ‘Multi-Agent Simulation of Adoption of Alternative Fuels’, *Transportation Research Part D: Transport and Environment* **15**(6), 326–342.

Vidal, O., Goffé, B. and Arndt, N. (2013), ‘Metals for a Low-Carbon Society’, *Nature Geoscience* **6**(11), 894.

Vogt-Schilb, A., Meunier, G. and Hallegatte, S. (2018), 'When Starting with the Most Expensive Option Makes Sense: Optimal Timing, Cost and Sectoral Allocation of Abatement Investment', *Journal of Environmental Economics and Management* **88**, 210–233.

von Weizsäcker, C. C. (2005), 'The Welfare Economics of Adaptive Preferences'.

Voudouris, V., Stasinopoulos, D., Rigby, R. and Di Maio, C. (2011), 'The ACEGES Laboratory for Energy Policy: Exploring the Production of Crude Oil', *Energy Policy* **39**(9), 5480–5489.

Wagner, G. and Weitzman, M. L. (2016), *Climate Shock: The Economic Consequences of a Hotter Planet*, Princeton University Press.

Warr, B. and Ayres, R. U. (2012), 'Useful Work and Information as Drivers of Economic Growth', *Ecological Economics* **73**, 93–102.

Weitzman, M. L. (2007), 'A Review of the Stern Review on the Economics of Climate Change', *Journal of Economic Literature* **45**(3), 703–724.

Weitzman, M. L. (2009), 'On Modeling and Interpreting the Economics of Catastrophic Climate Change', *The Review of Economics and Statistics* **91**(1), 1–19.

Weitzman, M. L. (2012), 'GHG Targets as Insurance Against Catastrophic Climate Damages', *Journal of Public Economic Theory* **14**(2), 221–244.

Weitzman, M. L. (2013), 'Tail-Hedge Discounting and the Social Cost of Carbon', *Journal of Economic Literature* **51**(3), 873–82.

Wittmann, T. (2008), *Agent-Based Models of Energy Investment Decisions*, Springer Science & Business Media.

Wolf, S., FüRst, S., Mandel, A., Lass, W., Lincke, D., Pablo-Martí, F. and Jaeger, C. (2013), 'A Multi-Agent Model of Several Economic Regions', *Environ. Model. Softw.* **44**, 25–43.

Woodford, M. (2013), 'Macroeconomic Analysis Without the Rational Expectations Hypothesis', *Annu. Rev. Econ.* **5**(1), 303–346.

Wright, T. P. (1936), 'Factors Affecting the Cost of Airplanes', *Journal of the Aeronautical Sciences* **3**(4), 122–128.

Xu, M., Hu, Z., Wu, J. and Zhou, Y. (2008), 'A Hybrid Society Model for Simulating Residential Electricity Consumption', *International Journal of Electrical Power & Energy Systems* **30**(10), 569–574.

Young, A. (1928), Increasing Returns and Economic Progress, *in* 'Readings In The Economics Of The Division Of Labor: The Classical Tradition', World Scientific, pp. 234–248.