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Analysis

Ecological macroeconomics: An application to climate change☆

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ABSTRACT

Ecological economics has not paid sufficient attention to the macroeconomic level both in terms of theory and modeling. Yet, key topics debated in the field of ecological economics such as sustainable consumption, reduction in working time, the degrowth debate, the energy–exergy link, and the rebound effect require a holistic and macro perspective. While this deficiency has been identified before and Keynesian economics has been generally suggested as a potent vehicle to establish economic systemic thinking, very little concrete theorizing and practical suggestions have been put forward. We give further credence to this suggestion and demonstrate the value of tackling key concerns of ecological economics within a Keynesian growth framework. Contextualized by an application to climate change we suggest that policy relevant recommendations need to be based on a consistent view of the macroeconomy. We end with laying out key building blocks for a Keynesian model framework for an ecological macroeconomics.

1. Introduction

Climate change has been the intense subject of economic analysis over more than two decades. More recently, since the publication of the Stern review (Stern, 2006) and IPCC's 4th assessment report there have been many challenges to the standard theory that has dominated the discipline (IPCC — Intergovernmental Panel on Climate Change, 2007). Many novel suggestions and critique for furthering the economics of climate change have been brought forward recently such as a call for better considering critical thresholds such as the 2° target and an emphasis on uncertainty and risk linked to a framing of “dangerous climate change” rather than a focus on “optimal warming” policies based on optimization rationale (Barker, 2008; Barker and Scrieciu, 2010; Weitzman, 2009). Some of the critical contributions, such as considering thresholds and “true limits to growth” can be attributed to the school of ecological economics, which emphasizes a comprehensive inter- and transdisciplinary perspective and broader integration of analyses of economic with ecological systems. Also, it has approached the issue of climate change and of natural systems more generally from a microeconomic perspective. In this line of thought, individual actions and choices are interlinked with the environmental system's dynamics leading into analyses of coupled socio-ecological systems.

Yet, although most of its thinking stems from the recognition of the importance of a taking a system-wide perspective and keeping within broad biophysical limits, ecological economics has neglected the macroeconomic dimension in terms of theory and modeling in its analysis (Spash and Schandl, 2009). Economic investigations in this tradition have mostly been limited to empirical studies and measurement of increasing resource use. This is surprising and a deficit given that the macroeconomic scale is a crucial analytical level for the study of environment–economy interactions and provides important insight regarding effective and acceptable climate policies.

In this paper, we suggest and demonstrate that consistent macroeconomic theorizing and modeling interlinked with a true consideration of ecological limits is essential to inform the debate on climate economics. Going beyond theory, we work towards operationalizing key cornerstones of a consistent and more complete macroeconomic model of economic growth, which respects key tenets of ecological economics. Contextualized by the presentation of these cornerstones, we demonstrate that and how many of the current debates about economic growth can be accommodated within such a framework of ecological macroeconomics. These include discussions on exergy, degrowth, sustainable consumption, the rebound effect, uncertainty and risk, and multi-criteria analysis. In using climate change as a point in case, we aim at making our conceptual theorizing concrete.

The application to climate change allows us to work out the difference of our approach to the standard theory, which is organized

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around neoclassical models of economic growth. These models assume that markets are functioning sufficiently well to ensure the clearing of all markets at all times. In their stronger variant, neoclassical models of economic growth additionally assume that prices correctly reflect intertemporal scarcity, thereby steering the economy to the first best solution. In the context of climate change this assumption is particularly problematic, because one can argue that agents are unable to form rational expectations about highly uncertain future climate damages (Ackerman et al., 2010; Weitzman, 2009). In the past, the constraining expectations structure induced much of the debate on climate economics to focus on the concept of discounting and the realm of moral philosophy. In recent years the focus of analysis has shifted to various forms of market imperfections and failures, both static and intertemporal.

Our suggested macroeconomic modeling framework challenges this type of research by taking a systems perspective in both socio-economic and natural systems' analysis and systematically accounting for key building blocks of ecological economic thinking. Instead of adopting a supply-side approach to the macroeconomy, we argue that a demand-driven model of economic growth is better suited for the study of the social transformation necessary to achieve sustainability in its many facets. Following this route, we are able to shed light on key issues dear to ecological economics such as sustainable consumption, reduced working time, and the rebound effect when confronting the social imperative of growth and investment to ensure socially necessary employment levels with the limits of biophysical systems.

In Section 2, we briefly review prominent integrated economic assessment models used in the analysis of climate change, and then identify potential weaknesses in methodological assumptions usually made and their implications for policy responses to climate change.

Section 3 starts out from the familiar textbook macroeconomic model which centers on the investment–savings relation, we then add endogenous technical change. Increased labor productivity in turn requires energy use to increase which leads to deteriorating environmental quality. We argue that this view of the economy is more consistent with thinking respecting earth-system boundaries and absolute limits to growth, thinking which has importantly been coined by ecological economists. The framework we present provides a consistent structure to analyze the implications of policies advocated on the microeconomic level in the aggregate. In addition, in the absence of rational expectations the behavior of the macroeconomy can be simulated much in the way that large Integrated Assessment Model are, making such a model a natural candidate for the representation of the (energy) demand side in such larger models.

We then demonstrate how policy proposals environmental sustainability can be analyzed in macroeconomic terms, raising questions unseen at the microeconomic level. We also suggest the relationship between per capita income, and labor and energy productivity as the relevant node between growth and the accumulation of greenhouse gases (GHG). We end with reflections regarding the cross-fertilization between ecological thinking and macroeconomics theorizing.

2. Methodological Considerations: Beyond Neoclassical Approaches

2.1. The Neoclassical Approach

Most of contemporary economic discussion relies on the neoclassical approach and climate economics, too, has predominantly used neoclassical growth models. These can be characterized by the assumption that prices clear to ensure the full employment of resources. In doing so, markets also ensure the achievement of the first best solution. Imperfections such as market failures (e.g. in the market for carbon emissions) can usually be remedied by the imposition of optimal policies to correct price signals (Rezai et al., 2012).

The weaker manifestation of such growth models either assume exogenous GDP paths or are of Solow type in which consumption and saving decisions are exogenously determined. Prominent climate models of this type are the FUND model of Anthoff and Tol (2010) and the variant of the PAGE model used in the Stern review (Hope, 2006). Stronger assumptions are placed on growth models of Ramsey type. In these agents consumption and savings decisions are endogenized to maximize utility. Agents are assumed to have perfect foresight. The DICE and RICE models of Nordhaus (2008, 2010) are the most prominent and widely-used models of this type, and have had some policy influence particularly on US American climate policy in terms of suggesting a "carbon ramp" characterized by very moderate and slowly increasing mitigation action over the coming decades.

Ecological economists have criticized neoclassical approaches to environmental problems for various reasons (Barker, 2008). In the context of growth theory and its application to climate change, two are of particular importance. First, neoclassical macroeconomic theory usually employs an aggregate production function which allows ad infinitum factor substitution (Daly, 1997). Another criticism pertains to the usage of overly large discount rates by which potential future debilitating impacts, such as the ones that may be exerted by catastrophic climate change, are "discounted away" (Ackerman, 2008). While correct, both of these criticisms are is not incommensurable with the neoclassical paradigm, and can in principle be overcome by changing a model's functional forms (to Leontief production technology) and parameters (to non-positive discount rates).

We go further and argue that neoclassical approaches in general are less apt for assessing and addressing fundamental social change necessary for avoiding severe environmental destruction. In contrast, due to the built-in rationality and perfect foresight, perfect price signals ensure the realization of the "best of all worlds" once optimal environmental policy has been implemented. Obstacles like biophysical limits or scarce resources are always circumnavigated. Fundamental reorganizations of the economy shifting it to the (optimal) trajectory – even involving large contractions in output – are easily implemented in such models if biophysical limits are stringent enough.

To illustrate this point, we utilize the prominent DICE-07 of Nordhaus (2008), a model that has predominately been used to study optimal warming trajectories in terms of maximizing intertemporal welfare. The model assumes exogenous trajectories in population and productivity growth and finds the combination of consumption, investment, and mitigation choices which maximize the discounted sum of utility from consumption.[1] Nordhaus (2008) investigates what abatement policy is optimal to respect the 2 °C threshold, which has become the policy objective for many parties under the UNFCCC including the European Union,[2] In this first scenario, agents are allowed to implement optimal mitigation measures to stay within the 2° limit. We call this scenario "with abatement". In the second scenario, mitigation is fixed at zero and agents have to use their optimal investment and consumption decisions in a way which curbs emissions by reducing production directly to still limit global warming to 2 °C.[3] The admittedly extreme "without abatement" scenario is still optimal, i.e. welfare-maximizing given the imposed constraints.

Fig. 1 plots results of these two scenario runs in terms of the time profiles for the annualized growth rates of world GDP and per capita consumption for both scenarios. As DICE-07 operates on a decadal time scale; the reported growth rates compare the values of the decade before and after the year given on the x-axis.

Many issues are worth noting, but we limit our discussion to two points: Under the optimal mitigation program, the world economy and per capita consumption continue to grow significantly albeit at

[1] Rezai (2011) presents a detailed description of the DICE-07 model.

[2] The 2° target refers to global average surface warming to a baseline temperature in 1850, which is considered preindustrial.

[3] We use the program GAMS to solve the optimal control problem set out in the GAMS code accompanying Nordhaus (2008). The code which was extended by three command lines is available from the authors upon request.

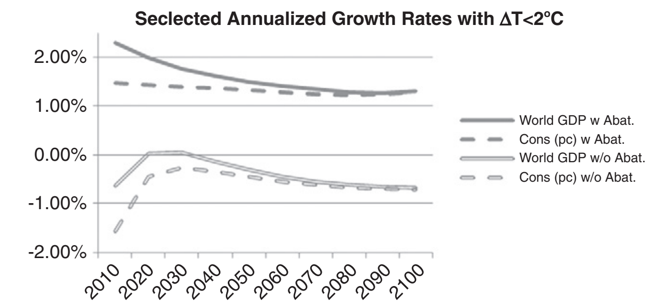

Fig. 1. Optimal growth trajectories with and without mitigation in a neoclassical framework.
Source: Authors' calculations.

decreasing rates. Respecting the 2-degree goal in this scenario is simply a question of diverting resources to mitigation away from consumption. The advent of environmental catastrophe, associated with high degrees of warming say 5 or 6°, can thus easily be averted by using available and new technology. In the second scenario, and the absence of mitigation as a policy option, emissions are reduced by avoiding the underlying economic activity altogether. The model suggests that the optimal response is to lower emission levels which would lead into a century-long recession, albeit of mild dimensions. Over this period, world output and per capita consumption shrink by less than 1% each year.

Both optimal mitigation as well as optimal non-mitigation scenarios thus lead to adjustment paths that seem at odds with reality and policy. While the discussion around stabilizing at 2° warming centers a lot around socio-technological transformation (Loorbach et al., 2008), the world economy in this neoclassical optimal growth model setup easily respects constraints on economic activity and adjusts smoothly.

Smoothness of adjustment is no singular model result, but a property of neoclassical optimal growth models, where adjustment *always* occurs smoothly. In the case of output contraction, capital stock is instantaneously run down in order to guarantee that targeted output can be achieved under full employment of capital and labor. Such macroeconomic behavior contrasts strongly with the experience of the Great Recession. Clearly, any concerns and deliberations of concern for the "degrowth" movement (Kallis, 2011; Martinez-Alier, 2009) are completely absent in this kind of model world.

This shortcoming has also been realized by the modelers themselves. As Nordhaus states (Nordhaus, 2010, p. 11,725): "Analyses using integrated assessment economic models present an unrealistically smooth and harmonious picture of the functioning of economic and political systems in much the way that global climate models miss the turbulence of small-scale weather systems." and Nordhaus (1997, p. 322) for further warning to base policies on model results: "Along the economically efficient emission path, the longrun global average temperature after 500 years is projected to increase 6.2 °C over the 1900 global climate. While we have only the foggiest idea of what this would imply in terms of ecological, economic, and social outcomes, it would make the most thoughtful people, even economists, nervous to induce such a large environmental change." Nonetheless, policy advice from economists on this issue remains based on insight derived from solely neoclassical models.

2.2. Towards Ecological Economics: Considering Thresholds and Instabilities

Stepping outside the model world, the suggestion that the economy needs to stabilize in order to respect the limitations implied by the finiteness of resources and other environmental constraints is an important topic within climate science and ecological economics. Ecological economists reject the smoothness of transitions to a steady state implied by neoclassical growth models. However, there has been relatively little concrete macroeconomic theorizing on the growth–environment nexus (notable exceptions are Barker et al., 2012; Daly, 1973; Harris and Goodwin, 2003; Victor, 2012). Few studies have explored the implications of a zero growth economy; recently, Jackson (2009) and Jackson and Victor (2011), Victor (2008, 2012), have begun to explore the structural drivers of growth and the manner in which a zero-growth economy could function, questions also prominent in the "degrowth" movement (Martinez-Alier et al., 2010; Schneider et al., 2011). The strong sustainability paradigm generally follows from the laws of thermodynamics (Ayres et al., 1998; Georgescu-Roegen, 1971). Given the fact that in a currently closed system (the earth) entropy (heat or disorder) is bound to increase and free energy (exergy) to decrease, the feedback from large entropy on human activity should finally lead to rising costs of resource use and limits on economic growth (Ayres and Warr, 2009; Smil, 2005).[4] Unless the economy manages to tap into the large amounts of energy the earth receives from the sun, this creates tensions with the economic trend of rising energy use per capita as the mechanism to raise labor productivity.

Söderbaum (1999) and Speth (2008) highlight the important societal adjustment necessary to achieve a macroeconomic reconfiguration and the current institutional and behavioral roadblocks preventing and it. Yet, neoclassical models of climate change continue to ignore society and institutions, and as a consequence, climate policies like "Contract and Converge" (Contraction of emissions to a safe level and convergence to equal per capita emissions) are easily implemented in this modeling world.

Modeling approaches that truly reflect the issues at heart of the conflict between the social growth imperative and biophysical limits are in dire demand. As many argue, a consistent modeling approach to economic growth in the tradition of Domar (1946), Harrod (1939), Kaldor (1961), Kalecki (1971) and Keynes (1936) is able to address this conflict (Gowdy, 1991; Holt et al., 2010; Kronenberg, 2010a; Spash, 2007). Such models assume a different kind of macroeconomic causality, a different model "closure" (Sen, 1963; Taylor, 2004; Taylor and Lysy, 1979). These modeling frameworks are more comprehensive; they can in fact encompass neoclassical closure rules: full employment of resources due to utility and profit maximization and saving-determined investment based on loanable-funds theory. Yet, importantly, whereas neoclassicists rule out involuntary unemployment due to the assumption that all prices, including the wage, will adjust until supply meets demand, Keynesian closures feature involuntary unemployment, an empirical fact and concern of any social policy. In Keynesian models, the nominal wage is usually seen as set by past periods or by social institutions. Causality runs from autonomous saving and investment decisions to output adjustment in the usual "IS" textbook fashion. Realized investment and consumption plans can be large enough to use all of available capacity, but mostly they fall short of this level and involuntary unemployment results. Demand growth through fiscal expansion is one way to avoid the social instability associated underutilization.

Keynesian macroeconomics has not been dormant and has made major advances over the past 50 years. This includes the theory of endogenous technical change as spelled out in Kaldor (1978) and Foley and Michl (1999). Labor productivity is viewed as increasing due to increasing returns and wage cost pressures. If unemployment falls as working time is reduced, workers can ask for higher wages and capitalists presumably search for ways in substituting labor by machines, increasing unemployment and labor productivity. Macroeconomic aggregates such as unemployment are therefore important determinants of the economy and its interactions with the environment and policy prescriptions must include a consistent view of the

[4] Strictly speaking, the world is an open system because it interacts with open space, receiving energy from the sun and other sources and remitting heat. Given current technologies, such interactions are of minor importance for the economy.

macroeconomy. A further advantage of non-neoclassical approaches is that they permit behavioral assumptions other than utility maximization and for various objective metrics, including rules derived from multi-criteria analysis. Thereby, our approach adheres to the value pluralism characteristic of ecological economics (Gowdy and Erickson, 2005; Norgaard and Richard, 1989; Røpke, 2005).

Another commonality with ecological economics is the fact that Keynesian theory perceives the macroeconomy as the sum of collective social actors (as compared to the standard neoclassical assumption of the representative agent). Traditionally recognized "classes" such as wage earners and industrial and financial capitalists would be typical examples. This enables the study of the effects of redistribution of income or wealth on effective demand and output. A cornerstone of Keynesian, or demand-driven, macroeconomics is the *Paradox of Thrift*. At the aggregate level, output adjusts to bring saving and investment into equality. If one set of actors, e.g. households as a group, try to save more than the current level of capital formation, then their reduced overall consumption will lead income generated by production to fall, until total saving comes back into equality with investment. Higher thrift does not increase output or capital formation. This Paradox of Thrift stands in exact opposition to neoclassical theory. The Paradox of Thrift also has important implications when considering the implications of environmental policy as discussed below.

Overall, Keynesian theory and its key building blocks can serve as a much-needed conceptual framework to investigate the aggregate macroeconomic effects of policy for sustainability and thus provide a foundation of ecological macroeconomics. In addition to the rebound effect, implications of degrowth, which in their very nature are macroeconomic, can be usefully discussed in such a setting. The same holds true for the interrelated questions of sustainable consumption and reduced working time, which we discuss below.

Keynesian macro models have been used in combination with ecological economics before, yet with remaining, important deficiencies (Jackson and Victor, 2011; Stern, 2006; Victor, 2008, 2012). Importantly, Gowdy embarked on a search for common ground between *bio-economics* and post Keynesian economics (1991). The model of Victor and Rosenbluth (2007) is an application to climate change of such an approach to the study of feed-back mechanisms between policies promoting economic growth and biophysical limits. Using a basic Keynesian model, a set of growth and degrowth scenarios for Canada are examined with the conclusion that reliance on economic growth is not necessary and even in a zero growth society with the right policy mix, unemployment can be reduced dramatically, poverty eliminated and (relatively weak) Kyoto set greenhouse gas emissions targets achieved at the same time. While zero-growth in these scenarios is not the objective, it is not a hindrance to achieving environmental and social policy objectives. Also, Victor and Rosenbluth (2007) cast doubt on the belief that restructuring of final demand towards resource-unintensive goods as suggested by Harris (2009) and Kronenberg (2010b) such that the economy can continue to grow is in itself sufficient.

While previous studies trace out the implications of economic stagnation for distribution, resource use, and social and fiscal policy, they do not consider relationships that we deem essential in the discussion of ecological growth models, such as the nexus between energy intensity and labor productivity or the one between sustainable consumption and reduced working time.

3. Macroeconomic Analysis for "True" Climate Policy

Frank Ackerman (2008) recently argued that for "true" climate policy employing a low discount rate is fundamental in order not to discard future dangerous climate change. We argue there are additional analytical "ingredients" necessary in order to arrive at a more complete economic analysis of climate change.

In the previous section, we demonstrated the limits to the neoclassical growth concepts in terms of addressing biophysical limits. Yet, one might ask why care about the macroeconomy at all? In this section, we provide examples how macroeconomic trends importantly determine the economy and its exchange with the environment. We also demonstrate how easily concerns of ecological economics can be addressed within a non-neoclassical growth framework.

It is important to note that we are not trying to spell out a complete model and derive equilibrium conditions for it. The aim of this section, partially based on simple algebra, is to continue the search for common ground, which, among others, Gowdy (1991) started.

Relying on integral parts of a Keynesian growth model, we illustrate this common ground in the application to climate change. We, therefore, proceed with an expositional thematic treatment instead of a complete model setup, which remains for future work. We set out by identifying four issues as fundamental for a more complete economic analysis of climate change. All issues are associated with counterintuitive results if we use a more comprehensive Keynesian framework and indicate to us that there is value in having them compose the core of a more complete model. These issues are (i) sustainable consumption, (ii) reduced working time, and (iii) the role of labor productivity and energy intensity, and (iv) considering the rebound effect in a demand-driven version.

3.1. Sustainable Consumption

Ecological economists frequently discuss policies for "sustainable consumption" suggesting the need to stagnate or reduce consumption levels in order to respect key earth system's boundaries (such as keeping warming below 2° above preindustrial levels). At the macroeconomic level this concept presumably implies that the growth rate of consumption per capita should be low and/or falling as we may have already overstepped earth's carrying capacity (see Wackernagel et al., 2006).

To analyze the effects of sustainable consumption, we begin with the simple textbook investment–saving relation.

$$I = S = Y - C \tag{1}$$

Investment, I, has to equal saving, S, which equals the share of income that is not consumed. If consumption decreases, investment must rise to absorb the potential increase in the saving share of income. This is always the case under Say's Law and the assumption of full employment. The alternative is that the paradox of thrift kicks in and output contracts. However, a *low* saving rate would be required for the economy to settle at a steady state; saving would only be needed to maintain a constant level of the capital stock per capita by financing investment to offset loss of productive capacity due to depreciation. A falling saving rate also fits in with the long-term view adopted by Keynes (1930) in his essay on "Economic Possibilities for our Grandchildren" and Ramsey (1928) when he incorporated consumption satiation at a level of "Bliss" in his original optimal growth model. The idea of lowering consumption is intuitive on the microeconomic level, but bears counterintuitive implications in the aggregate.

3.2. Reduced Working Time

Veblen (1899) further argues that consumption satiation is precluded by the contemporary form of capitalism. Even if he was incorrect and consumption could be lowered to sustainable levels and economic output shrunk, unemployment would result. Ecological economists are aware of the importance of continuous economic growth for the creation of employment in an advanced capitalist economy. Schor (2010) and others argue that reducing hours worked per capita can be a remedy to this problem. The reasoning is not completely clear but to avoid ever lower levels of working time, this policy prescription seems to imply that labor productivity growth comes to a halt under output stabilization. Implicit tradeoffs in fact are rather more complicated.

There is little reason to assume that technical change would come to a halt given the current social relations of production. Reducing working time is equivalent to a tightening labor market. As unemployment falls, wage earners are able to bid for higher wages (Okun, 1962) which induces firm owners to reduce the wage bill through technical advancement (Foley and Michl, 1999). Labor is shed until the wage pressures ease sufficiently. Reducing hours worked per capita can in fact worsen environmental problems by spurring increases in labor productivity. Whether higher productivity spills over into further job loss or higher per capita output is a question that can only be addressed by looking at the economy in the aggregate.

3.3. Labor Productivity and Energy Intensity

Historically, a crucial factor supporting rising labor productivity and per capita income has been increasing use of energy. This has been demonstrated abundantly and is widely accepted among ecological economists, but never fully taken on board by the professional mainstream. It dates back to the "energetics" movement of the last half of the 19th century (Martinez-Alier and Schlüpmann, 1990; Mirowski, 1989) but not much further.[5] A slightly overstated paraphrase is "The currency of the world is not the dollar, it's the joule" (Lewis, 2007). As outlined above, productivity growth responds positively to output growth itself and employment expansion. The dynamics of labor productivity, then, can easily determine the dynamics of energy use and of GHG accumulation. Increases in income per capita and labor productivity may come with increases in energy use and carbon emissions.

Improvements in energy efficiency as a "silver bullet" solution to the conflicting goals of economic growth and environmental sustainability are often cited in the public debates on climate change. As pointed out above, the rebound effect is one of the reasons why sound economic and environmental policies need to consider alternatives to such a quick fix. Empirical data also cast doubt on this position (Dittrich et al., 2012).

Simple algebra in the widely-used form of growth accounting (Syrquin, 1988) can be used to illustrate the issues involved. Let X be real output, and assume that the both labor force and population are proportional to a variable L (that is, labor force participation rates are stable). Energy use at any time is E. Let $\lambda = X/L$ and $\varepsilon = X/E$ stand for labor and energy productivity respectively. If $e = E/L$ is energy intensity then it is easy to see that $\lambda = \varepsilon e$. In the context of climate change this identity is part of the well-known Kaya Identity (Waggoner and Ausubel, 2002).[6] Let a "hat" over a variable denote its growth rate, e.g $\hat{X} = (dX/dt)/X = \dot{X}/X$. It follows that

$$\hat{\lambda} = \hat{\varepsilon} + \hat{e} \quad (2)$$

or labor productivity growth is the sum of the growth rates of energy intensity and energy productivity. Taylor (2009) uses data to illustrate this relationship and demonstrates the robustness of the relationship between growth in energy use per worker, $\hat{e}$, and labor productivity growth, $\hat{\lambda}$. In Fig. 2 the slope of the relationship on a world level for the period 1990–2004 is around 0.6, suggesting a substantial contribution of more energy use per worker to higher productivity. This finding is consistent with the view of Smil (2005) and others that much productivity-increasing technical change relies on higher energy use per unit employment. Foley (2012) and Haberl et al. (2011) regard the extension of the life-style currently practiced in the Global North to everybody as unsustainable given material and energetic requirements.

[5] Leibniz proposed the basic concept of energy around 1680 but it did not take its modern form until the 1840s.

[6] Let θ be the carbon intensity of energy, such that emissions $Z = \theta E$, then the Kaya identity it says that $Z = (\lambda/\varepsilon)\theta$.

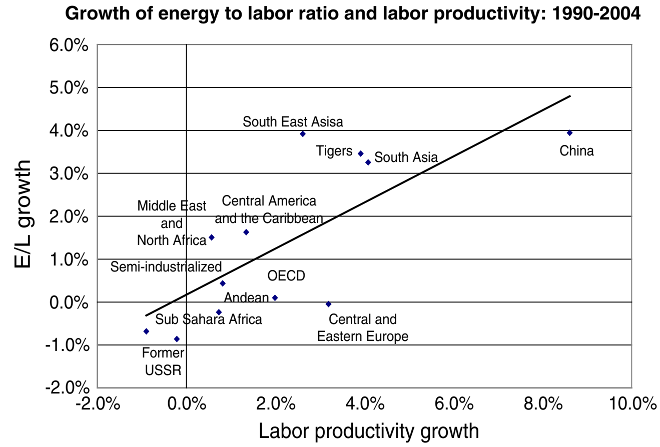

Fig. 2. Relationship between the growth rates of labor productivity and energy intensity.
Source: Taylor (2009).

3.4. Demand-driven Version of the Rebound Effect

If Veblen (1899) is right and consumption levels cannot be lowered for social or cultural reasons (Brekke and Howarth, 2002, ch.7), continuous improvements in energy efficiency, $\hat{\varepsilon}$, could offset the deleterious effect of growth in consumption and output. Ecological economists have cast doubt on this idea based on the empirical finding that improvements in efficiency are off-set by increases in demand. This "rebound effect" or "Jevon's Paradox" (Jevons, 1866) is usually explained on a microeconomic level using price and income effects: improvements in efficiency reduce the price of using a good or service which increases the demand for this good (Sorrell, 2007; Sorrell and Dimitropoulos, 2008).

Barker et al. (2009) and Saunders (2000) explore the rebound effect on a macroeconomic and industry level based on the Paradox of Thrift. They challenge the notion that in the context of climate change, the trade-off between sustainable consumption and working time set out above could be overcome if saving is partially directed toward enhanced efforts at greenhouse gas mitigation. They find that in a demand-driven world, increases in expenditure (e.g. through a government decarbonization program involving a carbon tax) would increase output and thereby carbon emissions. This is a truly macroeconomic variant of the "rebound effect" which is independent of price and income effect on the microeconomic level (in most cases this rebound effect is partial, implying that the net efficiency gain is still positive). Adding to our simple framework, we restate Eqs. (3′) and (3″) to include mitigation as follows.

Let μ be the share of output dedicated to mitigation efforts. In the short run output will be determined by the requirement that investment has to equal available saving.

$$I + \mu Y = S = Y - C \quad (3')$$

$$Y = \frac{I + C}{1 - \mu} \quad (3'')$$

This means that an increase in mitigation expenditure increases the investment multiplier and thus output. With constant carbon intensity of output, additional expenditure will increase carbon emissions, thereby partially counteracting the initial aim of a reduction in carbon emissions.[7] It is important to note that this effect operates

[7] The assumption that carbon intensity is constant is based on the belief that mitigation goods have to be produced given the current carbon intensity (e.g. windmills have to be produced using fossil-based energy sources).

through the paradox of thrift and cannot occur in a neoclassical model of full employment. In an optimal growth model the level of output and associated emissions are fixed in each unit of time. The optimizing agent only decides on the composition of the expenditure basket (consumption, investment, and mitigation). In contrast, in a demand-driven world, additional demand injections can affect the level of economic activity and emissions, an important and policy relevant finding.

3.5. Identifying the Building Blocks of a (More) Complete Model

The elements set out in the previous section can be combined with macroeconomic reasoning to form a comprehensive framework of the interactions between the macroeconomy, GHG dynamics, and climate change. Fig. 3 illustrates how the growth dynamics of output, labor productivity, employment, energy use, and carbon emissions would interact in such a demand-driven model.

The flow of information would be as follows: Assume there is growth, macroeconomic theory predicts that this leads to higher productivity. Increases in productivity growth have multiple effects. First, in the absence of further output growth, it leads to unemployment, a crucial aspect of the degrowth debate. The proposal to reduce working time to counter unemployment might decrease unemployment temporarily. Due to endogenous productivity growth, this can lead to further productivity growth to ease wage pressures on the labor market. Second, the debate around energy and exergy predicts that higher labor productivity also entail higher energy use. Higher energy use either leads to higher resource use and emissions or it is offset through sufficient efficiency increases. The debate around the rebound effect predicts that this leads to yet higher growth.

Such a dynamic model involving all these features is clearly complex and would be characterized by at least four state variables — the capital stock growth rate (or the output/capital ratio), the capital stock per capita, GHG concentration per capita, and the output/GHG ratio. Feedbacks, such as linkages between output, distribution, productivity growth, employment, and climate change, not considered in the analysis of the previous section would have to be taken into account. This requires numerical simulations; results would probably be characterized by inherent instability and complexity. Such analysis is beyond the scope of this paper. However, we want to mention how such a model would relate to the existing integrated assessment models used in environmental and climate science.

A demand driven approach is of importance for economically framed analyses of environmental policies; it is of similarly high relevance for the larger field of integrated assessment models, which are the workhorses of environmental and climate change analysis.[8] Such analysis has been key for assessing climate change policy and exploring the complex, future interactions between factors like land and energy use, economic development, greenhouse gas emissions (GHG), the climate system and ecosystem impacts (Van Vuuren et al., 2010).

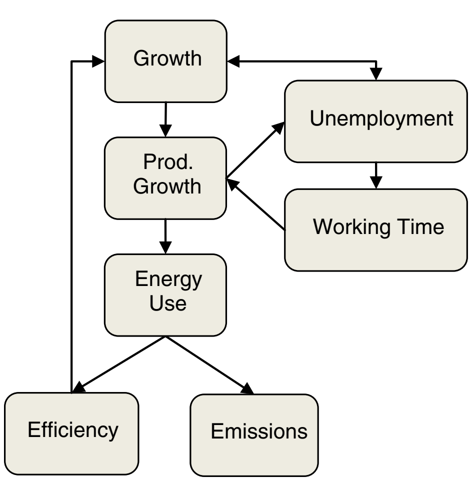

Fig. 3. Key dynamic modeling elements.

More comprehensive integrative assessment models, consisting of several coupled modules as compared to the simpler economic frameworks discussed above, have studied the implications of (unmitigated) climate change using scenario analysis. As one example, the most prominent climate scenarios in wide usage by analysts, the SRES emissions scenarios, which were produced for the third assessment report of the IPCC (Nakicenovic and Swart, 2000), work around four narrative storylines, describing key drivers of greenhouse emissions and their evolution up to 2100 for the globe and large world regions. Each storyline combines a set of demographic, social, economic, technological, and environmental trends along the lines of the Kaya identity. These drivers however do not interact and eventually develop in very different and increasingly irreversible directions. For the new generation of IAMs to be used in the Fifth Assessment report of the IPCC, integration of mitigation and feedbacks are key issues to be tackled. As recently suggested by Moss et al. (2010) there is a need for enhanced information from such integrated analysis and a better study of feedbacks as only a limited amount of possible feedbacks has been assessed as of today. Particularly, it will be important to better study key feedbacks leading from drivers of demand for energy and land to mitigation and back to income and economic growth as drivers (Fig. 4). If absolute decoupling of energy use and growth is considered infeasible, as suggested by the evidence in the literature, emission reduction to achieve low carbon futures, such as a 2° trajectory, avoiding "dangerous" climate change would need to be achieved otherwise, i.e. by cutting growth intentionally or as a result of stringent international or national policies. A demand-driven approach can readily shed light into the macroeconomic and social implications of such measures.

4. Conclusions: Ecological Economics and the New Limits to Growth

Ecological economics has developed rapidly over the last two decades; many important insights have been derived. Yet, we argue that it is has not paid sufficient attention to the macroeconomic level. This deficiency has been identified before and Keynesian economics has been suggested as a potent vehicle to establish economic system's thinking, yet very few concrete ideas and details have been put forward. We give further reasons to this suggestion and outline how such ecological macroeconomic reasoning in the Keynesian tradition could look like. We do so by using macroeconomic relations to evaluate concepts developed to tackle ever-increasing resource consumption in an application to climate change. Important tenets of Keynesian thinking, money and fundamental uncertainty, are not properly treated in this analysis. These aspects are left for further research.

Neoclassical economics imposes the constraining assumptions of optimizing behavior and rational expectations about the future on its models. This limits the scope of research questions considerably. By adopting a demand-driven approach in which full employment is not the rule, many important issues discussed by ecological economists can be addressed, assessed and checked against the popular wisdom. Many times, results derived are counterintuitive and thus bring along valuable and policy relevant information.

Abandoning Say's Law of sufficient demand creates the social imperative of economic growth as a means to ensure socially-accepted

[8] The above discussed economic models are generally considered integrated ECONOMIC assessment models and form a group of their own in this model class.

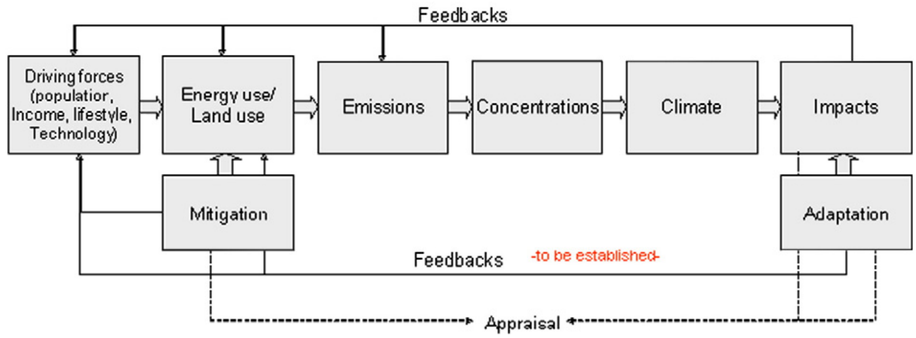

Fig. 4. Integrated assessment analysis framework for assessing climate change policies including suggested feedback loops.
Source: Van Vuuren et al., 2010.

employment levels (the growth–degrowth debate). Increasing economic growth and income levels require higher energy use per capita which entails higher carbon emissions (the Energy–Exergy–Entropy debate). Mitigation can be used to avoid negative environmental impacts, but abatement efforts might not be as effective due to their positive effects on output (a macroeconomic variant of the rebound effect). If biophysical limits are, however, binding such that further growth is impossible despite large mitigation efforts, the social implications of such a growth – or more appropriately – steady state strategy need to be reinvestigated (sustainable consumption and reduced working time).

While it is important to infuse ecological thinking into macroeconomics theories, it is also important to infuse macroeconomic thinking into ecological theories. A consistent macroeconomic framework allows disentangling and improving the implications of policy recommendations advocated by Ecological Economists for the economy as a whole. Sustainable consumption, reduced working time, and "green" investment are important and excellent examples where the macroeconomic implications of these policies are not immediately obvious, sometimes counterintuitive, and deserve further thought and more comprehensive analysis.

Appendix A. Supplementary Data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2012.10.008.

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