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A stock-flow-fund ecological macroeconomic model

Yannis Dafermos [a,*], Maria Nikolaidi [b], Giorgos Galanis [c]

[a] Department of Accounting, Economics and Finance, University of the West of England, Bristol, UK
[b] Department of International Business and Economics, University of Greenwich, London, UK
[c] Institute of Management Studies, Goldsmiths, University of London; New Economics Foundation, London, UK

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ABSTRACT

This paper develops a stock-flow-fund ecological macroeconomic model that combines the stock-flow consistent approach of Godley and Lavoie with the flow-fund model of Georgescu-Roegen. The model has the following key features. First, monetary and physical stocks and flows are explicitly formalised taking into account the accounting principles and the laws of thermodynamics. Second, Georgescu-Roegen's distinction between stock-flow and fund-service resources is adopted. Third, output is demand-determined but supply constraints might arise either due to environmental damages or due to the exhaustion of natural resources. Fourth, climate change influences directly the components of aggregate demand. Fifth, finance affects macroeconomic activity and the materialisation of investment plans that determine ecological efficiency. The model is calibrated using global data. Simulations are conducted to investigate the trajectories of key environmental, macroeconomic and financial variables under (i) different assumptions about the sensitivity of economic activity to the leverage ratio of firms and (ii) different types of green finance policies.

1. Introduction

Ecological macroeconomics is an emerging interdisciplinary field that examines the macroeconomy as part of the ecosystem, taking explicitly into account the biophysical limits of a finite planet (Jackson, 2009; Rezai et al., 2013; Rezai and Stagl, 2016). It largely draws on the synthesis of ecological economics and post-Keynesian macroeconomics which has been identified as a fruitful avenue for the combined examination of economic and ecological issues (Mearman, 2009; Kronenberg, 2010; Fontana and Sawyer, 2013, 2016).

Recent research has contributed to the development of the building blocks of ecological macroeconomics. Victor and Rosenbluth (2007), Victor (2012) and Barker et al. (2012) have presented simulation econometric models with Keynesian features that incorporate various environmental issues. Jackson (2009), Fontana and Sawyer (2013), Rezai et al. (2013) and Taylor et al. (2016) have put forward theoretical frameworks that combine ecological with Keynesian (or post-Keynesian) insights. Berg et al. (2015), Jackson and Victor (2015), Naqvi (2015) and Fontana and Sawyer (2016) have examined environmental aspects within stock-flow consistent or monetary circuit models that include a financial sector.

However, there is still a lack of an integrated ecological macroeconomic model that combines physical variables with monetary variables in a consistent way. This paper develops such a model by combining the stock-flow consistent (SFC) approach of Godley and Lavoie (2007) with the flow-fund model of Georgescu-Roegen (1971, ch. 9; 1979, 1984). Our stock-flow-fund model has the following key features. First, monetary and physical stocks and flows are explicitly formalised taking into account the accounting principles and the laws of thermodynamics. Second, Georgescu-Roegen's distinction between stock-flow resources and fund-service resources is adopted. Third, output is demand-determined but supply constraints might arise either due to environmental damages or due to the exhaustion of natural resources. Fourth, climate change influences directly the components of aggregate demand. Fifth, finance affects macroeconomic activity and the materialisation of investment plans that determine ecological efficiency. The model is calibrated using global data. Simulations are conducted to illustrate the channels through which the ecosystem, the financial system and the macroeconomy interact. Particular attention is paid to the non-neutral role of finance in the ecosystem-macroeconomy interactions.

The paper is organised as follows. Section 2 describes briefly the foundations of the model. Section 3 analyses the structure of the model. Section 4 presents our simulation analysis. Section 5 summarises and concludes.

2. Foundations of the model

The key innovation of the post-Keynesian SFC approach developed by Godley and Lavoie (2007) is the explicit integration of accounting

* Corresponding author at: University of the West of England, Frenchay Campus, Coldharbour Lane, Bristol BS16 1QY, UK.
E-mail address: Yannis.Dafermos@uwe.ac.uk (Y. Dafermos).

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into dynamic macro modelling. This integration permits the detailed exploration of the links between the real and the financial spheres of the macroeconomy. However, a prominent drawback of the SFC models is that they ignore the transformation of matter and energy that takes place due to economic processes and the environmental problems caused by this transformation. This feature comes in stark contrast with the fundamental propositions of ecological economists according to which the macroeconomy is part of the ecosystem and economic activity unavoidably respects the laws of thermodynamics (see Daly and Farley, 2011).

The flow-fund model of Georgescu-Roegen (1971, ch. 9; 1979; 1984) encapsulates the fundamental propositions of ecological economics. His model relies on a multi-process matrix that depicts the physical inflows and outflows that take place during the various economic processes, drawing explicitly on the First and the Second Law of Thermodynamics. His model also makes a crucial distinction between the stock-flow resources and the fund-service resources (see also Mayumi, 2001; Kurz and Salvadori, 2003; Daly and Farley, 2011). The stock-flow resources (non-renewable energy and material resources) are transformed into what they produce (including by-products), can theoretically be used at any rate desired and can be stockpiled for future use. The fund-service resources (labour, capital and Ricardian land) are not embodied in the output produced, can be used only at specific rates and cannot be stockpiled for future use. Crucially, these types of resources are not substitutable: they are both necessary for the production process.

Our stock-flow-fund ecological macroeconomic model integrates the post-Keynesian SFC approach with Georgescu-Roegen's flow-fund model. The model that we develop relies on four matrices: 1) the physical flow matrix; 2) the physical stock-flow matrix; 3) the transactions flow matrix; 4) the balance sheet matrix. The first matrix is a simplification of the matrix that Georgescu-Roegen's used in his flow-fund model. The second matrix captures the dynamic interaction between physical stocks and flows and is a natural extension of the physical flow matrix. The third matrix and the fourth matrix describe the changes in the stocks and flows of the macroeconomic and the financial system, following the traditional formulations in the SFC literature.

In line with the post-Keynesian tradition, output in the model is determined by aggregate demand. However, supply-side constraints might arise primarily due to environmental problems. This is formalised by using a Leontief-type production function that specifies the supply-determined output drawing on Georgescu-Roegen's distinction between stock-flow and fund-service resources. It is assumed that environmental problems affect in a different way each type of resources. Depletion problems affect the stock-flow resources (i.e. non-renewable energy and material resources can be exhausted) while degradation problems, related to climate change and the accumulation of hazardous waste, damage the fund-service resources (by destroying them directly or by reducing their productivity). Climate change and its damages are modelled using standard specifications from the integrated assessment modelling literature (see Nordhaus and Sztorc, 2013). However, a key departure from this literature is that global warming damages do not affect in our model an output determined via a neoclassical production function. Instead, they influence the fund-service resources of our Leontief-type production function and the components of aggregate demand.

3. Structure of the model

The model portrays the global macroeconomy without a government sector. There is one type of material good that can be used for durable consumption and (conventional and green) investment purposes. Firms produce this good by using: (i) matter which has to be extracted from the ground (non-metallic minerals and metal ores); (ii) matter that has been recycled using demolished/discarded socio-economic stock[1]; and (iii) energy that comes either from non-renewable sources (e.g. oil, gas and coal) or renewable sources (e.g. sun, wind).[2] The by-products of the production process are CO_2 emissions, waste and dissipated energy.[3]

Production can be made by using either green capital or conventional capital. Compared to conventional capital, green capital is characterised by lower energy intensity, lower material intensity and higher recycling rate. Moreover, green capital produces energy using renewable sources while conventional capital produces energy using non-renewable sources. Hence, the use of green capital is conducive to a low-carbon economy.

Firms invest in conventional and green capital by using retained profits and loans. Banks impose credit rationing on firm loans, playing thereby a crucial role in the determination of output and the accumulation of green capital. Households provide their labour services to firms. They buy durable consumption goods and accumulate wealth in the form of deposits. They do not take out loans. Commercial banks distribute all their profits to households. To avoid complications related to inflation, it is assumed that the price of consumption and investment goods is constant and equal to unity. Using US dollar ($) as a reference currency, this means that each good values 1 US$.

3.1. Ecosystem

Table 1 depicts the physical flow matrix of our model. This matrix captures the First and the Second Law of Thermodynamics. The First Law of Thermodynamics implies that energy and matter cannot be created or destroyed when they are transformed during the economic processes. This is reflected in the material and energy balance. The first column in Table 1 depicts the material balance in Gigatonnes (Gt).[4] According to this balance, the total inputs of matter into the socio-economic system over a year (extracted matter, the carbon mass of non-renewable energy and the oxygen included in CO_2 emissions) should be equal to the total outputs of matter over the same year (industrial CO_2 emissions and waste) plus the change in socio-economic stock. The second column in Table 1 depicts the energy balance in Exajoules (EJ). According to this balance, the total inputs of energy into the socio-economic system over a year should be equal to the total outputs of energy over the same year. Symbols with a plus sign denote inputs into the socio-economic system. Symbols with a minus sign denote outputs or changes in socio-economic stock. The Second Law of Thermodynamics is captured by the fact that the economic processes transform low-entropy energy (e.g. fossil fuels) into high-entropy dissipated energy (e.g. thermal energy).

Table 2 displays the physical stock-flow matrix of our model.[5] This matrix presents the dynamic change in those physical stocks that are considered more important for human activities. These are the material and non-renewable energy reserves, the atmospheric CO_2 concentration, the socio-economic stock and the stock of hazardous waste. The first row of the matrix shows the stocks of the previous year. The last row presents the stocks at the end of the current year after the additions to stocks and the reductions of stocks have taken place. Additions are denoted by a plus sign. Reductions are denoted by a minus sign.

The reserves of matter and non-renewable energy are those volumes expected to be produced economically using the existing technology. The reserves stem from the resources which are the volumes presenting

[1] The socio-economic stock includes capital goods and durable consumption goods.

[2] For brevity, the energy produced from (non-)renewable sources is henceforth referred to as (non-)renewable energy in the paper.

[3] For simplicity, the model does not incorporate energy and matter from biomass. However, the figure used for the share of renewable energy in our calibrations includes bioenergy to facilitate comparison with other studies.

[4] For the use of the material balance in material flow accounting see Fischer-Kowalski et al. (2011).

[5] For a similar presentation of the physical stock-flow interactions see United Nations (2014).