Ecological Economics 131 (2017) 191–207

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

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

ARTICLE INFO

Article history:
Received 31 January 2016
Received in revised form 22 May 2016
Accepted 12 August 2016
Available online xxxx

Keywords:
Ecological macroeconomics
Stock-flow consistent modelling
Laws of thermodynamics
Climate change
Finance

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).

http://dx.doi.org/10.1016/j.ecolecon.2016.08.013

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).

Table 1
Physical flow matrix.

	Material balance	Energy balance
Inputs		
Extracted matter	$+M$	
Renewable energy		$+ER$
Non-renewable energy	$+CEN$	$+EN$
Oxygen	$+O2$	
Outputs		
Industrial CO_2 emissions	$-EMIS_{IN}$	
Waste	$-W$	
Dissipated energy		$-ED$
Change in socio-economic stock	$-\Delta SES$	
Total	0	0

Note: The table refers to annual global flows. Matter is measured in Gt and energy is measured in EJ.

technical difficulties, are costly to extract or have not yet been discovered. When resources are converted into reserves, it means that people have a higher stock of matter and energy to rely on for economic processes. Note that although this conversion is important for human activities, it does not represent a physical transformation.

Tables 1 and 2 imply that in our model the laws of thermodynamics are important for three reasons. First, the First Law of Thermodynamics allows us to incorporate explicitly the harmful by-products of energy and matter transformation (CO_2 emissions and hazardous material waste). As will be explained below, these by-products cause the degradation of ecosystem services with feedback effects on the economy. Second, the Second Law of Thermodynamics implies that in the very long run the economic processes cannot rely on the energy produced from fossil fuels. Since the fossil fuel resources are finite and the economic processes transform the low-entropy energy embodied in these resources into high-entropy energy, sustainability requires the reliance of economic processes on renewable energy sources (even if there was no climate change). Third, by combining the laws of thermodynamics with Georgesu-Roegen's analysis of material degradation, it turns out that recycling might not be sufficient to ensure the availability of the material resources that are necessary for the economic processes. Hence, the depletion of matter needs to be checked separately.

We proceed to describe the equations of the model that refer to the ecosystem.

3.1.1. Matter, recycling and waste

$$MY = \mu Y \tag{1}$$

$$M = MY - REC \tag{2}$$

$$REC = \rho DEM \tag{3}$$

$$DEM = \mu(\delta K_{-1} + \xi DC_{-1}) \tag{4}$$

$$SES = SES_{-1} + MY - DEM \tag{5}$$

$$W = M + CEN + O2 - EMIS_{IN} - \Delta SES \tag{6}$$

$$CEN = \frac{EMIS_{IN}}{car} \tag{7}$$

$$O2 = EMIS_{IN} - CEN \tag{8}$$

$$HWS = HWS_{-1} + hazW \tag{9}$$

$$hazrario = \frac{HWS}{SURF} \tag{10}$$

$$REV_M = REV_{M-1} + CON_M - M \tag{11}$$

$$CON_M = con_M RES_{M-1} \tag{12}$$

$$RES_M = RES_{M-1} - CON_M \tag{13}$$

$$dep_M = \frac{M}{REV_{M-1}} \tag{14}$$

The goods produced every year (Y) embody a specific amount of matter, MY (Eq. (1)). Material intensity (μ) is defined as the matter included in each output produced. Not all of the matter embodied in the produced output needs to be extracted from the ground (M). As shown in Eqs. (2) and (3), a part of MY comes from the amount of demolished/discarded socio-economic stock that is recycled (REC); ρ denotes the recycling rate. The demolished/discarded socio-economic stock (DEM) is equal to the material content of the depreciated capital goods and the end-of-life durable consumption goods (Eq. (4)); δ is the depreciation rate of capital goods (K) and ξ is the proportion of durable consumption goods (DC) discarded every year. Eq. (5) shows that socio-economic stock (SES) increases as a result of the production of new goods and decreases due to the demolition/discard of old material goods.

Eq. (6) reflects the material balance depicted in Table 1. The waste (W) generated during the production process is used as a residual. Regarding non-renewable energy, only its carbon mass, CEN, has been included as input in the material balance. As shown in Eq. (7), this mass is estimated from the industrial emissions ($EMIS_{IN}$) by using the conversion rate of Gt of carbon into Gt of CO_2 (car). Carbon exits the socio-economic system in the form of CO_2 emissions. Oxygen ($O2$) is introduced as an input in the material balance because it is necessary in the fossil fuel combustion process. Eq. (8) gives the mass of the oxygen that is part of the CO_2 emissions. Note that by combining Eqs. (2), (5), (6) and (8) it can be easily shown that $W = DEM - REC$.

Table 2
Physical stock-flow matrix.

	Material reserves	Non-renewable energy reserves	Atmospheric CO_2 concentration	Socio-economic stock	Hazardous waste
Opening stock	REV_{M-1}	REV_{E-1}	$CO2_{AT-1}$	SES_{-1}	HWS_{-1}
Additions to stock					
Resources converted into reserves	$+CONV_M$	$+CONV_E$			
CO_2 emissions			$+EMIS$		
Production of material goods				$+MY$	
Non-recycled hazardous waste					$+hazW$
Reductions of stock					
Extraction	$-M$	$-EN$			
Net transfer to oceans/biosphere			$+(\varphi_{11}-1)CO2_{AT-1}+\varphi_{21}CO2_{UP-1}$		
Demolished/disposed material goods				$-DEM$	
Closing stock	REV_M	REV_E	$CO2_{AT}$	SES	HWS

Note: The table refers to annual global stocks and flows. Matter is measured in Gt and energy is measured in EJ.

Only a small proportion (haz) of the waste produced every year is hazardous, i.e. it is harmful to human health or the environment.[6] This hazardous waste is added to the accumulated stock of hazardous waste, HWS (Eq. (9)). Eq. (10) defines the hazardous waste accumulation ratio which expresses the accumulated stock of hazardous waste in Gt per million km^2 of earth surface ($SURF$).

The material stock-flow dynamics are presented in Eqs. (11)–(14). Eq. (11) shows that the material reserves (REV_M) decline when matter is extracted and increase when resources are converted into reserves. The annual conversion (CON_M) is given by Eq. (12). An exogenous conversion rate, con_M, has been assumed. Eq. (13) describes the change in material resources (RES_M). To capture the scarcity of matter we define the matter depletion ratio (dep_M), which is the ratio of matter that is extracted every year relative to the remaining material reserves (Eq. (14)). The higher this ratio the greater the matter depletion problems.

3.1.2. Energy

$$E = \varepsilon Y \tag{15}$$

$$ER = \theta E \tag{16}$$

$$EN = E - ER \tag{17}$$

$$ED = EN + ER \tag{18}$$

$$REV_E = REV_{E-1} + CON_E - EN \tag{19}$$

$$CON_E = con_E RES_{E-1} \tag{20}$$

$$RES_E = RES_{E-1} - CON_E \tag{21}$$

$$dep_E = \frac{EN}{REV_{E-1}} \tag{22}$$

The energy required for production (E) is a function of output (Eq. (15)). When energy intensity (ε) declines, the energy required per unit of output becomes lower. As shown in Eqs. (16) and (17), energy is generated either from renewable (ER) or non-renewable sources (EN). The share of renewable energy in total energy is denoted by θ. The dissipated energy (ED) is determined based on the energy balance (Eq. (18)).

Eqs. (19)–(22) represent the stock-flow dynamics of the energy produced from non-renewables. Eq. (19) shows the change in the non-renewable energy reserves (REV_E). CON_E denotes the amount of resources converted into reserves every year. This amount is determined by Eq. (20), where con_E is the conversion rate. The resources of non-renewable energy (RES_E) change every year according to Eq. (21). The energy depletion ratio, which captures scarcity problems, shows the extracted energy relative to the remaining reserves (Eq. (22)).

3.1.3. Emissions and climate change

$$EMIS_{IN} = \omega EN \tag{23}$$

$$EMIS_L = EMIS_{L-1}(1 - lr) \tag{24}$$

$$EMIS = EMIS_{IN} + EMIS_L \tag{25}$$

$$CO2_{AT} = EMIS + \phi_{11} CO2_{AT-1} + \phi_{21} CO2_{UP-1} \tag{26}$$

$$CO2_{UP} = \phi_{12} CO2_{AT-1} + \phi_{22} CO2_{UP-1} + \phi_{32} CO2_{LO-1} \tag{27}$$

$$CO2_{LO} = \phi_{23} CO2_{UP-1} + \phi_{33} CO2_{LO-1} \tag{28}$$

$$F = F_{2\times CO2} \log_2 \frac{CO2_{AT}}{CO2_{AT-PRE}} + F_{EX} \tag{29}$$

$$F_{EX} = F_{EX-1} + fex \tag{30}$$

$$T_{AT} = T_{AT-1} + t_1 \left(F - \frac{F_{2\times CO2}}{S} T_{AT-1} - t_2 (T_{AT-1} - T_{LO-1}) \right) \tag{31}$$

$$T_{LO} = T_{LO-1} + t_3 (T_{AT-1} - T_{LO-1}) \tag{32}$$

Our formalisation of emissions and climate change follows closely the traditional integrated assessment models (see Nordhaus and Sztorc, 2013). Every year industrial CO_2 emissions ($EMIS_{IN}$) are generated due to the use of the non-renewable energy sources (Eq. (23)). CO_2 intensity (ω) is defined as the industrial emissions produced per unit of non-renewable energy. Every year land-use CO_2 emissions ($EMIS_L$) are also generated because of changes in the use of land (Eq. (24)). These emissions are assumed to decline exogenously at a rate lr. Eq. (25) gives the total emissions ($EMIS$).

The atmospheric CO_2 concentration ($CO2_{AT}$) is driven by these emissions and the carbon cycle. The carbon cycle, represented by Eqs. (26)–(28), shows that every year there is exchange of carbon between the atmosphere and the upper ocean/biosphere and between the upper ocean/biosphere and the lower ocean; $CO2_{UP}$ is the upper ocean/biosphere CO_2 concentration and $CO2_{LO}$ is the lower ocean CO_2 concentration. The higher the net transfers of carbon from the atmosphere into the other two reservoirs the lower the atmospheric CO_2 concentration. The accumulation of atmospheric CO_2 and other greenhouse gases increases radiative forcing, F (Eq. (29)), placing upward pressures on the atmospheric temperature, T_{AT} (Eq. (31)). $F_{2\times CO2}$ is the increase in radiative forcing (since the pre-industrial period) due to doubling of CO_2 concentration from pre-industrial levels ($CO2_{AT\text{-}PRE}$). For simplicity, the radiative forcing due to non-CO_2 greenhouse gas emissions (F_{EX}) is determined exogenously (Eq. (30)). Eq. (32) shows the change in the temperature of the lower ocean (T_{LO}).

3.1.4. Ecological efficiency and technology

$$\omega = \omega_{-1}(1 + g_\omega) \tag{33}$$

$$g_\omega = g_{\omega-1}(1 - \zeta_1) \tag{34}$$

$$\mu = \kappa_{-1}\mu_G + (1 - \kappa_{-1})\mu_C \tag{35}$$

$$\mu_G = \mu_{G-1}\left(1 + g_{\mu G}\right) \tag{36}$$

$$g_{\mu G} = g_{\mu G-1}(1 - \zeta_2) \tag{37}$$

$$\rho = \kappa_{-1}\rho_G + (1 - \kappa_{-1})\rho_C \tag{38}$$

$$\rho_G = \rho_{G-1}\left(1 + g_{\rho_G}\right) \tag{39}$$

$$g_{\rho G} = g_{\rho G-1}(1 - \zeta_3) \tag{40}$$

$$\varepsilon = \kappa_{-1}\varepsilon_G + (1 - \kappa_{-1})\varepsilon_C \tag{41}$$

$$\varepsilon_G = \varepsilon_{G-1}(1 + g_{\varepsilon G}) \tag{42}$$

$$g_{\varepsilon G} = g_{\varepsilon G-1}(1 - \zeta_4) \tag{43}$$

$$\theta = \left(1 + \frac{1}{\pi(K_{G-1}/K_{C-1})}\right)^{-1} \tag{44}$$

[6] Asbestos, heavy metals and fluoride compounds are examples of hazardous waste. For an analysis of hazardous waste and its impact on health and the environment see Misra and Pandey (2005).

The ecological efficiency of production is considered to be higher the lower is the energy, material and CO_2 intensity and the higher is the recycling rate. Ecological efficiency also increases when the share of renewable energy in total energy goes up. CO_2 intensity changes in an exogenous way. As shown in Eqs. (33) and (34), every year technical progress reduces CO_2 intensity with a declining rate ($g_\omega<0$ and $\zeta_1>0$).[7] Material intensity, energy intensity and recycling rate are not affected only by exogenous technical progress. Since green capital is characterised by lower material and energy intensity and by higher recycling rate, the efficiency related to these indicators increases when the ratio, κ, of green capital (K_G) to total capital (K) rises. This is shown in Eqs. (35), (38) and (41) where μ_G, ρ_G and ε_G denote, respectively, the material intensity, recycling rate and energy intensity of green capital and μ_C, ρ_C and ε_C are the respective indicators for conventional capital. Eqs. (36), (37), (39), (40), (42) and (43) reflect the fact that exogenous technical progress improves (with a declining rate) the ecological efficiency of green capital ($g_{\mu G}<0$, $g_{\rho G}>0$, $g_{\varepsilon G}<0$, $\zeta_2>0$, $\zeta_3>0$ and $\zeta_4>0$). The ecological efficiency of conventional capital is assumed to be constant. The share of renewable energy in total energy (θ) is higher the higher is the ratio of green capital stock to conventional capital stock (Eq. (44)).

3.2. Macroeconomy and financial system

Table 3 and Table 4 portray the transactions flow matrix and the balance sheet matrix of our macroeconomy (these types of matrices have been presented in detail by Godley and Lavoie, 2007). The transactions flow matrix shows the transactions that take place between the various sectors of the economy (each row represents a category of transactions). For each sector inflows are denoted by a plus sign and outflows are denoted by a minus sign. The upper part of the matrix shows transactions related to the revenues and expenditures of the various sectors. The bottom part of the matrix indicates changes in financial assets and liabilities that arise from transactions. The columns represent the budget constraints of the sectors. For firms and commercial banks a distinction is made between current and capital accounts. The current accounts register payments made or received. The capital accounts show the changes in assets and liabilities as well as the funds that are used to finance investment (in the case of firms). At the aggregate level, monetary inflows are equal to monetary outflows.

Table 4 shows the assets and the liabilities of the sectors. We use a plus sign for the assets and a minus sign for the liabilities. Households and firms have non-zero net worth. Commercial banks have a zero net worth due to the assumption that they distribute all their profits. Accounting requires that at the aggregate level financial assets are equal to financial liabilities. Hence, the net worth of the economy is equal to the real assets which include the capital stock of firms and the durable consumption goods of households.

In the next subsections we present the equations for the macroeconomy and the financial system.

3.2.1. Output determination and damages

$$Y^*_M = \frac{REV_{M-1}+REC}{\mu} \tag{45}$$

$$Y^*_E = \frac{REV_{E-1}}{(1-\theta)\varepsilon} \tag{46}$$

$$Y^*_K = vK \tag{47}$$

$$Y^*_N = \lambda h LF \tag{48}$$

[7] See Nordhaus and Sztorc (2013) for a similar assumption.

$$Y^* = min\left(Y^*_M, Y^*_E, Y^*_K, Y^*_N\right) \tag{49}$$

$$Y = C + I \tag{50}$$

$$um = \frac{Y}{Y^*_M} \tag{51}$$

$$ue = \frac{Y}{Y^*_E} \tag{52}$$

$$u = \frac{Y}{Y^*_K} \tag{53}$$

$$re = \frac{Y}{Y^*_N} \tag{54}$$

$$D_T = 1-\frac{1}{1+\eta_1 T_{AT}+\eta_2 {T_{AT}}^2+\eta_3 {T_{AT}}^{6.754}} \tag{55}$$

$$D_{TP} = pD_T \tag{56}$$

$$D_{TF} = 1-\frac{1-D_T}{1-D_{TP}} \tag{57}$$

We assume a Leontief-type production function that incorporates Georgescu-Roegen's distinction between stock-flow and fund-service resources. The stock-flow resources are matter and non-renewable energy. The fund-service resources are labour and capital. We define four different types of potential output. The matter-determined potential output (Y^*_M) is defined in Eq. (45) and is higher the higher are the material reserves, the higher is the recycled matter and the lower is the material intensity. The energy-determined potential output (Y^*_E) is defined in Eq. (46) and is higher the higher are the non-renewable energy reserves, the lower is the energy intensity and the higher is the share of renewable energy in total energy. The capital-determined potential output (Y^*_K) is defined in Eq. (47) and is higher the higher is the capital stock and the productivity of capital (v). Lastly, the labour-determined potential output (Y^*_N) is defined in Eq. (48) and is higher the higher is the labour force (LF), the hourly labour productivity (λ) and the annual working hours per employee (h). The overall potential output (Y^*) is the minimum of all these potential outputs (Eq. (49)).

In line with the post-Keynesian tradition, actual output (Y) is demand-determined (Eq. (50)): it is equal to consumption demand (C) plus investment demand (I). However, as shown in Eqs. (62)–(67) below, demand is not independent of supply. When actual output approaches potential output, demand tends to decline as a result of supply-side constraints. We define four ratios which capture the extent to which potential output is utilised (Eqs. (51)–(54)). The first two ratios are the matter utilisation rate (um) and the energy utilisation rate (ue), which refer to the use of stock-flow resources. When these ratios increase, the output produced approaches the potential output determined by the material and energy reserves. The last two ratios are the utilisation rate (u) and the rate of employment (re) which refer to the use of fund-service resources. A rise in these ratios reflects a higher scarcity of capital and labour.

Global warming causes damages to the fund-service resources (capital and labour), reducing thereby the potential output determined by them. There are two types of damages: the damages that affect directly the funds (capital stock and labour force) and the damages that affect the productivities of the funds (capital productivity and labour productivity). Capital stock is affected because climate change can destroy infrastructure by causing storms or inundations, or it can trigger the abandonment of capital in coastal areas by causing a rise in the sea level (see Dietz and Stern, 2015; Naqvi, 2015; Taylor et al., 2016). Labour force can be reduced since climate change can adversely affect morbidity, mortality, air quality and the vector and proliferation of infectious

Table 3
Transactions flow matrix.

	Households	Firms		Commercial banks		Total
		Current	Capital	Current	Capital	
Consumption	$-C$	$+C$				0
Conventional investment		$+I_C$	$-I_C$			0
Green investment		$+I_G$	$-I_G$			0
Wages	$+wN$	$-wN$				0
Firms' profits	$+DP$	$-TP$	$+RP$			0
Commercial banks' profits	$+BP$			-BP		0
Interest on deposits	$+int_D D_{-1}$			$-int_D D_{-1}$		0
Capital depreciation		$-\delta K_{-1}$	$+\delta K_{-1}$			0
Interest on conventional loans		$-int_C L_{C\text{-}1}$		$+int_C L_{C\text{-}1}$		0
Interest on green loans		$-int_G L_{G\text{-}1}$		$+int_C L_{G\text{-}1}$		0
Change in deposits	$-\Delta D$				$+\Delta D$	0
Change in conventional loans			$+\Delta L_C$		$-\Delta L_C$	0
Change in green loans			$+\Delta L_G$		$-\Delta L_G$	0
Total	0	0	0	0	0	0

Note: The table refers to annual global flows in trillion US$.

diseases. It can also lead to storms and floods that injure and kill people (Toll, 2002). All these phenomena might reduce the population or the proportion of the population that can participate in the labour force. Capital productivity can be driven down since climate change might create a hostile environment that can reduce the ability of firms to use capital effectively (Stern, 2013; Dietz and Stern, 2015). Finally, by affecting the health of the workers, the rise in temperature might decrease their ability to perform work tasks, reducing labour productivity (Kjellstrom et al., 2009; Dell et al., 2014; Taylor et al., 2016).

Aggregate demand is affected by these damages in two ways. First, the catastrophes caused by climate change might increase the fears of entrepreneurs that their capital will be destroyed or that it will have very low returns. This reduces their desired investment.[8] Moreover, observing the natural disasters and the health problems, households might be induced to save more for precautionary reasons. This can lead to less consumption. Measures that restrict consumption directly might also be adopted. Second, since global warming damages tends to reduce Y_K^* and Y_N^*, they place upward pressures on u and re. As mentioned above, this rise in the scarcity of capital and labour can reduce demand.

Importantly, societies do not react passively to the climate change-related effects on fund-service resources. They take adaptation measures that limit global warming damages. Following de Bruin et al. (2009), we thereby make a distinction between gross damages and net damages. Gross damages are the initial damages caused by climate change if there were no adaptation measures and net damages are the damages that remain after the implementation of adaptation measures.[9]

Eq. (55) is the damage function, which shows how atmospheric temperature and damages are linked. D_T is the proportional gross damage which lies between 0 (no damage) and 1 (complete catastrophe). The form of Eq. (55) has been suggested by Weitzman (2012) who argues that the quadratic forms of damage functions used in the traditional literature of integrated assessment models do not adequately capture high-temperature damages. This issue is tackled by inserting the term $\eta_3 {T_{AT}}^{6.754}$ where η_3 and the corresponding exponent have been selected such that $D_T = 0.5$ when $T_{AT} = 6$ °C.

In most integrated assessments models D_T affects directly the supply-determined output. On the contrary, as mentioned above, in our model D_T affects the potential output and the aggregate demand. Hence, the variable D_T enters into both (i) the determination of funds and their productivities (see Eqs. (84), (85), (88) and (96)) and (ii) the consumption and investment demand (see Eqs. (62) and (93)). It is also necessary to partition the gross damage between the fund (D_{TF}) and its productivity (D_{TP}), so as to warrant that when $D_T = x\%$ the capital-determined potential output and the labour-determined potential output would be reduced by $x\%$ if there were no adaptation measures. This is done by Eqs. (56) and (57).[10]

The impact of adaptation is captured by the parameters ad_p, ad_k and ad_{LF} that represent the proportion of the gross damage (of productivity, capital stock and labour force respectively) which is eliminated due to adaptation measures. We have that $0 \le ad_P, ad_K, ad_{LF} \le 1$. This means that, for example, the proportional net damage to productivity is given by $(1 - ad_P)D_{TP}$. We assume that adaptation does not affect investment and consumption demand: firms and households make decisions based on gross damages.

3.2.2. Firms

$$TP = Y - wN - int_C L_{C-1} - int_G L_{G-1} - \delta K_{-1} \tag{58}$$

$$RP = s_F TP_{-1} \tag{59}$$

$$DP = TP - RP \tag{60}$$

$$r = RP/K \tag{61}$$

$$I^D = [(\alpha_0 + \alpha_1 r_{-1} + \alpha_2 u_{-1} - \alpha_3 g_{\varepsilon-1})K_{-1} + \delta K_{-1}](1 - D_{T-1}) \tag{62}$$

$$\alpha_0 = \alpha_{00} - \gamma_1(um_{-1} - um_T) - \gamma_2(ue_{-1} - ue_T) - \gamma_3(u_{-1} - u_T) - \gamma_4(re_{-1} - re_T) \tag{63}$$

$$\gamma_1 = \gamma_{10} \;\; iff \;\; um_{-1} \ge um_T; \;\; \text{otherwise} \;\; \gamma_1 = 0 \tag{64}$$

$$\gamma_2 = \gamma_{20} \;\; iff \;\; ue_{-1} \ge ue_T; \;\; \text{otherwise} \;\; \gamma_2 = 0 \tag{65}$$

$$\gamma_3 = \gamma_{30} \;\; iff \;\; u_{-1} \ge u_T; \;\; \text{otherwise} \;\; \gamma_3 = 0 \tag{66}$$

$$\gamma_4 = \gamma_{40} \;\; iff \;\; re_{-1} \ge re_T; \;\; \text{otherwise} \;\; \gamma_4 = 0 \tag{67}$$

$$I_G^D = \beta I^D \tag{68}$$

$$I_C^D = I^D - I_G^D \tag{69}$$

$$\beta = \beta_0 + \beta_1 - \beta_2(int_G - int_C) + \beta_3 D_{T-1} \tag{70}$$

$$\beta_0 = \beta_{0-1}\left(1 + g_{\beta 0}\right) \tag{71}$$

[8] Taylor et al. (2016) have postulated a negative impact of climate change on investment demand by assuming that greenhouse gas concentration reduces the profit share.

[9] We do not include the financial cost of the adaptation measures in net damages.

[10] See also Moyer et al. (2014).

Table 4
Balance sheet matrix.

	Households	Firms	Commercial banks	Total
Conventional capital		$+K_C$		$+K_C$
Green capital		$+K_G$		$+K_G$
Durable consumption goods	$+DC$			$+DC$
Deposits	$+D$		-D	0
Conventional loans		$-L_C$	$+L_C$	0
Green loans		$-L_G$	$+L_G$	0
Total (net worth)	$+V_H$	$+V_F$	0	$+K_C+K_G+DC$

Note: The table refers to annual global stocks in trillion US$.

$$g_{\beta 0}=g_{\beta 0-1}(1-\zeta_5) \tag{72}$$

$$NL_G^D=I_G^D-\beta RP+repL_{G-1}-\delta K_{G-1} \tag{73}$$

$$NL_C^D=I_C^D-(1-\beta)RP+repL_{C-1}-\delta K_{C-1} \tag{74}$$

$$I_G=\beta RP+(L_G-L_{G-1})+\delta K_{G-1} \tag{75}$$

$$I_C=RP+(L_C-L_{C-1})+(L_G-L_{G-1})+\delta K_{-1}-I_G \tag{76}$$

$$I=I_C+I_G \tag{77}$$

$$L=L_C+L_G \tag{78}$$

$$K_G=K_{G-1}+I_G-\delta K_{G-1} \tag{79}$$

$$K_C=K_{C-1}+I_C-\delta K_{C-1} \tag{80}$$

$$K=K_C+K_G \tag{81}$$

$$\kappa=K_G/K \tag{82}$$

$$lev=L/K \tag{83}$$

$$\delta=\delta_0+(1-\delta_0)(1-ad_K)D_{TF-1} \tag{84}$$

$$v=v_{-1}(1+g_v)[1-(1-ad_P)D_{TP-1}] \tag{85}$$

$$g_\lambda=\sigma_0+\sigma_1+\sigma_2 g_{Y-1} \tag{86}$$

$$\sigma_0=\sigma_{0-1}(1-\zeta_6) \tag{87}$$

$$\lambda=\lambda_{-1}(1+g_\lambda)[1-(1-ad_P)D_{TP-1}] \tag{88}$$

$$w=s_W\lambda h \tag{89}$$

$$N=\frac{Y}{h\lambda} \tag{90}$$

$$ur=1-re \tag{91}$$

The total profits of firms (TP) are given by Eq. (58); w is the wage rate, N is the number of employed workers, int_C is the interest rate on conventional loans, int_G is the interest rate on green loans, L_C is the amount of conventional loans, L_G is the amount of green loans and δ is the depreciation of capital stock (which is assumed to be the same for green capital and conventional capital). Firms' retained profits (RP) are a proportion (s_F) of their total profits (Eq. (59)). The distributed profits of firms (DP) are determined as a residual (Eq. (60)). Eq. (61) gives the rate of retained profits (r).

Firms' investment is formalised as a two-stage process. At a first stage, firms decide their overall desired investment in both green and conventional capital. At a second stage, they allocate their desired investment between the two types of capital. Eq. (62) captures the first stage. The desired investment (I^D), adjusted for the damage effect, is equal to net investment plus the depreciated capital. As in most Kaleckian models, net investment is a positive function of the rate of (retained) profits and the rate of capacity utilisation. We also postulate that investment depends on the growth rate of energy intensity (g_ε) to capture the rebound effect associated with a lower growth rate of energy intensity. The idea is that a lower energy intensity reduces the costs of production inducing firms to invest more. This increases their energy use outweighing partially the beneficial effects of a lower energy intensity.[11]

Eqs. (62)–(67) show that investment demand is reduced when actual output approaches potential output ($\gamma_{10},\gamma_{20},\gamma_{30},\gamma_{40}>0$). In particular, when the utilisation of matter passes the um_T threshold and/or the utilisation of energy passes the ue_T threshold, investment demand is curbed because the prices of matter and energy rise significantly as a result of scarcity, leading to higher production costs. Additionally, when the rate of capacity utilisation and the rate of employment are higher than the thresholds u_T and re_T respectively, labour and capital shortages could lead to rising wages and prices that, under certain conditions, affect negatively investment demand. Labour shortages also make firms uncertain about their ability to recruit workers, deteriorating business confidence (see Ryoo and Skott, 2008; Lavoie, 2014, ch. 6).

The second stage of the investment process is reflected in Eqs. (68)–(72). At this stage firms decide about the proportion, β, of green investment (I_G^D) in the overall desired investment (Eq. (68)). Desired conventional investment (I_C^D) is determined as a residual (Eq. (69)). The proportion of green investment depends on three factors (Eq. (70)). The first factor is captured by the term $\beta_0+\beta_1$ which reflects exogenous developments, such as the cost of installing and using green capital relative to conventional capital or institutional changes that promote green investment. It is assumed that β_0 increases every year but with a declining rate (Eqs. (71)–(72)). β_1 is constant but can change due to exogenous institutional or technology shocks. The second factor is the divergence between the interest rate on green loans and the interest rate on conventional loans. The interest rate differential captures the borrowing cost of investing in green capital relative to conventional capital.[12] The third factor is captured by the variable D_T which reflects the fact that climate change might lead to mitigation measures that promote green investment or may induce entrepreneurs to make investments that are conducive to less environmental damage.

Due to the existence of credit rationing, only a proportion of the new loans that are demanded by firms are provided by banks.[13] Eq. (73) gives the desired new green loans (NL_G^D) and Eq. (74) gives the desired new conventional loans (NL_C^D). The green, conventional and total investment goods after credit rationing are shown in Eqs. (75)–(77); I_G is green investment and I_C is conventional investment. The total loans of firms (L) are equal to conventional loans plus green loans (Eq. (78)). The change in green and conventional capital stock is equal to gross investment minus the depreciation of capital (Eqs. (79) and (80)). Eq. (81) shows that total capital (K) is equal to conventional capital (K_C) plus green capital (K_G). The ratio of green capital to total capital is given by Eq. (82). The leverage ratio of firms (lev) is defined in Eq. (83).

Eq. (84) shows the rate of capital depreciation. Interestingly, a higher depreciation due to climate change has two countervailing effects on economic growth. On the one hand, capital-determined potential output is reduced, placing adverse supply-side effects on economic activity (see Eq. (47)). On the other hand, aggregate demand tends to

[11] For a description of the rebound effects see Barker et al. (2009). In our model firms' payments on energy are netted out due to the consolidation of the firm sector. Therefore, a lower energy intensity does not affect the aggregate profitability of firms. However, it is crucial to incorporate the expansionary effect of lower energy intensity into the investment function; otherwise, improvements in energy efficiency would have only beneficial effects on energy use.

[12] For some empirical evidence about the effects of interest rates on green investment see Eyraud et al. (2013).

[13] See also Dafermos (2012) and Nikolaidi (2014).

increase because a higher depreciation leads to higher gross investment (see Eq. (62)).

Eqs. (85)–(88) refer to capital and labour productivity. As argued above, both productivities are influenced by climate change. Capital productivity, before damages, is assumed to grow at an exogenous rate, g_v. Labour productivity is affected by exogenous technology factors reflected in the term $\sigma_0+\sigma_1$. These factors increase productivity growth every year but with a declining rate. Also, is line with the Kaldor-Verdoorn law (see Lavoie, 2014, ch. 6), the growth rate of labour productivity is positively affected by the growth rate of output (g_Y). Note that, although a lower labour productivity can reduce the unemployment rate for a given level of output, it has adverse effects on the supply side by driving down the labour-determined potential output (see Eq. (48)).

Eq. (89) gives the wage rate. The wage share (s_W) is assumed to be exogenous. The number of employees is determined by Eq. (90). The unemployment rate is defined in Eq. (91).

3.2.3. Households

$$Y_H = wN + DP + BP + int_D D_{-1} \tag{92}$$

$$C = (c_1 Y_{H-1} + c_2 D_{-1})(1 - D_{T-1}) \tag{93}$$

$$D = D_{-1} + Y_H - C \tag{94}$$

$$DC = DC_{-1} + C - \xi DC_{-1} \tag{95}$$

$$LF = LF_{-1}(1 + g_{LF})[1 - (1 - ad_{LF})D_{TF-1}] \tag{96}$$

$$g_{LF} = lf_0 + lf_1 - lf_2 ur_{-1} - lf_3 hazratio_{-1} \tag{97}$$

$$lf_0 = lf_{0-1}(1 - \zeta_7) \tag{98}$$

Eq. (92) gives the disposable income of households (Y_H); BP denotes the profits of banks, int_D is the interest rate on deposits and D is the amount of deposits. Households' consumption, adjusted for global warming damages, depends on lagged income (which is a proxy for the expected one) and lagged deposits (Eq. (93)). Recall that all consumption goods in our economy are durable (i.e. they have a life higher than one year). Every year the stock of durable goods increases due to the production of new consumption goods and decreases due to the discard of the accumulated durable goods (Eq. (95)).

As mentioned above, climate change reduces labour force (Eq. (96)). However, there are three additional factors that drive the change in labour force (Eq. (97)). First, in line with the population projections of United Nations (2015), there are some fundamental dynamics that influence fertility and mortality and tend to reduce the growth rate of the population (and, thus, the growth rate of the labour force). This is reflected in the term lf_0+lf_1. Second, a higher unemployment rate places downward pressures on the growth rate of the labour force. The is because unemployment (i) adversely affects mortality/fertility and suicidal behaviour (see Clemens et al., 2011) and (ii) discourages people's participation in the labour force. Third, the accumulation of hazardous waste creates health problems (e.g. carcinogenesis, congenital anomalies) that affect labour force growth.

3.2.4. Banks

$$BP = int_C L_{C-1} + int_G L_{G-1} - int_D D_{-1} \tag{99}$$

$$CR_C = r_0 + r_1 lev_{-1} \tag{100}$$

$$CR_G = l_0 + l_1 lev_{-1} \tag{101}$$

$$L_C = L_{C-1} + (1 - CR_C)NL_C^D - repL_{C-1} \tag{102}$$

$$L_G = L_{G-1} + (1 - CR_G)NL_G^D - repL_{G-1} \tag{103}$$

$$D = L \tag{104 – red}$$

The profits of banks are equal to the interest on both conventional and green loans minus the interest on deposits (Eq. (99)). Banks impose credit rationing based on the leverage ratio of firms (Eqs. (100) and (101)). The higher the degree of credit rationing the lower the proportion of new desired loans that are provided (Eqs. (102) and (103)). Due to the risky nature of green investments (see Campiglio, 2016), it is assumed that (without government or central bank interventions) green loans are characterised by higher lending interest rates and credit rationing compared to conventional loans. Eq. (104-red) is the redundant equation of the system described in Table 3 and Table 4: it is logically implied by all the other equations of this system.

3.3. Summary of the interactions between the ecosystem, the financial system and the macroeconomy

Fig. 1 summarises the most important channels through which the ecosystem, the financial system and the macroeconomy interact in our model:

- *Degradation channel*: Higher economic activity, which is accompanied by the use of matter and non-renewable energy, leads to CO_2 emissions and the generation of hazardous waste. The overall result is the degradation of the ecosystem services due to the CO_2-induced increase in atmospheric temperature and the harmful effects of waste accumulation.
- *Depletion channel*: The extraction of matter and non-renewable energy sources that are necessary for the production process places upward pressures on the depletion ratios. In other words, economic growth tends to deplete finite natural resources.
- *Damage channel*: The degradation of the ecosystem services damages the fund-service resources (capital and labour) either by destroying them directly or by reducing their productivities. These damages might impose supply-side constraints on economic activity. The environmental damages also affect the behaviour of households and firms, which respond to these damages by cutting consumption and investment expenditures, respectively. As a result, aggregate demand falls, reducing economic growth.
- *Natural resources constraint channel*: The depletion of natural resources reduces the availability of the stock-flow resources that are necessary in the production process (matter and non-renewable energy). This might impose supply-side constraints on economic activity.
- *Green financing channel*: The financial system finances green investment via loans, contributing to the improvement of material intensity, energy intensity and recycling rate as well as to the increase in the use of renewable energy. Hence, the credit rationing and the interest rates determined by banks play an important role in the decoupling of economic growth from environmental problems.
- *Growth channel*: The financial system has both positive and negative effects on economic activity. The positive effects include the provision of finance that increases investment and, hence, economic growth. The negative effects are related to the potential rise in the leverage ratio of firms that, under certain conditions, can harm economic activity by reducing desired investment and credit availability.
- *Financial (in)stability channel*: The stability of the financial system is affected by macroeconomic activity. However, the links are not clear-cut. High economic growth is conducive to the expansion of the financial system, which might be associated with higher financial fragility (reflected in higher leverage ratios). Low economic

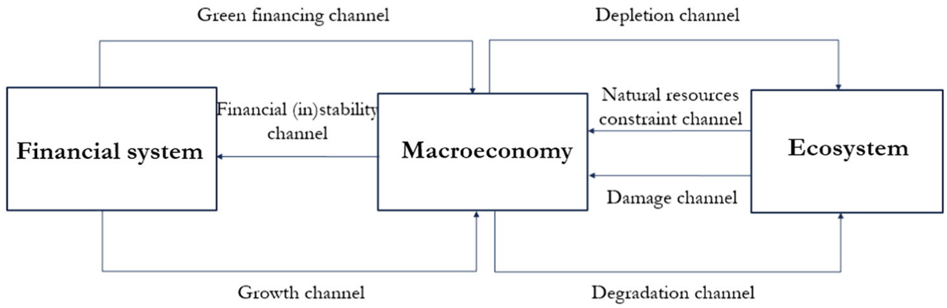

Fig. 1. Main interactions between the ecosystem, the financial system and the macroeconomy in the model.

activity creates debt repayment difficulties that affect the stability of the financial system.

4. Simulations

The model has been calibrated using the available global data. Parameter values have been selected in three different ways: a first set of parameters have been taken from other studies or have been calculated based on the global data; a second set of parameters have been selected such that the model generates the baseline scenario described below; a third set of parameters have been selected from a reasonable range of values. Appendix A and Appendix B report the related details.

The model is simulated for 100 years starting from 2015.[14] The purpose of our simulation exercises is to analyse potential long-run developments that stem from the interactions between the ecosystem, the financial system and the macroeconomy. We do not pay attention to short-run fluctuations and business cycles. The baseline scenario represents a 'business as usual' pathway whereby the global economy continues to expand quite smoothly and ecological efficiency improves moderately. In particular, in our baseline scenario the global economy grows at around 2.7–3% and the unemployment rate remains equal to around 6% till 2050, as it has been the case over the last two decades or so. In general line with the United Nations (2015) population projections (medium fertility variant), the labour force grows at a declining rate in the next years, increasing from 3.4bn people in 2015 to around 4.5bn people in 2050 (assuming a constant labour force-population ratio). Furthermore, the share of renewable energy is increased to about 30% by the end of the century (from about 14% which is the current level), while CO_2 intensity, material intensity and energy intensity are assumed to become approximately 10%, 15% and 30% lower in 2050 compared to their current levels. Finally, the recycling rate is postulated to increase by about 40% till 2050.

The simulation results are shown in Figs. 2 and 3. In the baseline scenario output increases exponentially for about 60 years (Fig. 2a). Since the share of renewable energy in total energy remains low (Fig. 2b), economic growth generates an almost continuous rise in CO_2 emissions till the end of the 21st century (Fig. 2c). The resulting rise in CO_2 concentration and radiative forcing leads to severe global warming: in 2100 atmospheric temperature becomes 4 °C higher than the pre-industrial levels (Fig. 2d). The rise in atmospheric temperature makes gradually the damage channel stronger. Hence, the growth rate of output declines, becoming very close to 0% at the beginning of the 22nd century. Declining economic growth leads to a gradual rise in the unemployment rate (Fig. 2e).[15] Low economic activity, combined with the destruction of capital due to climate change, places upward pressures on the leverage ratio of firms (Fig. 2g). The rise in the leverage ratio reinforces the recessionary effects caused by global warming (growth channel) because it reduces desired investment and increases credit rationing. Fig. 2f shows the adverse impact that the damages have on the labour force. Remarkably, these damages are not only linked to the effects of global warming; they are also related to the health effects from the accumulation of hazardous waste. Two additional developments are worth mentioning. First, low economic growth leads ultimately to a reduction in CO_2 emissions (Fig. 2c). Ironically, this cut is primarily produced by nature – which has forced the economy to slow – and not by any specific human design. Second, the expansion of the economy and the low use of renewables makes the non-renewable energy sources more scarce via the depletion channel (Fig. 2h).

A crucial question is how these baseline results are modified when key parameters change or when environmental policies are implemented. Although space limitations do not allow us to explore these issues in depth, in what follows we present a sensitivity analysis and two policy scenarios that illuminate the non-neutral impact of finance on the ecosystem-macroeconomy interactions.

The sensitivity analysis focuses on the effects of firm leverage on economic activity. A rise in the leverage ratio of firms has both contractionary and expansionary effects (see also Nikolaidi, 2014). The contractionary effects stem from the fact that a rise in leverage reduces desired investment and increases credit rationing. The expansionary effects are basically related to the fact that a rise in firm loans is always accompanied by a rise in household deposits which boosts consumption expenditures via the wealth effect. There are also some effects on the disposable income of households which are less clear-cut: a rise in firm loans increases, on the one hand, the distributed profits of banks and the interest payments of households but, on the other hand, reduces the distributed profits of firms.

Based on the above, we have selected to modify the following parameters in the sensitivity analysis: (i) the sensitivity of the desired investment rate to profitability (a_1); (ii) the sensitivity of credit rationing to the leverage ratio of firms (r_1 and l_1); (iii) the propensity to consume out of deposits (c_2). In Sensitivity test I, a_1, r_1 and l_1 are relatively high and c_2 is relatively small. This means that the contractionary effects are strong relative to the expansionary ones. The opposite holds in Sensitivity Test II, where a_1, r_1 and l_1 are relatively small and c_2 is relatively high. Table 5 reports the parameter values used in the sensitivity analysis.

Fig. 2 shows the results. Under Sensitivity test I, the rise in the leverage ratio of firms caused by climate change generates stronger contractionary effects in comparison to the baseline scenario. Hence, output is lower (Fig. 2a) and unemployment rate is higher (Fig. 2e). However, there are beneficial environmental effects. Lower economic activity slows the build-up of atmospheric CO_2 concentration, resulting in slightly less severe global warming (Fig. 2d); it also leads to a lower use of the non-renewable energy reserves (Fig. 2h). On the contrary, under Sensitivity Test II, the adverse effects of a higher firm leverage

[14] The simulations have been performed using R. The code is available upon request.

[15] The impact of global warming on the unemployment rate depends to a great extent on the effects of the adaptation measures, which are captured by the parameters ad_P and ad_{LF}. If the adaptation measures do not limit the damages to labour productivity and labour force sufficiently, global warming might lead to a decline in the unemployment rate and might cause labour shortage problems.

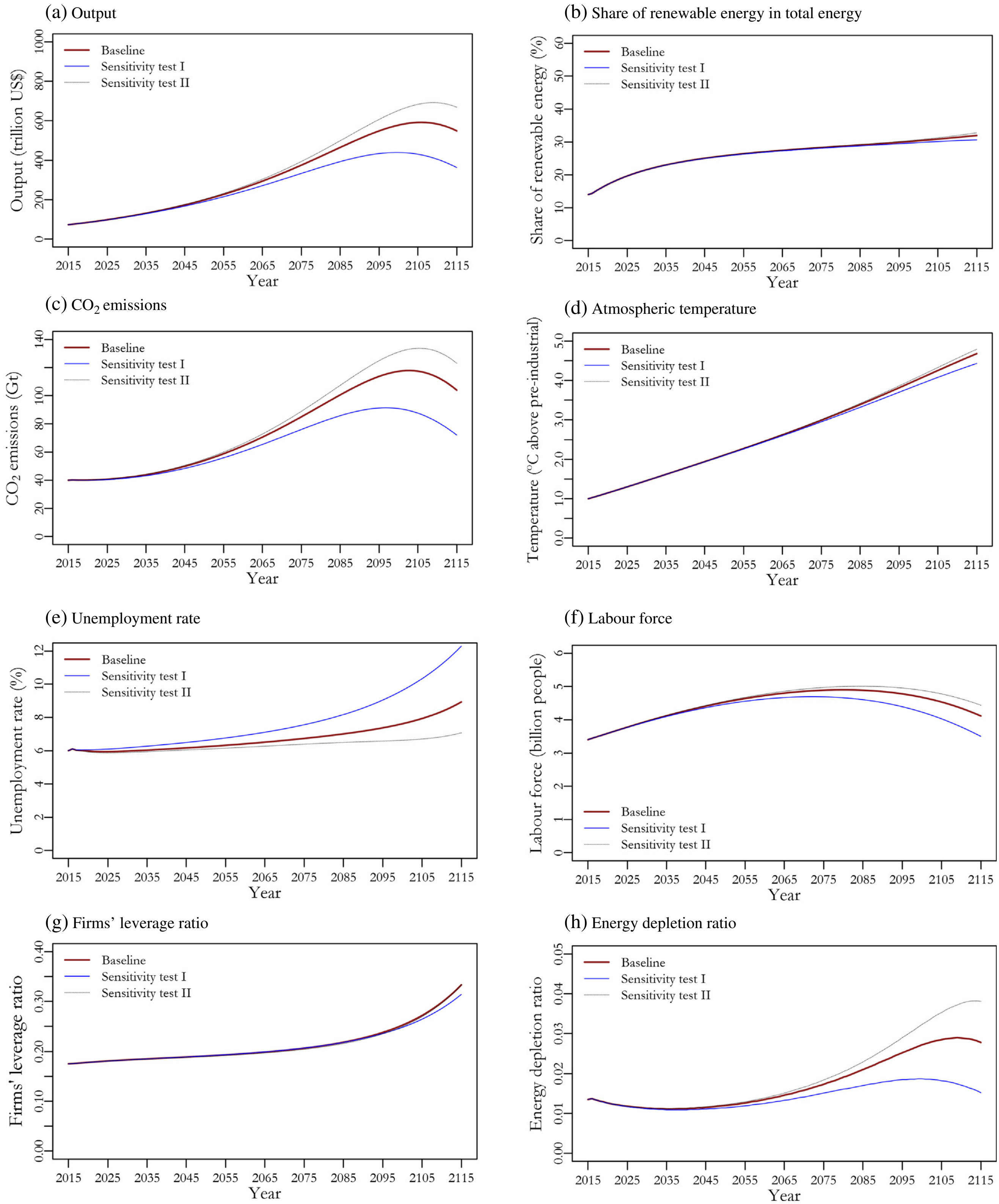

Fig. 2. Evolution of environmental, macroeconomic and financial variables, sensitivity analysis (a) Output (b) Share of renewable energy in total energy (c) CO_2 emissions (d) Atmospheric temperature (e) Unemployment rate (g) Firms' leverage ratio (f) Labour force (h) Energy depletion ratio Note: The values used in the simulation analysis are reported in Appendix A, Appendix B and Table 5. In Sensitivity test I (Sensitivity test II) a rising leverage ratio produces stronger (weaker) contractionary effects and weaker (stronger) expansionary effects compared to the baseline scenario.

ratio are less pronounced, allowing output to increase more than in the baseline scenario (Fig. 2a). This, of course, increases the environmental problems.

Overall, the results show that the responsiveness of economic activity to the leverage ratio affects the way that the ecosystem interacts with the macroeconomy. In the baseline scenario environmental

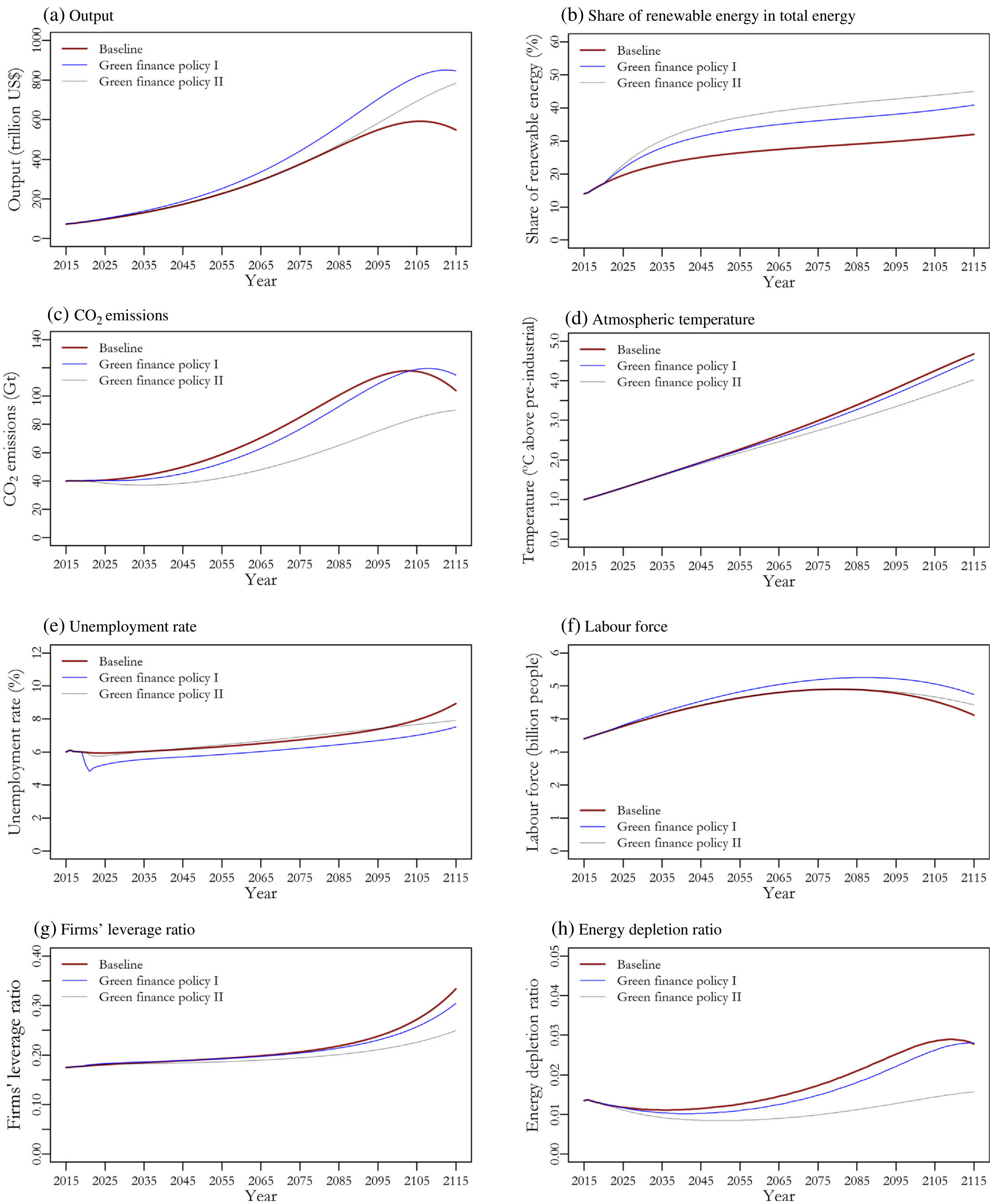

Fig. 3. Evolution of environmental, macroeconomic and financial variables, policy analysis (a) Output (b) Share of renewable energy in total energy (c) CO_2 emissions (d) Atmospheric temperature (e) Unemployment rate (g) Firms' leverage ratio (f) Labour force (h) Energy depletion ratio Note: The values used in the simulation analysis are reported in Appendix A, Appendix B and Table 5. In Green finance policy I the credit rationing and the interest rate on green loans are reduced, while the credit rationing and the interest rate on conventional loans remain unchanged. In Green finance policy II the decline in the credit rationing and the interest rate on green loans is accompanied by a rise in the credit rationing and the interest rate on conventional loans. The implementation of green finance policies starts in 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Values of key parameters in the sensitivity and policy analysis.

Parameter	Baseline scenario	Sensitivity test I	Sensitivity test II	Green finance policy I	Green finance policy II
Sensitivity of desired investment rate to profitability (α_1)	0.2	0.5	0.05	0.2	0.2
Sensitivity of conventional loans' credit rationing to the leverage ratio of firms (r_1)	0.2	0.4	0.05	0.2	0.2
Sensitivity of green loans' credit rationing to the leverage ratio of firms (l_1)	0.2	0.4	0.05	0.2	0.2
Propensity to consume out of deposits (c_2)	0.075	0.05	0.1	0.075	0.075
Autonomous desired investment rate (α_0)	0.028	0.021	0.032	0.028	0.028
Propensity to consume out of disposable income (c_1)	0.88	0.92	0.85	0.88	0.88
Autonomous credit rationing on green loans (l_0)	0.37	0.33	0.39	0.27	0.27
Autonomous credit rationing on conventional loans (r_0)	0.17	0.13	0.19	0.17	0.37
Interest rate on green loans (int_G)	0.08	0.08	0.08	0.06	0.06
Interest rate on conventional loans (int_C)	0.07	0.07	0.07	0.07	0.08

Notes: In Sensitivity test I (Sensitivity test II) a rising leverage ratio produces stronger (weaker) contractionary effects and weaker (stronger) expansionary effects compared to the baseline scenario. In the sensitivity analysis the change in parameters a_1, r_1 and l_1 and c_2 is accompanied by a change in parameters α_0, r_0 and l_0 and c_1 so as to ensure that the initial growth rate of output remains the same. In Green finance policy I the credit rationing and the interest rate on green loans are reduced, while the credit rationing and the interest rate on conventional loans remain unchanged. In Green finance policy II the decline in the credit rationing and the interest rate on green loans is accompanied by a rise in the credit rationing and the interest rate on conventional loans. The implementation of green finance policies starts in 2020.

damages reduce economic growth and destroy capital (via the damage channel), causing a rise in the financial fragility of firms (via the financial (in)stability channel). This, in turn, harms economic growth (via the growth channel), slowing environmental degradation and the depletion of natural resources. When the adverse impact of the leverage ratio on economic activity increases (decreases), the harmful economic effects of environmental damages are amplified (attenuated).

We now turn to analyse a set of policies linked with the financing conditions for green investment. In our model these conditions are captured by the credit rationing and the interest rate on green loans. An improvement in the green financing conditions means that credit rationing and interest rate on green loans are reduced, leading to a higher share of green investment in total investment. This can be the result of various types of policies, such as a bank regulation policy or a central bank policy that incentivise banks to provide a higher amount of green loans (see Campiglio, 2016).

We analyse two types of green finance policies. Under Green finance policy I, the credit rationing and the interest rate on green loans are reduced, while the credit rationing and the interest rate on conventional loans remain unchanged. This means that a higher share of green capital in total capital is accompanied by a higher economic growth. The latter partially offsets the beneficial environmental effects of higher green investment. Under green finance policy II, the decline in the credit rationing and the interest rate on green loans is accompanied by a rise in the credit rationing and the interest rate on conventional loans. This means that the favourable environmental effects of higher green investment are offset to a less extent by higher economic growth caused by credit expansion. Moreover, the share of green capital in total capital becomes even higher.

Fig. 3 reports the results. The implementation of both policies is assumed to start in 2020. As expected, under Green finance policy I, output increases more than in the baseline scenario due to the expansionary effects of higher credit availability and lower interest rates (Fig. 3a); this development is related to the growth channel. Credit expansion also has favourable effects on the unemployment rate (Fig. 3e). The increase in the share of green investment causes a rise in the use of renewable energy (Fig. 3b). Hence, CO_2 emissions grow less rapidly compared to the baseline scenario (Fig. 3c), leading to a slightly lower rise in atmospheric temperature. Since global warming is less severe, the damage channel is less strong and this allows the economy to expand for a slightly longer period compared to the baseline scenario (Fig. 3a).

Green finance policy II yields better environmental results. Since the provision of finance for conventional investment is reduced, economic growth is lower compared to the Green finance policy I scenario (Fig. 3a). The combination of a lower economic activity and a higher share of green investment in total investment generates lower CO_2 emissions (Fig. 3c) and, thereby produces a less rapid rise in the atmospheric temperature (Fig. 3d).

Particular attention needs to be paid to the trajectory of the leverage ratio of firms (Fig. 3g). Although credit expands significantly under Green finance policy I, the leverage ratio turns out to be lower compared to the baseline scenario. The main driving force behind this development is the enhancement of green investment which reduces the damages (green financing channel), allowing output and capital stock to increase more. Furthermore, when the proportion of green credit in total credit becomes even higher (Green finance policy II), the leverage ratio decreases further despite the fact that economic growth is lower than in the Green finance policy I scenario. This has to do with the fact that global warming – and hence damages - are less severe when the proportion of green credit increases.

5. Conclusion

This paper developed a stock-flow-fund ecological macroeconomic model that analyses the complex interactions between the ecosystem, the financial system and the macroeconomy. The foundations of the model lie in the post-Keynesian SFC approach and the flow-fund model of Georgescu-Roegen. We calibrated the model using global data and we performed simulations 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. Our simulations indicated that as the contractionary effects of a higher leverage ratio become stronger, the economic damages caused by the environmental changes are reinforced. They also showed that green finance policies have favourable effects on environmental variables and the financial fragility of firms. More importantly, these favourable effects are enhanced when the expansion of green credit is accompanied by a restriction of conventional credit.

Our analysis can be extended in various directions. First, more realistic structures can be introduced into our macroeconomy and financial system. Examples include the incorporation of the equity/bond/energy market, the government sector and the central bank. Second, additional aspects of the ecosystem can be incorporated, such as tipping points or a more sophisticated carbon cycle. Third, various simulation exercises can be conducted – using the current model or its future extensions – in order to explore how our results change when different types of environmental policies are implemented. All these extensions can contribute to a more integrated understanding of the ways through which macroeconomic and financial stability can be combined with ecological sustainability.

Acknowledgements

We are grateful to Sebastian Berger, Peter Bradley, Vince Daly, Duncan Foley, Ewa Karwowski, Andrew Mearman, Jo Michell, Oliver Richters, Engelbert Stockhammer and Rafael Wildauer for valuable comments. We are also grateful to two anonymous referees for constructive suggestions. Earlier versions of this paper were presented at the 19th SCEME Seminar in Economic Methodology, Bristol, May 2014, the 18th Conference of the Research Network Macroeconomics and Macroeconomic Policies (FMM), Berlin, October-November 2014, the 25th Annual Workshop of the Post-Keynesian Economics Study Group, London, May 2015, the 11th Conference of the European Society for Ecological Economics, Leeds, June–July 2015, the Political Economy seminar series of Kingston University, London, December 2015 and the MISUM research seminar series of Stockholm School of Economics, December 2015. We thank the participants for helpful comments. This research is part of a project conducted by the New Economics Foundation. The financial support from the Network for Social Change is gratefully acknowledged. The usual disclaimers apply.

Appendix A. Initial values for endogenous variables

Symbol	Description	Value	Remarks/sources
BP	Profits of banks (trillion US$)	3.7	Calculated from Eq. (99) using the initial values of L_C, L_G and D
C	Consumption (trillion US$)	47.1	Calculated from Eq. (50) using the initial values of Y and I
CEN	Carbon mass of the non-renewable energy sources (Gt)	9.8	Calculated from Eq. (7) using the initial value of $EMIS_{IN}$
$CO2_{AT}$	Atmospheric CO_2 concentration (Gt)	3,120	Taken from NOAA/ESRL (National Oceanic & Atmospheric Administration/Earth System Research Laboratory)
$CO2_{UP}$	Upper ocean/biosphere CO_2 concentration (Gt)	5,628.8	Based on Nordhaus and Sztorz (2013); Gt of carbon have been transformed into Gt of CO_2
$CO2_{LO}$	Lower ocean CO_2 concentration (Gt)	36,706.7	Based on Nordhaus and Sztorz (2013); Gt of carbon have been transformed into Gt of CO_2
CON_E	Amount of non-renewable energy resources converted into non-renewable energy reserves (EJ)	1,626.0	Calculated from Eq. (20) using the initial value of RES_E
CON_M	Amount of material resources converted into material reserves (Gt)	194	Calculated from Eq. (12) using the initial value of RES_M
CR_C	Degree of credit rationing for conventional loans	0.2	Calculated from Eq. (100) using the initial value of lev
CR_G	Degree of credit rationing for green loans	0.4	Calculated from Eq. (101) using the initial value of lev
D	Deposits (trillion US$)	66.6	Calculated from Eq. (104-red) using the initial value of L
DC	Stock of durable consumption goods (trillion US$)	1,185	Calculated from Eq. (4) using the initial values of K, DEM, δ and μ
DEM	Demolished/discarded socio-economic stock (Gt)	17.0	Based on Haas et al. (2015)
dep_E	Energy depletion ratio	0.013	Calculated from Eq. (22) using the initial values of EN and REV_E
dep_M	Matter depletion ratio	0.008	Selected from a reasonable range of values
DP	Distributed profits of firms (trillion US$)	6.4	Calculated from Eq. (60) using the initial values of TP and RP
D_T	Total proportional damage caused by global warming	0.0028	Calculated from Eq. (55) using the initial value of T_{AT}
D_{TF}	Part of damage that affects directly the fund-service resources	0.0026	Calculated from Eq. (57) using the initial values of D_T and D_{TP}
D_{TP}	Part of damage that reduces the productivities of fund-service resources	0.0003	Calculated from Eq. (56) using the initial value of D_T
E	Energy necessary for the production of output (EJ)	580.0	Based on IEA (International Energy Agency); total primary energy supply is used
ED	Dissipated energy (EJ)	580.0	Calculated from Eq. (18) using the initial values of EN and ER
$EMIS$	Total CO_2 emissions (Gt)	40.0	Calculated from Eq. (25) using the initial values of $EMIS_{IN}$ and $EMIS_L$
$EMIS_{IN}$	Industrial CO_2 emissions (Gt)	36.0	Based on CDIAC (Carbon Dioxide Information Analysis Center)
$EMIS_L$	Land-use CO_2 emissions (Gt)	4.0	Based on CDIAC (Carbon Dioxide Information Analysis Center)
EN	Energy produced from non-renewable sources (EJ)	498.8	Calculated from Eq. (17) using the initial values of E and ER
ER	Energy produced from renewable sources (EJ)	81.2	Calculated from Eq. (16) using the initial values of θ and E
F	Radiative forcing over pre-industrial levels (W/m^2)	2.30	Calculated from Eq. (29) using the initial values of $CO2_{AT}$ and F_{EX}
F_{EX}	Radiative forcing, over pre-industrial levels, due to non-CO_2 greenhouse gases (W/m^2)	0.28	Based on Nordhaus and Sztorz (2013)
g_{LF}	Growth rate of labour force before global warming damages	0.012	Based on United Nations (2015)
g_Y	Growth rate of output	0.030	Calibrated such that the model generates the baseline scenario described in Section 4
$g_{\beta 0}$	Growth rate of the autonomous share of green investment in total investment	0.001	Calibrated such that the model generates the baseline scenario described in Section 4
$g_{\varepsilon G}$	Growth rate of green energy intensity	−0.050	Calibrated such that the model generates the baseline scenario described in Section 4
g_λ	Growth rate of labour productivity	0.018	Calculated from Eq. (86) using the initial values of g_Y and σ_0
$g_{\mu G}$	Growth rate of green material intensity	−0.013	Calibrated such that the model generates the baseline scenario described in Section 4
$g_{\rho G}$	Growth rate of green recycling rate	0.01	Calibrated such that the model generates the baseline scenario described in Section 4
g_ω	Growth rate of CO_2 intensity	−0.005	Calibrated such that the model generates the baseline scenario described in Section 4
$hazratio$	Hazardous waste accumulation ratio (Gt/million km^2)	0.03	Calculated from Eq. (10) using the initial value of HWS
HWS	Stock of hazardous waste (Gt)	14.0	Calculated assuming a constant ratio of hazardous waste to GDP since 1960
I	Total investment (trillion US$)	26.1	Calibrated such that the model generates the baseline scenario described in Section 4
I_C	Conventional investment (trillion US$)	15.7	Calculated from Eq. (77) using the initial values of I and I_G
I_C^D	Desired conventional investment (trillion US$)	17.5	Calculated from Eq. (69) using the initial values of I^D and I_G^D
I^D	Desired total investment (trillion US$)	31.3	Selected such that it is reasonably higher than I
I_G	Green investment (trillion US$)	10.4	Calculated by assuming that I_G/I is slightly lower than β; the initial values of β and I are used
I_G^D	Desired green investment (trillion US$)	13.8	Calculated from Eq. (68) using the initial values of β and I^D
K	Total capital stock (trillion US$)	380.6	Calculated from the identity $K = (K/Y) * Y$ by using the initial value of Y and assuming that $K/Y = 5.2$ (this value has been selected such that the model generates the baseline scenario described in Section 4)
K_C	Conventional capital stock (trillion US$)	290.3	Calculated from Eq. (81) using the initial values of K and K_G

(continued on next page)

Appendix A (*continued*)

Symbol	Description	Value	Remarks/sources
K_G	Green capital stock (trillion US$)	90.4	Calculated from Eq. (82) using the initial values of K and κ
L	Total loans of firms (trillion US$)	66.6	Calculated from Eq. (83) using the initial values of lev and K
L_C	Conventional loans (trillion US$)	50.8	Calculated from Eq. (78) using the initial values of L and L_G
L_G	Green loans (trillion US$)	15.8	Calculated by assuming that $L_G/L = K_G/K = \kappa$; we use the initial values of κ and L
lev	Firms' leverage ratio	0.18	Calculated from the identity $lev = (L/Y)/(K/Y)$; L/Y is taken from BIS (Bank for International Settlements); the credit to the non-financial corporations in percent of GDP is used; K/Y is assumed to be equal to 5.2 (this value has been selected such that the model generates the baseline scenario described in Section 4).
LF	Labour force (billion people)	3.4	Based on World Bank
lf_0	Autonomous growth rate of the labour force	0.012	Calibrated such that initial growth rate of the labour force is equal to the current one
M	Extraction of new matter from the ground, excluding the matter included in non-renewable energy sources (Gt)	48.0	Based on the data provided by www.materialflows.net; the figure includes industrial and construction minerals plus ores
MY	Output in material terms (Gt)	53.1	Calculated from Eq. (2) using the initial values of M and REC
N	Number of employees (billion people)	3.2	Calculated from the definition of the rate of employment ($re = N/LF$) using the initial values of re and LF
NL_C^D	Desired new amount of conventional loans (trillion US$)	6.0	Calculated from Eq. (74) using the initial values of I_C^D, β, RP, L_C, δ and K_C
NL_G^D	Desired new amount of green loans (trillion US$)	7.8	Calculated from Eq. (73) using the initial values of I_G^D, β, RP, L_G, δ and K_G
$O2$	Oxygen used for the combustion of fossil fuels (Gt)	26.2	Calculated from Eq. (8) using the initial values of $EMIS_{IN}$ and CEN
r	Rate of retained profits	0.024	Calculated from Eq. (61) using the initial values of RP and K
re	Rate of employment	0.94	Calculated from Eq. (91) using the initial value of ur
REC	Recycled socio-economic stock (Gt)	5.1	Calculated from Eq. (3) using the initial values of ρ and DEM
RES_E	Non-renewable energy resources (EJ)	542,000	Based on BGR (2015, p. 33)
RES_M	Material resources (Gt)	388,889	Calculated by assuming $RES_M/REV_M = 64.8$ (based on UNEP, 2011)
REV_E	Non-renewable energy reserves (EJ)	37,000	Based on BGR (2015, p. 33)
REV_M	Material reserves (Gt)	6,000	Calculated from Eq. (14) using the initial values of M and dep_M
RP	Retained profits of firms (trillion US$)	9.0	Calculated from Eq. (59) using the initial value of TP
SES	Socio-economic stock (Gt)	1,135.6	Calculated from the identity $SES = \mu(K + DC)$ using the initial values of μ, K and DC
T_{AT}	Atmospheric temperature over pre-industrial levels (°C)	1.0	Based on Met Office
T_{LO}	Lower ocean temperature over pre-industrial levels (°C)	0.0068	Taken from Nordhaus and Sztorz (2013)
TP	Total profits of firms (trillion US$)	15.4	Calculated from Eq. (58) using the initial values of Y, w, N, L_C, L_G, δ and K
u	Rate of capacity utilisation	0.72	Based on World Bank, Enterprise Surveys
ue	Rate of energy utilisation	0.01	Calculated from Eq. (52) using the initial values of Y and Y_E^*
um	Rate of matter utilisation	0.01	Calculated from Eq. (51) using the initial values of Y and Y_M^*
ur	Unemployment rate	0.06	Based on World Bank
v	Capital productivity	0.27	Calculated from Eqs. (47) and (53) using the initial values of Y, u and K
w	Annual wage rate (trillion US$/billions of employees)	11.91	Calculated from Eq. (89) using the initial value of λ
W	Waste (Gt)	11.90	Calculated from the identity $W = DEM\text{-}REC$ using the initial values of DEM and REC
Y	Output (trillion US$)	73.2	Taken from IMF, World Economic Outlook (current prices)
Y^*	Potential output (trillion US$)	77.9	Calculated from Eq. (49) using the initial values of Y_M^*, Y_E^*, Y_K^* and Y_N^*
Y_E^*	Energy-determined potential output (trillion US$)	5,429.8	Calculated from Eq. (46) using the initial values of REV_E, θ and ε
Y_H	Disposable income of households (trillion US$)	49.2	Calculated from Eq. (92) using the initial values of w, N, DP, BP and D
Y_K^*	Capital-determined potential output (trillion US$)	101.7	Calculated from Eq. (47) using the initial values of v and K
Y_M^*	Matter-determined potential output (trillion US$)	8,278.2	Calculated from Eq. (45) using the initial values of REV_M, REC and μ
Y_N^*	Labour-determined potential output (trillion US$)	77.9	Calculated from Eq. (48) using the initial values of λ and LF
α_0	Autonomous desired investment rate	0.028	Since there are no supply-side constraints, this is equal to α_{00}
β	Share of desired green investment in total investment	0.44	Calibrated such that the model generates the baseline scenario described in Section 4
β_0	Autonomous share of desired green investment in total investment	0.46	Calibrated such that the model generates the baseline scenario described in Section 4
γ_1	Sensitivity of the desired investment rate to the difference between um and um_T	0	Since $um < um_T$, there are no matter-related supply-side constraints
γ_2	Sensitivity of the desired investment rate to the difference between ue and ue_T	0	Since $ue < ue_T$, there are no energy-related supply-side constraints
γ_3	Sensitivity of the desired investment rate to the difference between u and u_T	0	Since $u < u_T$, there are no capital-related supply-side constraints
γ_4	Sensitivity of the desired investment rate to the difference between re and re_T	0	Since $re < re_T$, there are no labour-related supply-side constraints
δ	Depreciation rate of capital stock	0.04	Calculated from Eq. (84) using the initial value D_{TF}
ε	Energy intensity (EJ/trillion US$)	7.92	Calculated from the definition of energy intensity ($\varepsilon = E/Y$) using the initial values of E and Y
ε_G	Energy intensity of green capital (EJ/trillion US$)	6.65	Selected such that it is reasonably lower than ε_C
θ	Share of renewable energy in total energy	0.14	Based on IEA (International Energy Agency); total primary energy supply is used
κ	Ratio of green capital to total capital	0.24	Calculated from Eqs. (44) and (82) using the initial value of θ
λ	Hourly labour productivity (trillion US$/(billions of employees * annual hours worked per employee))	0.01	Calculated from Eq. (90) using the initial values of Y and N
μ	Material intensity (kg/US$)	0.73	Calculated from the definition of material intensity ($\mu = MY/Y$) using the initial values of MY and Y
μ_G	Material intensity of green capital (kg/US$)	0.61	Selected such that it is reasonably lower than μ
ρ	Recycling rate	0.30	Based on Haas et al. (2015)
ρ_G	Recycling rate of green capital	0.48	Selected such that it is reasonably higher than ρ
σ_0	Autonomous growth rate of labour productivity	−0.03	Calibrated such that the model generates the baseline scenario described in Section 4
ω	CO_2 intensity (Gt/EJ)	0.07	Calculated from Eq. (23) using the initial values of $EMIS_{IN}$ and EN

Appendix B. Values for parameters and exogenous variables (baseline scenario)

Symbol	Description	Value	Remarks/sources
ad_K	Fraction of gross damages to capital stock avoided through adaptation	0.75	Selected from a reasonable range of values
ad_{LF}	Fraction of gross damages to labour force avoided through adaptation	0.95	Selected from a reasonable range of values
ad_P	Fraction of gross damages to productivity avoided through adaptation	0.50	Selected from a reasonable range of values
c_1	Propensity to consume out of disposable income	0.88	Calibrated such that the model generates the baseline scenario described in Section 4
c_2	Propensity to consume out of deposits	0.075	Selected from a reasonable range of values
car	Coefficient for the conversion of Gt of carbon into Gt of CO_2	3.67	Taken from CDIAC (Carbon Dioxide Information Analysis Center)
$CO2_{AT\text{-}PRE}$	Pre-industrial CO_2 concentration in atmosphere (Gt)	2,156.2	Taken from Nordhaus and Sztorz (2013); Gt of carbon have been transformed into Gt of CO_2
$CO2_{LO\text{-}PRE}$	Pre-industrial CO_2 concentration in upper ocean/biosphere (Gt)	36,670.0	Taken from Nordhaus and Sztorz (2013); Gt of carbon have been transformed into Gt of CO_2
$CO2_{UP\text{-}PRE}$	Pre-industrial CO_2 concentration in lower ocean (Gt)	4,950.5	Taken from Nordhaus and Sztorz (2013); Gt of carbon have been transformed into Gt of CO_2
con_M	Conversion rate of material resources into reserves	0.0005	Selected from a reasonable range of values
con_E	Conversion rate of non-renewable energy resources into reserves	0.003	Selected from a reasonable range of values
F_{2xCO2}	Increase in radiative forcing (since the pre-industrial period) due to doubling of CO_2 concentration from pre-industrial levels (W/m^2)	3.8	Taken from Nordhaus and Sztorz (2013)
fex	Annual increase in radiative forcing (since the pre-industrial period) due to non-CO_2 agents (W/m^2)	0.005	Based on Nordhaus and Sztorz (2013)
g_v	Growth rate of capital productivity before global warming damages	0.001	Calibrated such that the model generates the baseline scenario described in Section 4
h	Annual working hours per employee	1,800	Based on Penn World Table 8.1
haz	Proportion of hazardous waste in total waste	0.04	EEA (2012, p. 22) reports a figure equal to 3.7% for EU-27
int_C	Interest rate on conventional loans	0.07	Based on World Bank
int_D	Interest rate on deposits	0.015	Based on World Bank
int_G	Interest rate on green loans	0.08	Based on World Bank; it is assumed that int_G-$int_C = 0.01$
l_0	Autonomous credit rationing on green loans	0.37	Selected from a reasonable range of values
l_1	Sensitivity of green loans' credit rationing to the leverage ratio of firms	0.2	Selected from a reasonable range of values
lf_1	Autonomous growth rate of labour force	0.012	Calibrated such that the model generates the baseline scenario described in Section 4
lf_2	Sensitivity of the growth rate of labour force to the unemployment rate	0.2	Calibrated such that the model generates the baseline scenario described in Section 4
lf_3	Sensitivity of the growth rate of labour force to the hazardous waste accumulation ratio	0.001	Calibrated such that the model generates the baseline scenario described in Section 4
lr	Rate of decline of land-use CO_2 emissions	0.044	Taken from Nordhaus and Sztorz (2013); has been adjusted to reflect a 1-year time step
p	Share of productivity damage in total damage caused by global warming	0.1	Selected from a reasonable range of values
r_0	Autonomous credit rationing on conventional loans	0.17	Selected from a reasonable range of values
r_1	Sensitivity of conventional loans' credit rationing to the leverage ratio of firms	0.2	Selected from a reasonable range of values
re_T	Threshold rate of employment above which supply-side constraints arise	0.96	Selected from a reasonable range of values
rep	Loan repayment ratio	0.1	Selected from a reasonable range of values
S	Equilibrium climate sensitivity, i.e. increase in equilibrium temperature due to doubling of CO_2 concentration from pre-industrial levels (°C)	3	Taken from Dietz and Stern (2015)
$SURF$	Earth surface (million km^2)	510.1	Taken from the World Factbook
s_F	Firms' retention rate	0.6	Selected from a reasonable range of values
s_W	Wage income share	0.52	Based on Penn World Table 8.1
t_1	Speed of adjustment parameter in the atmospheric temperature equation	0.027	Calculated using the formula in Calel et al. (2015, p. 132); effective heat capacity is assumed to be equal to 1.2 GJm^{-2} K^{-1}
t_2	Coefficient of heat loss from the atmosphere to the lower ocean (atmospheric temperature equation)	0.018	Taken from Nordhaus and Sztorz (2013); has been adjusted to reflect a 1-year time step
t_3	Coefficient of heat loss from the atmosphere to the lower ocean (lower ocean temperature equation)	0.005	Taken from Nordhaus and Sztorz (2013); has been adjusted to reflect a 1-year time step
u_T	Threshold rate of capacity utilisation above which supply-side constraints arise	0.85	Selected from a reasonable range of values
ue_T	Threshold rate of energy utilisation above which supply-side constraints arise	0.05	Selected from a reasonable range of values
um_T	Threshold rate of matter utilisation above which supply-side constraints arise	0.05	Selected from a reasonable range of values
α_{00}	Autonomous desired investment rate	0.028	Calibrated such that the model generates the baseline scenario described in Section 4
α_1	Sensitivity of desired investment rate to the rate of retained profits	0.2	Selected from a reasonable range of values
α_2	Sensitivity of desired investment rate to the rate of capacity utilisation	0.01	Selected from a reasonable range of values
α_3	Sensitivity of desired investment rate to the growth rate of energy intensity	0.1	Selected from a reasonable range of values
β_1	Autonomous share of desired green investment in total investment	0.02	Calibrated such that the model generates the baseline scenario described in Section 4
β_2	Sensitivity of the desired green investment share to the green loan-conventional loan interest rate differential	4	Selected from a reasonable range of values
β_3	Sensitivity of the desired green investment share to global warming damages	0.5	Selected from a reasonable range of values
γ_{10}	Sensitivity of the desired investment rate to the matter-related supply-side constraints	0.5	Selected from a reasonable range of values
γ_{20}	Sensitivity of the desired investment rate to the energy-related supply-side constraints	0.5	Selected from a reasonable range of values
γ_{30}	Sensitivity of the desired investment rate to the capital-related supply-side constraints	0.5	Selected from a reasonable range of values

(continued on next page)

Appendix B (*continued*)

Symbol	Description	Value	Remarks/sources
γ_{40}	Sensitivity of the desired investment rate to the labour-related supply-side constraints	0.5	Selected from a reasonable range of values
δ_0	Depreciation rate of capital stock when there are no global warming damages	0.04	Based on Penn World Table 8.1
ε_C	Energy intensity of conventional capital (EJ/trillion US$)	8.32	Selected such that it is reasonably lower than ε
ζ_1	Rate of decline of the (absolute) growth rate of CO_2 intensity	0.03	Calibrated such that the model generates the baseline scenario described in Section 4
ζ_2	Rate of decline of the (absolute) growth rate of green capital material intensity	0.001	Calibrated such that the model generates the baseline scenario described in Section 4
ζ_3	Rate of decline of the growth rate of green capital recycling rate	0.02	Calibrated such that the model generates the baseline scenario described in Section 4
ζ_4	Rate of decline of the (absolute) growth rate of green capital energy intensity	0.005	Calibrated such that the model generates the baseline scenario described in Section 4
ζ_5	Rate of decline of the growth rate of β_0	0.015	Calibrated such that the model generates the baseline scenario described in Section 4
ζ_6	Rate of decline of the autonomous (absolute) growth rate of labour productivity	0.007	Calibrated such that the model generates the baseline scenario described in Section 4
ζ_7	Rate of decline of the autonomous growth rate of labour force	0.018	Calibrated such that the model generates the baseline scenario described in Section 4
η_1	Parameter of damage function	0	Based on Weitzman (2012); $D_T = 50\%$ when $T_{AT} = 6\ °C$
η_2	Parameter of damage function	0.00284	Based on Weitzman (2012); $D_T = 50\%$ when $T_{AT} = 6\ °C$
η_3	Parameter of damage function	0.000005	Based on Weitzman (2012); $D_T = 50\%$ when $T_{AT} = 6\ °C$
μ_C	Material intensity of conventional capital (kg/US$)	0.76	Selected such that it is reasonably higher than μ
ξ	Proportion of durable consumption goods discarded every year	0.007	Selected such that the initial growth of DC is equal to 3%
π	Parameter linking the green capital-conventional capital ratio with the share of renewable energy	0.54	Calculated from Eq. (44) by assuming that $\theta = 0.35$ when $K_G = K_C$
ρ_C	Recycling rate of conventional capital	0.24	Selected such that it is reasonably lower than ρ
σ_1	Autonomous growth rate of labour productivity	0.029	Calibrated such that the model generates the baseline scenario described in Section 4
σ_2	Sensitivity of labour productivity growth to the growth rate of output	0.6	Calibrated such that the model generates the baseline scenario described in Section 4
φ_{11}	Transfer coefficient for carbon from the atmosphere to the atmosphere	0.9817	Calculated from the formula $\varphi_{11} = 1 - \varphi_{12}$ (see Nordhaus and Sztorz (2013))
φ_{12}	Transfer coefficient for carbon from the atmosphere to the upper ocean/biosphere	0.0183	Taken from Nordhaus and Sztorz (2013); has been adjusted to reflect a 1-year time step
φ_{21}	Transfer coefficient for carbon from the upper ocean/biosphere to the atmosphere	0.0080	Calculated from the formula $\varphi_{21} = \varphi_{12}(CO2_{AT\text{-}PRE}/CO2_{UP\text{-}PRE})$ (see Nordhaus and Sztorz (2013))
φ_{22}	Transfer coefficient for carbon from the upper ocean/biosphere to the upper ocean/biosphere	0.9915	Calculated from the formula $\varphi_{22} = 1 - \varphi_{21}\text{-}\varphi_{23}$ (see Nordhaus and Sztorz (2013))
φ_{23}	Transfer coefficient for carbon from the upper ocean/biosphere to the lower ocean	0.0005	Taken from Nordhaus and Sztorz (2013); has been adjusted to reflect a 1-year time step
φ_{32}	Transfer coefficient for carbon from the lower ocean to the upper ocean/biosphere	0.0001	Calculated from the formula $\varphi_{32} = \varphi_{23}(CO2_{UP\text{-}PRE}/CO2_{LO\text{-}PRE})$ (see Nordhaus and Sztorc (2013))
φ_{33}	Transfer coefficient for carbon from the lower ocean to the lower ocean	0.9999	Calculated from the formula $\varphi_{33} = 1 - \varphi_{32}$ see (Nordhaus and Sztorz (2013))

References

Barker, T., Dagoumas, A., Rubin, J., 2009. The macroeconomic rebound effect and the world economy. Energy Effic. 2, 411–427.

Barker, T., Anger, A., Chewpreecha, U., Pollitt, H., 2012. A new economics approach to modelling policies to achieve global 2020 targets for climate stabilisation. Int. Rev. Appl. Econ. 26 (2), 205–221.

Berg, M., Hartley, B., Richters, O., 2015. A stock-flow consistent input–output model with applications to energy price shocks, interest rates, and heat emissions. New J. Phys. 17, 1–21.

BGR, 2015. Energy Study 2015: Reserves, Resources and Availability of Energy Resources. Federal Institute for Geosciences and Natural Resources (BGR).

Calel, R., Stainforth, D.A., Dietz, S., 2015. Tall tales and fat tails: the science and economics of extreme warming. Clim. Chang. 132 (1), 127–141.

Campiglio, E., 2016. Beyond carbon pricing: the role of banking and monetary policy in financing the transition to a low-carbon economy. Ecol. Econ. 121, 220–230.

Clemens, T., Boyle, P., Popham, F., 2011. Unemployment, mortality and the problem of health related selection: evidence from the Scottish and England & Wales (ONS) longitudinal studies. ONS Health Stat. Q. 43, 7–13.

Dafermos, Y., 2012. Liquidity preference, uncertainty, and recession in a stock-flow consistent model. J. Post Keynesian Econ. 34 (4), 749–776.

Daly, H.E., Farley, J., 2011. Ecological Economics: Principles and Applications. Island Press, Washington DC.

de Bruin, K.C., Dellink, R.B., Tol, R.S.J., 2009. AD-DICE: an implementation of adaptation in the DICE model. Clim. Chang. 95 (1), 63–81.

Dell, M., Jones, B.F., Olken, B.A., 2014. What do we learn from the weather? The new climate-economy literature. J. Econ. Lit. 52 (3), 740–798.

Dietz, S., Stern, N., 2015. Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions. Econ. J. 125 (583), 574–620.

EEA, 2012. Material Resources and Waste – 2012 Update: The European Environment State and Outlook 2010. EEA, Copenhagen.

Eyraud, L., Clements, B., Wane, A., 2013. Green investment: trends and determinants. Energy Policy 60, 852–865.

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., Weisz, H., 2011. Methodology and indicators of economy-wide material flow accounting: state of the art and reliability across sources. J. Ind. Ecol. 15 (6), 855–876.

Fontana, G., Sawyer, M., 2013. Post-Keynesian and Kaleckian thoughts on ecological macroeconomics. Eur. J. Econ. Econ. Policies Interv. 10 (2), 256–267.

Fontana, G., Sawyer, M., 2016. Towards post-Keynesian ecological macroeconomics. Ecol. Econ. 121, 186–195.

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge, UK.

Georgescu-Roegen, N., 1979. Energy analysis and economic valuation. South. Econ. J. 45 (4), 1023–1058.

Georgescu-Roegen, N., 1984. Feasible recipes versus viable technologies. Atl. Econ. J. 12 (1), 21–31.

Godley, W., Lavoie, M., 2007. Monetary Economics: An Integrated Approach to Credit, Money, Income, Production and Wealth. Palgrave Macmillan, Basingstoke, UK.

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy? An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. J. Ind. Ecol. 19 (5), 765–777.

Jackson, T., 2009. Prosperity Without Growth: Economics for a Finite Planet. Routledge, UK and USA.

Jackson, T., Victor, P.A., 2015. Does credit create a 'growth imperative'? A quasi-stationary economy with interest-bearing debt. Ecol. Econ. 120, 32–48.

Kjellstrom, T., Kovats, R.S., Lloyd, S.J., Holt, T., Tol, R.S.J., 2009. The direct impact of climate change on regional labor productivity. Arch. Environ. Occup. Health 64 (4), 217–227.

Kronenberg, T., 2010. Finding common ground between ecological economics and post-Keynesian economics. Ecol. Econ. 69, 1488–1494.

Kurz, H.D., Salvadori, N., 2003. Fund-flow versus flow-flow in production theory: reflections on Georgescu-Roegen's contribution. J. Econ. Behav. Organ. 51 (4), 487–505.

Lavoie, M., 2014. Post-Keynesian Economics: New Foundations. Edward Elgar, Cheltenham, UK and Northampton, MA, USA.

Mayumi, K., 2001. The Origins of Ecological Economics: The Bioeconomics of Georgescu-Roegen. Routledge, UK and USA.
Mearman, A., 2009. Recent developments in Post Keynesian methodology and their relevance for understanding environmental issues. In: Holt, R.P.F., Pressman, S., Spash, C.L. (Eds.), Post Keynesian and Ecological Economics: Confronting Environmental Issues. Edward Elgar, Cheltenham, UK and Northampton, MA, USA.
Misra, V., Pandey, S.D., 2005. Hazardous waste, impact on health and environment for development of better waste management strategies in future in India. Environ. Int. 31 (3), 417–431.
Moyer, E.J., Woolley, M.D., Matteson, N.J., Glotter, M.J., Weisbach, D.A., 2014. Climate impacts on economic growth as drivers of uncertainty in the social cost of carbon. J. Leg. Stud. 43 (2), 401–425.
Naqvi, A., 2015. Modeling growth, distribution, and the environment in a stock-flow consistent framework. Working Paper Institute for Ecological Economics No. 2015/02.
Nikolaidi, M., 2014. Margins of safety and instability in a macrodynamic model with Minskyan insights. Struct. Chang. Econ. Dyn. 31, 1–16.
Nordhaus, W., Sztorc, P., 2013. DICE 2013R: introduction and user's manual. http://www.econ.yale.edu/~nordhaus/homepage/documents/DICE_Manual_103113r2.pdf.
Rezai, A., Stagl, S., 2016. Ecological macroeconomics: introduction and review. Ecol. Econ. 121, 181–185.
Rezai, A., Taylor, L., Mechler, R., 2013. Ecological macroeconomics: an application to climate change. Ecol. Econ. 85, 69–76.
Ryoo, S., Skott, P., 2008. Financialization in Kaleckian economies with and without labor constraints. Eur. J. Econ. Econ. Policies Interv. 5 (2), 357–386.
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. J. Econ. Lit. 51 (3), 838–859.
Taylor, L., Rezai, A., Foley, D.K., 2016. An integrated approach to climate change, income distribution, employment, and economic growth. Ecol. Econ. 121, 196–205.
Toll, R.S.J., 2002. Climate, development and malaria: an application of FUND. Working Paper FNU No. 16.
UNEP, 2011. Estimating long-run geological stocks of metals. UNEP Working Paper April 6.
United Nations, 2014. System of Environmental-Economic Accounting 2012 Central Framework. United Nations, New York.
United Nations, 2015. World Population Prospects: Key Findings and Advance Tables. United Nations, New York.
Victor, P.A., 2012. Growth, degrowth and climate change: a scenario analysis. Ecol. Econ. 84, 206–212.
Victor, P.A., Rosenbluth, G., 2007. Managing without growth. Ecol. Econ. 61, 492–504.
Weitzman, M.L., 2012. GHG targets as insurance against catastrophic climate damages. J. Public Econ. Theory 14 (2), 221–244.