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Sraffian Supermultiplier, Mission-Oriented Innovation Policies and Ecological Sustainability: A Stock-Flow Dynamic Model

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Abstract. This work builds upon four different traditions or schools of economic thought: i. the Sraffian supermultiplier approach; ii. the Schumpeterian framework of evolutionary economics that emphasises the entrepreneurial role of the State; iii. the so-called 'stock-flow consistent' approach to macroeconomic modelling; iv. recent developments in ecological economics literature aiming at cross-breeding post-Keynesian theories and models with more traditional 'green' topics. Our main purpose is to develop a simple analytical tool that can help examine the impact of government spending on private innovation, of innovation on economic growth and ecological sustainability, and of ecological sustainability on economic growth and government spending effectiveness. We find that, in principle, government can be successful in supporting innovation and growth while limiting material and (non-renewable) energy reserves' depletion, even though the latter may well affect government policy effectiveness.

Keywords: Sraffian super-multiplier, Mission-oriented policy, Stock-Flow consistent modelling, Ecological economics

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1. Introduction

This work builds upon four different traditions or schools of thought in economics: i. the Sraffian supermultiplier approach (e.g. Serrano 1995, Freitas and Serrano 2015); ii. the Schumpeterian framework of evolutionary economics that emphasises the entrepreneurial role of the State (e.g. Mazzucato 2013, 2016, 2017); iii. the so-called 'stock-flow consistent' approach to macroeconomic modelling (e.g. Godley and Lavoie 2007); iv. recent developments in ecological economics literature aiming at cross-breeding post-Keynesian theories and models with more traditional 'green' topics. In this sense, our work shows a resemblance to the contributions by Fontana and Sawyer (2016), Dafermos et al. (2017, 2018) and other advocates of the post-Keynesian ecological macroeconomics. Our main purpose is to develop a simple analytical tool that can help address the following questions: what is the impact of different types of fiscal policy on innovation and total green spending? What is the impact of the latter on economic growth and the depletion rate of material and (non-renewable) energy reserves? What is the impact of feedback mechanisms between these rates on fiscal policy effectiveness? Finally, what is the (indirect) impact of material and energy reserves' depletion on the stock market?

To address the research questions above, the paper is organised as follows. Section 2 provides a short review of the literature this paper is inspired to. This review enables us to identify the literature gap that our contribution aims to bridge, namely, the interaction between fiscal (and industrial) policies, private innovation and the ecosystem. Section 3 is methodological and theoretical. We highlight key features, assumptions and possible drawbacks of the model. In section 4 our preliminary findings are presented and discussed. More precisely, sub-section 4.1 performs standard economic shocks to shed light on the macroeconomic dynamics of the model without ecological constraints or feedbacks. Section 4.2, in contrast, shows how findings differ from the baseline scenario when the progressive depletion of material and energy reserves and its impact on narrowly-defined macroeconomic variables are considered. In section 5 we sum up our main results and we stress possible limitations and future directions of development of our work.

2. Literature review

As mentioned, our work is grounded in a four-fold theoretical approach, notably, the Sraffian supermultiplier, the Schumpeterian framework of evolutionary economics, the stock-flow consistent modelling, and the recent developments in ecological macroeconomics.

The main purpose of the Sraffian supermultiplier model, originally presented by Serrano (1995), is to determine output according to the principle of effective demand. It couples the traditional Keynesian multiplier with an investment function based on the flexible accelerator principle. Coherently with the Classical tradition, income distribution is exogenously determined by social and historical factors, affecting the bargaining power of social classes, and by customs and social norms about the fairness of wages. According to the model, which has been further discussed and developed by Cesaratto et al. (2003) and Freitas and Serrano (2015), output growth is shaped by the evolution of the autonomous components of aggregate demand. The Sraffian Supermultiplier is a demand-led growth model that displays some desirable properties: a) the extension of the so-called 'Keynesian hypothesis' to the long-run (e.g. Garegnani, 1992); b) an investment function that is based on the accelerator mechanism but does not engender Harrodian instability; c) the absence of any necessary relation between the rate of accumulation and normal income distribution; d) an equilibrium level for the degree of capacity utilisation that is equal to the normal, cost-minimizing, level. Since the seminal contribution of Serrano (1995), an intense theoretical debate has taken place (e.g. Trezzini, 1995; Trezzini, 1998; Park, 2000; Palumbo and Trezzini, 2003; Dejuán, 2005; Smith, 2012; Cesaratto and Mongiovi, 2015), which has helped clarify some possible misunderstandings and misconceptions. For instance, the model does not require assuming that productive capacity is continuously utilised at its normal level. Discrepancies between the actual and the normal degree of capacity utilisation are allowed in the out-of-equilibrium dynamics. Investment's reactions to these discrepancies drive the convergence of the economy towards a normal utilisation rate of the productive capacity. More recently, the Supermultiplier has re-gained momentum and has been endorsed by authors outside the boundaries of the Sraffian community (e.g. Allain, 2015; Lavoie, 2016; Hein, 2018; Fazzari et al. 2018).

The Neo-Schumpeterian view provide us with the theoretical framework we need to analyse the determinants of technical progress (see among others, Nelson and Winter, 1982; Mowery et al., 2010; Foray et al., 2012; Mazzucato, 2013; 2014; 2017). Targeted innovation government policies directed at strategic areas, such as mission-oriented innovation policies (MOIPs), create new landscapes (rather than simply fixing market failures), new visions, and new opportunities beyond the existing paradigms (e.g. Mazzucato, 2016, 2017). MOIPs include public spending on the military and aerospace sectors, as well as energy and clean-tech sectors, biotechnology and nanotechnology industries and IT sectors (e.g. Block and Keller, 2011). Historically, MOIPs have established the direction of the technical progress (Mazzucato, 2013). These policies have also created market opportunities for the private business sector (Mazzucato, 2016). Government spending, by allocating resources in strategic sectors, stimulates and leverages private R&D investment in new areas (e.g. Mazzucato, 2016; Deleidi and Mazzucato, 2018), thus accelerating the process of development and diffusion of innovation across the economy (e.g. Pivetti, 1992). Examples of MOIPs include the *Apollo Program* (EC, 2018b; Mazzucato, 2018) and the *Energiewende Programme* (EC, 2018c; Mazzucato, 2018). These programmes rely on a challenge-based approach and are aimed at creating systemic interactions and cross-sector fertilisations. In this view, technical progress is endogenous with respect to both private business expenditures (e.g. Nelson and Winter, 1982) and government intervention (e.g. Foray et al., 2012; Mowery et al., 2010; Mazzucato, 2013; 2017).

The so-called stock-flow consistent (SFC) approach to macroeconomic modelling is grounded in Tobin's seminal Nobel Prize Lecture in 1982. It was then fully developed by Wynne Godley and Marc Lavoie in the 2000s (e.g. Godley and Lavoie, 2007), who paved the way for the flourishing of SFC models of the last decade. SFC models are based on four accounting principles (e.g. Nikiforos and Zezza, 2017): flow consistency, meaning that every flow comes from somewhere and goes somewhere; stock consistency, meaning that financial liabilities of an economic unit must be held as financial assets by other economic units; stock-flow consistency, meaning that flows affect stocks and this impact must be accurately registered (including capital gains and losses); quadruple book-keeping, meaning that every transaction requires filling in four different entries.[1] Building upon these principles, a system of difference (or differential) equations is developed, coupling accounting identities and equilibrium conditions with behavioural (or stochastic) equations. This method allows developing medium- to large-scale structural macroeconometric models which are usually solved through computer simulations and then used to test reactions to shocks.[2]

The last crop of literature our work is inspired to is a recent strand in ecological economics which is sometimes referred to as 'post-Keynesian ecological macroeconomics' (PKEM) (see, for instance, Foley 2012; Rezai et al. 2013; Rezai and Stagl, 2016; Fontana and Sawyer, 2013, 2016; Taylor et al., 2016; Dafermos et al., 2017).[3] PKEM theorists aim at analysing the macroeconomy as part of the broad ecosystem based on three principles: i. the main force driving economic growth is effective demand; ii. supply-side constraints can emerge in the medium- to long-run due to environmental damages, the exhaustion of material and (non-renewable) energy reserves and climate changes linked with the production process; iii. there is a strong interconnection between the narrowly-defined economic system, the social environment and the ecosystem. As a result, feedback effects play major role in determining both the path of fixed capital accumulation and the depletion rate of material and energy reserves. In formal terms, our approach resembles the one adopted by Fontana and Sawyer (2016) and Dafermos et al. (2017, 2018). Using a simple Keynesian growth model, Fontana and Sawyer (2016) argue that economic growth is a 'double-edge sword': on the one hand, it can help reduce unemployment; on the other hand, it may well accelerate depletion of material and energy reserves. Dafermos et al. (2017) develop a complete ecological macroeconometric model where the SFC approach is coupled with Georgescu-Roegen's flow-fund model. They show that different green finance policies (meaning selective credit rationing and interest rate policies, favouring green activities over traditional ones) can impact positively on both the economy and the ecosystem in the long run. Their emphasis on the role of monetary policy is shared by other ecological economics theorists (e.g. Jackson and Victor, 2015; Campiglio, 2016; Fontana and Sawyer, 2016; Dafermos et al., 2018). Central

[1] More precisely, there must be always an inflow in favour of a unit, call it A, that matches the outflow faced by another unit, call it B, along with a reduction in assets held by (or an increase in liabilities of) unit A that matches the increase in assets held by (or the reduction in liabilities of) unit B.

[2] We refer again to Nikiforos and Zezza for an accurate survey of SFC models.

[3] The label 'post-Keynesian' is here used in a very broad sense to encompass all the 'dissenting' approaches to economics grounded in the contributions of Marx, Keynes, Sraffa, Kalecki, J. Robinson and Kaldor.

banks' rules of behaviour occupy centre stage in both mainstream economics models and the policy debate after all. By contrast, seldom the role of fiscal policy is examined, let alone a direct intervention of the State in the economy. Similarly, the cascade effect of MOIP on private innovation and green activities is usually ignored. Finally, the interaction between the productive sector and the ecosystem with the financial sphere is usually focused on credit market conditions and/or the green bonds' market. Feedback mechanisms between government policies, private innovation, material and energy reserves' availability and the stock market are usually not (utterly) investigated. Our paper can be regarded as an attempt at bridging this gap.

Notice that our work can help assess pros and cons of ecological policies and plans, such as the already-mentioned *Energiewende Programme* (EWP). EWP is an ambitious, risky and complex mission programme devoted at reducing carbon emissions. Launched in Germany by the Federal Ministry for Economic Affairs and Energy, EWP aims at reducing carbon emissions by reconverting the production system through a long-term strategy directed at the development of a national low-carbon energy system. The goal of EWP is to transform the Germany economy by enhancing energy efficiency, becoming strongly reliant on renewable energy resources and reducing Greenhouse Gas emissions (EC, 2018c). More specifically, the target of EWP is to allow Germany to stop the energy production derived by nuclear plants by 2022 and to become an economic system based on renewable energy resources by the 2050. To do so, EWP has established a clear and stable directionality in the economy, which has created favourable conditions and confidence for the private initiative offering new domestic and international opportunities. Indeed, the development of green technological innovation through government financed investment activities has led Germany towards a pioneering position in the supply of renewable energy technologies (EC, 2018c). While our work is mainly theoretical, it may help detect the general impact of this type of policies on main macroeconomic variables and the broader environment.

3. Theory and method

Based on the literature review above, the gaps we have identified and hence the research questions our paper aims at addressing are: what is the impact of fiscal policies on innovation and total green spending? What is the impact of the latter on economic growth and the depletion rate of material and energy reserves? What is the impact of feedback mechanisms between these rates on fiscal policy effectiveness? What is the (indirect) impact of material and energy reserves' depletion on the stock market? To address the questions above we follow a four-step process. First, we extend the supermultiplier model to account for mission-oriented innovation policies. Second, we 'implant' our extended supermultiplier mechanism into a complete stock-flow consistent model (including 115 endogenous variables and 73 exogenous variables and parameters overall). Third, we add green spending to the original model and we account for material and energy reserves, namely, we introduce the ecosystem. Fourth, we further extend the model to include the feedback between fiscal policies, public and private innovation, economic growth and the ecosystem.

3.1 Step one: developing an innovation-augmented supermultiplier model

We consider an open economy with a government sector and two types of households or social classes: workers and capitalists (or rentiers). The current level of output (Y) at time t is equal to aggregate demand, which is the sum of consumption (C), business expenditure for innovation purposes (BE), private investment in fixed capital (I), public expenditure (G), and net export (NX):[4]

$$Y = C + BE + I_f + G + NX \tag{1}$$

Total consumption can be split into workers' consumption and capitalists' consumption, both including an autonomous and an induced component (e.g. Pariboni 2016). The former is independent of current income. It is either funded by net wealth or financed through an endogenous money creation process in the credit market. The latter depends on disposable income. In formal terms:

$$C_w = C_{aw}(r_l, NW_w) + c_w \cdot YD_w \tag{2}$$
$$C_\pi = C_{a\pi}(r_l, NW_\pi) + c_\pi \cdot YD_\pi \tag{3}$$

As mentioned, C_{aw} and $C_{a\pi}$ represent autonomous consumptions financed out of net wealth or bank loans, which are negatively influenced by the interest rate level (r_l). The latter is influenced by both the policy rate (set exogenously by the central bank) and bank lending policies (embedded in variables NW_w and NW_π). A fall in the interest rate can increase the volume of loans demanded by borrowers to finance the purchase of houses[5] and consumption goods (e.g. Garegnani 2015; Deleidi 2017).[6] Autonomous consumption is also affected by general bank lending policies. Looking at equations (2) and (3), NW_π and NW_w are indices of capitalists' and workers' creditworthiness (say, their net wealth levels), respectively.[7] As usual, c_w and c_π are the marginal propensity to consume of workers and capitalists out of their respective income. We assume that $c_w > c_\pi$ (e.g. Kaldor 1955-56). Total consumption function is shown by equation (4) below:

[4] For the sake of simplicity, we omit the subscript t from model's variables. In addition, since we assume away intermediate consumption and taxes & subsidies on products, there is no difference between nominal output and GDP in our model.
[5] Although in the national account the purchase of houses is considered an investment, here we deal with it as a component of autonomous consumption.
[6] In addition, changes in the interest rate can affect the multiplier by changing income distribution between profit and wages (Pivetti 1990; Stirati 2001). However, for sake of simplicity, we neglect this point for now.
[7] Borrowers' creditworthiness is usually linked with the value of collaterals. A higher (lower) value of collaterals, NW_j (with $j = w, \pi$) allows households to access bank credit more (less) easily to fund their consumption plans.

$$C = C_a(r_l, NW_w, NW_\pi) - c_w \cdot T_{aw} - c_\pi \cdot T_{a\pi} +$$
$$+ [c_w \cdot \omega \cdot (1 - \tau_w) + c_\pi \cdot (1 - \omega) \cdot (1 - \tau_\pi)] \cdot Y \quad (4)$$

where T_{aw} and $T_{a\pi}$ are autonomous components of taxes paid by workers and capitalists, respectively, ω is the wage share, $1 - \omega$ is the profit share, and τ_w and τ_π are workers' and capitalists' tax rates, respectively.[8]

Private investment in fixed (or physical or manufactured) capital is assumed to be fully induced by the income level. If h is the investment share of total output, aggregate investment can be defined as:

$$I_f = h \cdot Y \quad (5)$$
$$h = h_{-1} + h \cdot \phi \cdot (u - u_n) \quad (6)$$

where $0 \leq \phi < 1$ is a reaction coefficient. Equation (6) shows that firms gradually adjust their investment plans to achieve the desired utilisation rate of plants, u_n.[9] At the macroeconomic level, these adjustments can be represented as changes in the investment share. So, equation (6) simply implies that entrepreneurs speed up (slow down) their investment relative to demand if they are over- (under-) utilising their productive capacity.

Combining equations (5) and (6), we obtain the rate of growth of investment:

$$g_i = \frac{\Delta I_f}{I_f} = g_y + \phi \cdot (u - u_n) \quad (7)$$

Focusing on total capital stock, the rate of accumulation is:

$$g_k = \frac{\Delta K_f}{K_f} = \frac{I}{K} - \delta_f = h \cdot \frac{u}{v} - \delta_f \quad (8)$$

where δ_f is the rate of capital depreciation.

In our model government spending is made up of two components: the purchase of goods and services, or routing spending (G_{rout}); and government spending promoting structural change, namely stimulating technical progress by means of industrial policies (G_{mois}). The former includes education and health spending, as well as expenditures in 'shovel-ready projects'. The latter includes different strands of public spending that trigger structural transformation through innovation across various sectors. Total government spending is therefore:

$$G = G_{rout} + G_{mois} \quad (9)$$

[8] For the sake of simplicity, government transfers are assumed away.
[9] The actual degree of capacity utilisation is defined as the ratio between actual and normal level of output. As a result, the normal degree of capacity utilisation is unity.

Notice that G_{mois} includes mission-oriented innovation spending (MOIS), which can lead to major technological advances.[10] This type of spending does not necessarily increase the stock of capital. Rather, it promotes the transformation and modernization of existing capital.

Turning to the private sector, we keep business expenditure (BE) apart from narrowly-defined investment. An autonomous and an endogenous component of BE can be identified. The former includes unproductive consumption (e.g. the purchase of company cars, executive jet, marketing expenditure, etc.) and a share of R&D driven by competition. However, R&D is also positively affected by public expenditure oriented to promote innovation (we refer to section 2). In formal terms:

$$BE = BE_a + \gamma \cdot G_{mois} \tag{10}$$

where γ is a positive reaction coefficient. As a result, an increase in G_{mois} leads to an endogenous expansion of private business expenditure, BE. The size of γ depends on the capacity of fiscal (and industrial) policy to target different sectors of the economy. Other things being equal, the higher the number of sectors involved, the higher γ (e.g. Mazzucato, 2017).

Finally, export and import are defined, respectively, as:

$$X = E(Y_{row}) \tag{11}$$
$$M = m \cdot Y \tag{12}$$
$$NX = X - M \tag{13}$$

where $0 \leq m < 1$ is the marginal propensity to import. Equation (11) states that export is driven by foreign sector's demand (Y_{row}). For this reason, it can be considered as an autonomous variable that is independent of domestic output. Equation (12) shows that import increases as domestic output increases. Finally, equation (13) defines net export.[11]

Equation (1), (4), (5), (9) and (12) allow us to determine the output supermultiplier:

$$Y = \frac{C_a(r_l, NW_w, NW_\pi) - c_w \cdot T_{aw} - c_\pi \cdot T_{a\pi} + BE_a + G_{rout} + (1+\gamma) \cdot G_{mois} + E(Y_f)]}{1 - [c_w \cdot \omega \cdot (1-\tau_w) + c_\pi \cdot (1-\omega) \cdot (1-\tau_\pi)] - h + m} = Z \cdot \frac{1}{\eta} \tag{14}$$

Equation (14) shows that the (quasi) steady-state level of output is defined by the overall value of autonomous components of aggregate demand (numerator), call it Z, and the

[10] Think of the DARPA's investment on ARPANET (that gave rise to internet), the ARPA-E's investments in renewable energy, and the National Institute of Health's investment in the biotechnology sector (e.g. Block and Keller 2009; Mazzucato 2013). Notice that G_{mois} is sometimes termed as 'strategic investment'. However, it is a peculiar type of investment, as it does not entail a direct expansion of productive capacity for the market.

[11] Domestic net export can be also affected by the technological progress driven by innovation. The latter enriches the productive matrix of the economy and increases its technical specialisation. This, in turn, enhances competitiveness of domestic products and export, while reducing import penetration (e.g. Cesaratto et al. 2003; Simonazzi et al. 2013). However, this neglect this complication hereafter.

supermultiplier coefficient (denominator), call it η. Clearly, η must be positive to assure an economically significant solution.

The overall marginal propensity to save out of income, s, can be defined as:

$$s = 1 - [c_w \cdot \omega \cdot (1 - \tau_w) + c_\pi \cdot (1 - \omega) \cdot (1 - \tau_\pi)] + m \tag{15}$$

Using equation (14) in equation (13), we can simplify the output supermultiplier as follows:

$$Y = Z \cdot \frac{1}{s-h} \tag{14B}$$

Equation (14B) shows that both a rise in the autonomous components of aggregate demand and an increase in the supermultiplier lead to an increase in total output. However, while the output trend growth rate is driven by the trend growth rate of the autonomous components, a change in, say, the marginal propensity to consume causes only a permanent level effect (e.g. Freitas and Serrano 2015).

Notice that the output level defined by equation (14B) does not necessarily imply a normal rate of capacity utilisation (u_n). However, u_n must be considered as a centre of gravitation for the actual rate of utilisation (u). There is a tendency of productive capacity to adjust to the effective demand conditions by means of gradual changes in the marginal propensity to invest. This is the flexible accelerator effect defined by equations (5) and (6). The dynamic counterpart of equation (14B) is rate of growth of output:

$$g_y = g_z + \frac{\Delta h}{s-h} \tag{16}$$

where g_z is the growth rate of the autonomous components of aggregate demand.

The law of movement of the utilisation rate of plants is given by:

$$u = u_{-1} + u \cdot (g_y - g_k) \tag{17}$$

Using equations (8) and (16) into equation 17, and imposing $\dot{h} = \dot{u} = 0$, we obtain:

$$g_y = g_k = g_z \tag{18}$$

Equation (18) shows that the equilibrium position of the model is characterized by the convergence of the actual growth rate and the rate of capital accumulation to the growth rate of autonomous demand components.[12] In the equilibrium position, the rate of capacity utilisation is at its normal level ($u = u_n$). Similarly, the investment share converges to its equilibrium value:

[12] See Freitas and Serrano (2015) for a discussion of the conditions that ensure the dynamic stability of the model.

$$h^* = (g_z + \delta_f) \cdot \frac{v}{u_n} \quad (19)$$

Finally, output converges towards its fully-adjusted level (Freitas and Serrano 2015):

$$Y^* = \frac{1}{s-(g_z+\delta_f)\cdot\frac{v}{u_n}} \cdot Z \quad (20)$$

This is the steady-state solution for total output level in our extended supermultiplier model.

3.2 Step two: deriving accounting identities and amending behavioural equations

The super-multiplier mechanism developed in previous sections can be now 'implanted' in a complete stock-flow consistent macroeconomic dynamic model (e.g. Brochier and Macedo e Silva, 2018). Table 1 and Table 2 display the sectoral balance-sheets and the transactions-flow matrix used to define the macroeconomic identities which assure the accounting coherence of the model. Six sectors are explicitly considered:

i. working-class households (i.e. the recipients of labour incomes and a share of interest payments on bank deposits);

ii. ii. capitalist households or rentiers (i.e. the recipients of the remaining interest payments on bank deposits, entrepreneurial profits and other financial incomes);

iii. production firms (or non-financial corporations) producing a homogenous good that can be used for both consumption and investment purposes;

iv. the financial sector (including commercial banks, financial intermediaries and the central bank);

v. the government sector (including both local and central government);

vi. the foreign sector (or rest of the world).

For the sake of simplicity, both production firms and banks (along with other financial intermediaries) are assumed to distribute their profits to rentiers, net of amortization funds or retained profits. Behavioural (or stochastic) equations defining spending decisions mirror those presented above, unless otherwise stated. Households' consumption is now explicitly modelled as a function of expected (real) income and net wealth:

$$C_j = c_j \cdot E(YD_j) \cdot \frac{p}{E(p)} + c_{aj} \cdot NW_{j,-1} \cdot \frac{p}{p_{-1}}, \qquad \text{with } j = w, \pi \quad (21)$$

Net wealth (NW_j) includes capital gains (or losses) and is crucial in determining households' creditworthiness. It is influenced by the structure of interest rates. This allows capturing the impact of borrowing costs on household consumption plans. Consumption is also affected by the social status of households: wage-earners are assumed to be characterised by a higher propensity to consume out of income than capitalists or rentiers. In addition, capitalists' disposable income is augmented to account for price revaluation of equity & shares holdings. Portfolio decisions of capitalists have been modelled in line with Tobinesque principles.[13] Net export has been considered using a constant growth rate for export, while defining import as a linear function of output.[14] A standard equilibrium condition has been also added to clear the stock market through price adjustments. In principle, a price mechanism could be used to clear the government bond market too. We have assumed that the Central Bank is willing to act as a lender of last resort to the government sector instead. In other words, the Central Bank buys the (residual) amount of government bonds which are left unsubscribed by private investors at a given price.[15]

Like households' consumption decisions, conventional investment plans can be affected by firms' expectations (about the output level). An adaptive behaviour is assumed in our model.[16] Accordingly, the three-equation subsystem (5)-(6)-(17) is developed to incorporate expectations, stocks and two different investment types. We obtain:

$$K_c = K_{c,-1} + I_c - DA_c \tag{22}$$
$$I_f = h \cdot E(Y) \tag{23}$$
$$h = h_{-1} + h \cdot \phi \cdot (u_{-1} - u_n) + h_0 \tag{24}$$
$$I_c = I_f - I_{gr} \tag{25}$$
$$u = u_{-1} + u_{-1} \cdot (g_y - g_k) \tag{26}$$
$$DA_c = \delta_c \cdot K_{c,-1} \tag{27}$$
$$K_f = K_c + K_{gr} \tag{28}$$

Equation (22) defines conventional fixed capital as past capital stock plus new investment minus depreciation allowances. These are simply defined as a percentage, δ_c, of conventional capital stock – equation (27). Equations (23) and (24) have been already discussed. They hold that investment is a share of total expected output. Conventional investment is the portion of total investment which is not devoted to green activities – equation (25). Equation (26) is nothing but a discrete time specification of equation (17). Finally, equations (28) defines total capital stock by summing up conventional capital and green capital. The higher the latter the lower the former, as firms first define total investment (as a share of output) and then choose its composition. Green variables are presented in the next section.

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[13] We refer again to Godley and Lavoie (2016). See also Table 4.

[14] Notice that we assume a balanced trade balance in our experiments, unless otherwise stated. The rationale is to focus on the behavior of domestic variables when no 'external' constraints show up.

[15] We have assumed a balanced budget in the baseline scenario. The starting value of the stock of debt is positive instead. Consequently, no *new* government bonds are issued, and no *new* reserves are created before the shocks take place.

[16] In formal terms: $E(x) = x_{-1} + \psi \cdot [E(x_{-1}) - x_{-1}]$, where x is the unknown variable (price, income, etc.) and ψ is a parameter defining how much agents adjust their current expectations based on previous errors. However, we assume that $\psi = 0$ in the simulations presented in section 4, so that: $E(x) = x_{-1}$.

3.3 Step three: modelling green spending and the ecosystem

The model developed in previous section is akin to most SFC models. As such, it is demand-led both in the short- and in the long-run. It is implicitly assumed that labour force is plentiful and does not represent a binding constraint for firms' production plans. This allows us to focus on the effect of a different type of constraint: the availability of material and energy reserves or 'natural capital' and the progressive depletion of it due to production activities. On the supply side, a Leontief production function is used to determine potential output. In other words, in line with Keynesian and Sraffian traditions, we reject the standard (neoclassical) hypothesis of smooth substitutability between inputs. As a result, no adjustment in production techniques through changes in relative prices is allowed. This modelling choice rules out the possibility of counter material and energy reserves' depletion through an increase in their market prices. Socially and ecologically suboptimal results are possible and persistent in our model. The role of the State and of the innovation cascade triggered by government MOIS is also considered.

More precisely, the link between government spending, innovation and private 'green investment' (meaning, investment that enables reducing the impact of economic growth on the depletion rate of material and energy reserves) is embedded in the following subset of equations:

$$G_{gr} = \alpha \cdot G_{mois} \tag{29}$$
$$I_{gr} = \gamma_{gr} \cdot G_{gr,-1} + DA_{gr} \tag{30}$$
$$K_{gr} = K_{gr,-1} + I_{gr} - DA_{gr} \tag{31}$$
$$DA_{gr} = \delta_{gr} \cdot K_{gr,-1} \tag{32}$$
$$Z_{gr} = I_{gr} + G_{gr} \tag{33}$$

Equation (29) defines government green innovation-oriented spending as a percentage, α, of MOIS. This type of expenditure helps reduce the impact of production activities on the ecosystem. It generates spin-offs through which green technologies are developed and diffused to the private sector. This effect is captured by equation (30), where γ_{gr} is a positive parameter.[17] Unlike other types of private innovation, green investment implies capital accumulation. Green capital must be rather regarded as a substitute than a complement of conventional capital. Equation (31) shows that it increases as green investment (net of depreciation) increases. Depreciation is simply calculated as a percentage, δ_{gr}, of capital stock, as shown by equation (32). Finally, equation (33) defines total green expenditure as the summation of private green investment and government green spending.[18]

[17] Private green investment at time t_n is likely to depend on the cumulative (not current) value of government green MOIS. In formal terms: $I_{gr} = \gamma_{gr} \cdot G_{gr,-1}^{\Sigma} + DA_{gr}$, with $G_{gr}^{\Sigma} = \sum_{t=0}^{t_n} G_{gr,t}$. However, we neglect this complication hereafter.

[18] See Appendix A for non-green innovative spending entries.

Table 5 shows the physical stock-flow matrix and the physical flow matrix, respectively. The former allows defining the change in the stocks of things that directly impact on human activities, namely, material and energy reserves and the socio-economic stock in our model.[19] The latter allows accounting for the First and the Second Law of Thermodynamics. Table 5's matrices provide the accounting structure the ecosystem is built upon.[20] More precisely, two subsets of equations can be identified. The first subsystem is related to material resources and reserves:

$$y_{mat} = \mu \cdot y_s \tag{34}$$
$$mat = y_{mat} - rec \tag{35}$$
$$rec = \rho_{rec} \cdot des \tag{36}$$
$$des = \mu \cdot \frac{DA_f}{p} \tag{37}$$
$$k_{se} = k_{se,-1} + y_{mat} - des \tag{38}$$
$$wa = mat - \Delta k_{se} \tag{39}$$
$$k_m = k_{m,-1} + conv_m - mat \tag{40}$$
$$conv_m = \max(\sigma_m \cdot res_{m,-1}, mat_{-1}) \tag{41}$$
$$res_m = res_{m,-1} - conv_m \tag{42}$$
$$p_m = p_m^0 + p_m^1 \cdot \left(mat_{-1} - \sigma_{m,-1} \cdot res_{m,-1}\right) \tag{43}$$
$$\sigma_m = \sigma_m^0 + \sigma_m^1 \cdot E(p_m) \tag{44}$$

Equation (34) defines the amount of matter embodied in total real supply through a material intensity coefficient, μ.[21] Equation (35) shows that matter extracted from the ground equals matter embodied in output net of the recycled socio-economic stock. Equation (36) defines recycled matter as a percentage of destructed or discarded socio-economic stock. As equation (37) shows, it is assumed that destructed matter equals real capital depreciation (of both conventional and green capital) times the material intensity coefficient. Equation (38) defines the change in socio-economic stock as matter embodied in newly-produced (capital) goods minus destroyed goods. Equation (39) determines waste as a residual, that is, extracted matter net of the change in socio-economic stock (see Table 5-b). Equation (40) defines the change in material reserves, which grow as more and more resources are converted into reserves and reduce as extractions proceed (see Table 5-a). Conversion of material resources into reserves is defined by equation (41). Conversion takes place at a normal (market price-driven) rate, σ_m, unless firms push for an even higher conversion based on previous period extractions. Equation (42) shows that material resources stock reduces as conversion into reserves proceeds. Equation (43) defines the unit price of extracted matter as a function of the gap between current demand (as determined by production needs) and normal supply

[19] Since there are no durable consumption goods in our model, the socio-economic stock is only made up of capital goods.
[20] Table 5's matrices are simplified versions of those developed and discussed by Dafermos et al. (2017, 2018). Consequently, we omit a detailed presentation here.
[21] We define y_s as the real supply of products, namely, $y_s = Y_d/p$.

(as determined by the normal rate of conversion, σ_m). Finally, equation (44) shows that the pace of extraction depends on the market price of matter: the higher the latter the higher the normal rate of extraction. So, the overall cumulative causation chain or sequence is: higher (lower) extraction in t → higher (lower) price → higher (lower) extraction rate → higher (lower) extraction in $t+1$ → etc.

We can now move to the second subsystem, which defines energy resources and reserves:

$$en = \varepsilon \cdot y_s \tag{45}$$
$$ed = en \tag{46}$$
$$k_{en} = k_{en,-1} + conv_{en} - en \tag{47}$$
$$conv_{en} = \max(\sigma_{en,-1} \cdot res_{en,-1}, en_{-1}) \tag{48}$$
$$res_{en} = res_{en,-1} - conv_{en} \tag{49}$$
$$p_{en} = p_{en}^0 + p_{en}^1 \cdot \left(en_{-1} - \sigma_{en,-1} \cdot res_{en,-1}\right) \tag{50}$$
$$\sigma_{en} = \sigma_{en}^0 + \sigma_{en}^1 \cdot E(p_{en}) \tag{51}$$

Equation (45) defines the amount of energy required for production purposes. For the sake of simplicity, we do not distinguish renewable from non-renewable energy sources. Equation (46) shows that dissipated energy equals the energy used in the production process. Equation (47) shows that the stock of energy reserves increases as conversion proceeds and decreases as energy reserves are used. Equation (48) defines newly-created energy reserves from energy resources. Equation (49) shows that the stock of energy resources declines as conversion proceeds. Finally, equations (50) and (51) determine the unit price of energy and the endogenous conversion rate, respectively. Unlike the unit price of output, which is determined by demand and reproduction conditions, natural resources prices are here treated as pure indices of scarcity.

3.4 Step four: modelling feedback mechanisms and production

On the one hand, current rates of depletion of material and energy reserves depend on the pace of extraction/use of matter/energy:

$$\rho_m = \frac{mat}{k_{m,-1}} \tag{52}$$
$$\rho_{en} = \frac{en}{k_{en,-1}} \tag{53}$$

On the other hand, natural reserves' growth rates depend on the rates of conversion of resources into reserves:

$$g_m = \frac{conv_m}{k_{m,-1}} \tag{54}$$
$$g_{en} = \frac{conv_{en}}{k_{en,-1}} \tag{55}$$

Since energy and matter are treated as complementary (not substitute) inputs of the production process, the actual speed of depletion of material and energy reserves is defined by the maximum depletion rate:

$$g_{ac} = \max(\rho_m, \rho_{en}) \tag{56}$$

The rate above must be compared to the 'sustainable' rate of depletion of material and energy reserves. We identify it with the minimum rate of growth of newly-created reserves:[22]

$$g_{su} = \min(g_m, g_{en}) \tag{57}$$

Given the total amount of natural resources, the higher g_{ac} compared to g_{su}, the lower the amount of matter and energy reserves available in future periods.

While government spending (and/or direct intervention) can help reduce depletion of material and energy reserves by inducing a change in the structure of output, the opposite may also occur. It is well known that the depletion of material and energy reserves can affect both the level and composition of output. Three main channels can be identified within our model:

i. the depletion of material and energy reserves can destroy existing capital (namely, accelerate conventional capital depreciation, δ_c) through the increase and intensification of natural catastrophes;

ii. the same phenomena can slow down the process of accumulation, as they can (temporarily) reduce the desired investment share, h;

iii. the depletion of material and energy reserves can also impact on the propensity to consume of households through a variety of sub-channels (for instance, by increasing ecological awareness and hence changing consumption habits of the population in an 'anti-consumerist' way and/or by increasing uncertainty, thus triggering hoarding behaviours).

These channels are embedded in the equations below:

$$\delta_c = \delta_0 + \delta_1 \cdot (g_{ac,-1} - g_{su,-1}) \tag{58}$$
$$h_0 = h_{00} + h_{01} \cdot (g_{ac,-1} - g_{su,-1}) \tag{59}$$
$$c_w = c_{w0} + c_{w1} \cdot (g_{ac,-1} - g_{su,-1}) \tag{60}$$

where $\delta_0, \delta_1, h_{00}, h_{01}, c_{w0}$ and c_{w1} are all positive parameters. The last two parameters refer to workers' propensity of consumption out of their disposable income. For the sake of

[22] Alternatively, it can be identified with the minimum growth rate of reserves based on the 'normal' rate of conversion of resources: $g_{su} = \max[(\sigma_{m,-1} \cdot res_{m,-1})/k_{m,-1}), (\sigma_{en,-1} \cdot res_{en,-1})/k_{en,-1})]$.

simplicity, we assume away the impact of resources' depletion on workers' propensity to consume out of net wealth and capitalists' consumption plans.

As mentioned, potential output is determined by a Leontief function, whose inputs are matter and energy reserves (stock-flow resources) and total real capital (fund-serve resources). The latter is obtained by summing up the deflated values of conventional capital and green capital stocks ($k_f = K_f/p$). Unlike natural reserves, green capital is not a complement but a substitute of conventional capital. Accordingly, the Leontief function is defined by the four-equation subsystem below:

$$y_f^* = a_f \cdot k_{f,-1} \tag{61}$$

$$y_m^* = \frac{k_{m,-1} + rec}{\mu} \tag{62}$$

$$y_{en}^* = \frac{k_{en,-1}}{\varepsilon} \tag{63}$$

$$y^* = \min(y_f^*, y_m^*, y_{en}^*) \tag{64}$$

Equation (61) defines the capital-determined potential output as a function of the real product per unit of (either conventional or green) capital, a_f. Equation (62) defines matter-determined potential output as a function of the material intensity coefficient, μ, and recycling. Equation (63) defines energy-determined potential output as a simple function of the energy intensity coefficient, ε. The overall production potential, y^*, is determined by the shortest side – equation (64).

Although conventional capital and green capital are substitutes, material- and energy-intensity coefficients depend on the technique of production chosen by the firms.[23] More precisely, we assume that the higher the amount of green capital relative to traditional capital, the lower the intensity coefficients:

$$\mu = \mu_{gr} \cdot \frac{K_{gr}}{K_f} + \mu_c \cdot \frac{K_c}{K_f} \tag{65}$$

$$\varepsilon = \varepsilon_{gr} \cdot \frac{K_{gr}}{K_f} + \varepsilon_c \cdot \frac{K_c}{K_f} \tag{66}$$

where $\mu_{gr} < \mu_c$ and $\varepsilon_{gr} < \varepsilon_c$ are the material and energy intensity coefficients implied by purely green and purely traditional capital inputs, respectively. As a result, the higher the green-capital intensity of the technique of production, the lower the impact on the depletion rate of natural resources.

Notice that production is still demand-led. Potential output only allows us to account for possible effects of demand pressure and material and energy reserves' shortages on the general price level:

[23] Output composition also matters, but we keep assuming that a homogenous good is produced for consumption purposes.

$$p = p_0 + p_1 \cdot [y_{-1} - y^*_{-1}] \tag{67}$$

where p_0 is an autonomous component (accounting for many factors, including labour costs and monopoly power of firms) and p_1 is the sensitivity of price level to output gap. Notice also that an increase in the price level can affect private sector's spending plans, as decisions are made based on expected real values.

Finally, we have assumed that labour force availability never constrains production, because firms can count on a plentiful 'reserve army of labour'. If we name a_l the real product per unit of labour, then we can derive firms' demand for labour inputs, l_d. Workers' supply, l_s, always matches firms' demand:

$$l_d = \frac{Y}{p \cdot a_l} \tag{68}$$

$$l_s = l_d \tag{69}$$

This does not entail full employment.[24] On the contrary, it implies a permanent excess of labour supply over demand, namely, an unemployment equilibrium. As a result, the wage rate is also dependent on firms' price setting decisions:

$$w = p \cdot \frac{a_l}{1+\mu_p} \tag{70}$$

where $\mu_p = 1/\omega - 1$ is the costing margin applied to unit labour costs. Equations (68)-(69)-(70) are just definitory and play no role in our model, whose dynamics is only driven by the interaction between spending decisions of firms, households and the government, financial conditions, and the ecosystem. In other words, we rule out workers' reaction to adverse labour market conditions to focus on ecological feedback mechanisms instead.[25]

3.5 Model calibration

The full set of identities, equilibrium conditions and stochastic equations our model is made up of is reported in the Appendix A. The model belongs to the class of SFC macroeconomic models. The latter resemble traditional structural macroeconometric models, but they are developed based on a set of principles aiming at assuring accounting consistency and financial relevance (we refer again to section 2). As such, parameter values and initial values for stocks and other lagged endogenous variables can be estimated using available time series. This can be done through simple equation by equation OLS or estimating the whole system of equations. Cointegration techniques (e.g. vector error correction models) can be also employed to identify the long-run stochastic trend of variables. Alternatively, SFC models can

[24] Notice that l_d can be taken to mean either the number of employed workers or the demanded quantity of labour hours or days, depending of the unit of measure used to define a_l. We ignore this complication hereafter.
[25] The interaction between class struggle and ecological feedback is an interesting topic to be developed. In principle, our model allows accounting for it. However, we focus on the ecological side only in this paper.

be calibrated by borrowing coefficient values from available literature, using realistic or reasonable values, and/or fine-tuning them to generate a specific baseline scenario. Since our purpose is to address general theoretical questions by developing a relatively new analytical tool, we opted for the second method. Parameters and initial values of lagged variables are shown by Table 3. Table 4 shows parameters of portfolio equations. The model is run for a very long period: from the first quarter of the twentieth century to the fourth quarter of 2040.[26] This allows achieving a stable baseline to be compared with alternative scenarios. Shocks are all imposed in the first quarter of 2018.

Figure A1 in Appendix A shows the baseline scenario assumed for GDP components, production conditions, natural resources and reserves, unit prices and firms' initial financial condition, respectively. Quadrant (*a*) shows that all GDP components are growing except for net export, which is assumed to be null in the baseline. Almost half GDP is made up of government spending, whereas private expenditures are dominated by capitalists' and workers' consumption – quadrant (*b*). Quadrant (*c*) shows that reserves are a binding constraint for potential output, even though current output is below its potential level. Both matter and energy reserves are declining a constant rate. Quadrant (*d*) shows that the decline in natural resources is even sharper than the decline in reserves. Accordingly, matter and energy price tend to increase over time, while the general price level is stagnating and the price of equity and shares faces a decline – quadrant (*e*). Firms are marked by a stable leverage ratio and their market value (expressed by the Tobin'q) is slightly increasing – see quadrant (*f*). We believe that this is a realistic scenario (for an early-industrialised country) to be used as a baseline for our experiments.[27] Notice that our findings are purely qualitative. The same goes for the chosen data frequency. No specific meaning should be attributed to absolute values of series, let alone to their adjustment time. Quantitative results can be only obtained after an accurate estimation of model's coefficients. However, this would require considering country-specific institutional features, which is at odds with the general theoretical purpose of our work.

4. Simulations and main findings

Model's reactions to shocks have been tested through numerical simulations. First, we check model's reaction following narrowly-defined economic shocks to government spending and taxation. Overall, our simulations track the dynamics described by the innovation-augmented supermultiplier model. Unsurprisingly, the key role of mission-oriented innovation spending (MOIS) is confirmed. We then introduce ecological constraints by turning on feedback effects linked with the progressive exhaustion of material and energy reserves. Government intervention is shown to be still effective in supporting innovation and growth, while reducing the negative impact of growth on the ecosystem. However, ecological feedback effects are

[26] All the simulations have been performed using *EViews*. Both model's program file and sensitivity tests and are available upon request.

[27] We also assume that the government is balancing its budget and is characterised by a stock of debt $\cong 38\%$.

found to affect government spending effectiveness. The main interactions between model's sectors and the ecosystem are displayed by Figure 1.

4.1 Innovation and macroeconomic dynamics

We test four different temporary fiscal shocks. Shocks are imposed in the first quarter of 2018. The size of each shock is 0.1% of current output. The policy scenarios we have considered are:

i. an increase in the absolute level of MOIS undertaken by the government;

ii. an increase in the absolute level of routine government spending;

iii. a cut in the absolute level of taxes on workers' income;

iv. a cut in the absolute level of taxes on rentiers' income.

The four scenarios are displayed by Figure 2 and Figure 3. Each series is expressed as relative to the baseline solution. Policies considered have all positive impacts on national output (and GDP). The latter is displayed in nominal terms, but results do not change when the real value of output is looked at. As mentioned, government MOIS is the policy entailing the highest multiplying effect on output (with a peak multiplier higher than 4, as shown by Figure 2-a), followed by routine spending (with a peak multiplier higher than 2, Figure 2-b). Tax reduction has also a positive impact on output and its components, mainly through an increase in consumption levels. However, the effect is lower than the impact of an increase in government spending (the peak multiplier is now around 2), due to household saving 'leakages'. In addition, tax reduction is more effective when it benefits wage-earners because the latter are assumed to have a lower propensity to save out income compared with the rentiers (Figure 3-a and Figure 3-b). Figure 4 summarises our findings with respect to output reaction to shocks (Figure 4-a). It is also shown that one of the channels through which government spending affects output in the short run is the change in the utilisation rate of plants, leading firms to adapt their investment plans to restore their desired spare capacity (Figure 4-b).

The impact of a loose fiscal policy on government budget is usually one of the main concerns for the policy makers. Figure 5-a shows that government MOIS is the "best" option for public finances. Government debt stock to GDP can even be falling following an increase in government spending, if its starting value and/or the supermultiplier are high enough. Figure 5-b compares a medium-low debt situation (≈ 38% of GDP in 2018) with a medium-high debt (≈ 83%) and a very low debt (≈ 8%) scenarios. Government MOIS boosts output, thereby smoothing the impact of additional spending on the debt to GDP ratio. As one might expect, routine spending is the second-best option for public finances, while tax reductions have a stronger impact on debt ratios (especially tax cuts on rentiers' income). We omit a detailed demonstration of these corollaries. The point is that government spending, particularly MOIS, triggers an innovation cascade in the private sector, thereby increasing steadily the growth rate of output. Other expansionary policies have also a positive impact on output, but their effects should be expected to be less dramatic (Figure 6-a). In addition,

Figure 6-b shows that, while the change in firms' innovation pace can be short-lived (purple dashed line), the impact on other output components turns out to be long-lasting.[28]

4.2 Green expenditure, ecological sustainability and feedbacks

While several studies have been published about the impact of economic policies on ecological sustainability, they usually deal with monetary policies. By contrast, we focus on fiscal (and industrial) policy effects.[29] For the sake of simplicity, we assume that green investment undertaken by private firms entails fixed capital accumulation, while non-green innovative spending (e.g. new technology programmes) does not. In addition, growth is assumed to be unsustainable in the baseline scenario.[30] The increase in MOIS leads to both a direct and an indirect effect on green expenditure: one the one hand, a share of MOIS is made up of government green expenditure (direct impact); on the other hand, it increases private green spending through the increase in the overall level of private innovative spending (indirect effect). This affects the actual depletion rates of material and energy reserves (or natural capital). The increase in green expenditures allows reducing the depletion rate of material and energy reserves per unit of output compared with both the baseline and a conventional spending scenario – Figure 7-a. However, this may not suffice to offset the higher depletion of natural resources due to output growth – Figure 7-b.

In section 3.4, we identified three main channels through which depletion of material and energy reserves can affect both level and composition of output: i. by accelerating capital depreciation; ii. by reducing the desired investment share; iii. by affecting the propensity to consume of households, particularly of working-class households. The impact of ecological feedbacks on nominal output and its components is displayed by figures 8 and 9. The effects triggered by (i), (ii) and (iii) are shown separately by Figure 8-a, 8-b and 9-a, respectively. Their combined impact is shown by figure 9-b. Overall, the impact on output is negative, even though consumption and investment can react differently to different shocks. Figure 10-a shows that an increase in government MOIS still entails a positive impact on output. However, ecological feedbacks can reduce its effectiveness. The impact on total depletion rate of material and energy reserves is shown by Figure 10b.[31]

Financial variables are also affected. Figure 11 and 12 show that ecological feedbacks affect dividend yields, the market value of shares, firms Tobin's q and their leverage ratio, respectively. Dividend yields always fall compared to their baseline values – Figure 11-a. An identical dynamics is recorded for the market value of equity & shares – Figure 11-b. In addition, the positive impact of MOIS policies is (partially) affected by ecological feedbacks.

[28] The adjustment of growth rates following exogenous shocks to other autonomous growth rates has also been tested. Model's reaction to a positive shock to export is shown by Figure B1 in Appendix B.

[29] However, since the model includes the banking sector and several financial variables, it can be also used to test different monetary policy stances. In fact, if one assumes that the desired pace of capital accumulation (meaning the desired investment share, h) is affected by the interest rate on loans, monetary authorities can influence investment and output growth rates by manipulating the policy rate (see Fontana and Sawyer 2016).

[30] This allows shedding light on the interaction between economic growth and depletion of available resources.

[31] Results for the output price level and potential output are shown by Figure C1 and Figure C2 in Appendix C.

By contrast, both the Tobin's q – Figure 12-a – and firms' leverage ratio – Figure 12-b – increase compared with their baseline values when ecological effects are considered. The reason is that capital accumulation slows down compared with both the market value of shares and firms' demand for new loans. The latter, in turn, are less affected than the market value of shares (in the short run at least). As a result, ecological feedbacks reduce the financial soundness of the firms' sector overall. On the other hand, both matter and energy prices reduce relative to their baseline values when economic growth is affected – see Figure 13. MOIS policies are still effective at supporting economic growth and tackling financial fragility. This may or may not entail a higher depletion rate of natural resources, depending on the size of efficiency gains generated by green spending.

5. Final remarks

We combined four different strands of economic thought (the Sraffian supermultiplier mechanism, the Schumpeterian innovation approach, the stock-flow consistent modelling approach and the post-ecological macroeconomics) to examine the interaction between government spending, innovation, economic growth and the ecosystem. We found that, in principle, government can be successful in supporting innovation and growth while limiting material and energy reserves' depletion. However, the over-consumption of material and energy reserves can affect government policy effectiveness. The main limitation of our work is that model coefficients are not estimated but borrowed from literature and/or fine-tuned in such a way to generate a realistic baseline scenario. In this sense, the model can be said to simply return us what we have assumed by defining its behavioural equations. In addition, the role of central bank is just sketched and the same goes for non-bank-financial institutions. Class struggle between workers and capitalists, and between the latter and narrowly-defined rentiers, is also ruled out. Finally, the ecosystem is highly stylised. In fact, it is reduced to a few feedback equations, with no accurate accounting of energy and matter flows and funds. Despite these limitations, the model allows shedding light on the role of the State in actively promoting green innovation, thus driving a change in the overall economic structure. It also provides a (relatively) simple mechanism to account for the tendency of early-industrialised countries' growth rates to slow down, while being incapable to address the progressive erosion of natural capital. In this sense, limitations above can be regarded as insights about possible future developments of our theoretical synthesis.

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Tables and figures

Table 1. Nominal balance sheets

	Households		Production firms	Banks & CB	Government	Foreign	Σ
	Workers	Capitalists					
Money	$+H_w$	$+H_\pi$		$-H_s$			0
Deposits	$+D_w$	$+D_\pi$		$-D_s$			0
Loans			$-L_d$	$+L_s$		$-L_{row}$	0
Conventional capital			$+K_c$				$+K_c$
Green capital			$+K_{gr}$				$+K_{gr}$
Shares		$+e_d \cdot p_e$	$-e_s \cdot p_e$				0
Gov. bonds		$+B_d$		$+B_{cb}$	$-B_s$		0
Balance (net worth)	$-NW_w$	$-NW_\pi$	$+NW_f$	0	$+GDEB$	$+ROWDEB$	$-K_f$
Σ	0	0	0	0	0	0	0

Notes: A '+' before a magnitude denotes an asset, whereas '–' denotes a liability (except for Balance's entries, where signs are reversed). The banking sector includes the Central Bank (CB) in addition to commercial banks and non-bank financial institutions.

Table 5. Simplified physical stock-flow matrix (*a*) and related physical flow matrix (*b*)

(*a*)

	Material reserves	Energy reserves	Socio-economic stock
Initial stock	$k_{m,-1}$	$k_{en,-1}$	$k_{se,-1}$
Resources converted into reserves	$+conv_m$	$+conv_{en}$	
Production of material goods			$+y_{mat}$
Extraction/use of matter/energy	$-mat$	$-en$	
Destruction of s.e.s.			$-des$

(*b*)

	Material balance	Energy balance
Inputs		
Extracted matter	$+mat$	
Non-renewable energy		$+en$
Outputs		
Waste and emissions	$-wa$	

Final stock	k_m	k_e	k_{se}

Dissipated energy		$-ed$
Change in s.e.s.	$-\Delta k_{se}$	
Σ	0	0

Notes: Matter is measured in Gt while energy is measure in EJ. In sub-table (*a*), a '+' sign denotes additions to the opening stock, whereas '–' denotes reductions; in sub-table (*b*), a '+' sign denotes inputs in the socio-economic system, whereas '–' denotes outputs.

Table 2. Transactions-flow matrix

	Workers	**Capitalists**	**Production firms**		**Banks & CB**	**Government**	**Foreign**	**Σ**
			Current	Capital				
Consumption	$-C_w$	$-C_\pi$	$+C_s$					0
Investment in conventional capital			$+I_{c,s}$	$-I_{c,d}$				0
Innovation spending (*BE*):								
- Green investment			$+I_{gr,s}$	$-I_{gr,d}$				0
- Other			$+BE_{tech,s}$	$-BE_{tech,d}$				0
Gov. routine spending			$+G_{rout}$			$-G_{rout}$		0
Gov. innovative sp. (G_{mois}):								
- Green spending			$+G_{gr}$			$-G_{gr}$		0
- Other			$+G_{tech}$			$-G_{tech}$		0
Taxes on income	$-T_w$	$-T_\pi$				$+T$		0
Net export			$+NX$				$-NX$	0
Wage bill	$+\omega \cdot Y$		$-\omega \cdot Y$					0
Depreciation allowances (and amortisation funds)			$-DA_c - DA_{gr}$	$+AF$				0
Interest on loans			$-r_{l,-1} \cdot L_{d,-1}$		$+r_{l,-1} \cdot L_{s,-1}$		$-r_{l,-1} \cdot L_{row,-1}$	0
Interest on deposits	$+r_{d,-1} \cdot D_{w,-1}$	$+r_{d,-1} \cdot D_{\pi,-1}$			$-r_{d,-1} \cdot D_{s,-1}$			0
Return on gov. bonds		$+r_{b,-1} \cdot B_{\pi,-1}$				$-r_{b,-1} \cdot B_{d,-1}$		0
Entrepreneurial profit		$+F$	$-F$					0

Change in money	$-\Delta H_{w}$	$-\Delta H_{\pi}$			$+\Delta H_{s}$			0
Change in loans				$+\Delta L_{f}$	$-\Delta L_{s}$		$+\Delta L_{row}$	0
Change in deposits	$-\Delta D_{w}$	$-\Delta D_{\pi}$			$+\Delta D_{s}$			0
Change in shares		$-\Delta e_{d} \cdot p_{e}$		$+\Delta e_{s} \cdot p_{e}$				0
Change in gov. bonds		$-\Delta B_{d}$			$-\Delta B_{cb}$	$+\Delta B_{s}$		0
Σ	0	0	0	0	0	0	0	0
Memo: capital gains		$-\Delta p_{e} \cdot e_{s,-1}$						

Notes: A '+' before a magnitude denotes a receipt or a source of funds, whereas '–' denotes a payment or a use of funds. No interest rate on government bonds held by CB.

Table 3. Parameter values and initial values of lagged variables

Symbol	Description	Kind	Value	Symbol	Description	Kind	Value
a_f	Real product per unit of fixed capital	X	2.50	ζ_1	Sensitivity of depletion of NR to economic growth	X	0.50
$c_{a\pi}$	Rentiers' propensity to consume out of wealth	X	0.05	ζ_2	Sensitivity of depletion of NR to green spending	X	0.50
c_{aw}	Workers' propensity to consume out of wealth	X	0.05	μ_1	Risk premium of interest rate on government bonds	X	0.00
c_{π}	Rentiers' propensity to consume out of income	X	0.65	μ_2	Risk premium of interest rate on loans	X	0.01
c_w	Workers' propensity to consume out of income	X	0.85	μ_c	Matter intensity coefficient, conventional prod.	X	0.219
p_0	Autonomous component of output price level	X	1.00	μ_{gr}	Matter intensity coefficient, green production	X	0.18
p_1	Sensitivity of price level to output gap	X	0.0001	τ_{π}	Tax rate on rentiers' income	X	0.15
p_m^0	Autonomous component of matter price	X	1.00	τ_w	Tax rate on workers' income	X	0.40
p_m^1	Sensitivity of matter price to demand gap	X	0.20	ρ_{rec}	Recycling rate	X	0.25
p_{en}^0	Autonomous component of energy price	X	1.00	σ_{en}^0	Auton. comp. of energy conversion rate	X	0.000025
p_{en}^1	Sensitivity of energy price to demand gap	X	0.20	σ_{en}^1	Sensitivity of conversion rate to energy price	X	0.00001
$r_{cb,b,d}$	Target interest rate set by the central bank	X	0.01	σ_m^0	Auton. comp. of matter conversion rate	X	0.000025
u_n	Normal utilisation rate of plants	X	0.80	σ_m^1	Sensitivity of conversion rate to matter price	X	0.00001
α	Percentage of MOIS devoted to green innovation	X	0.50	υ_{rout}	Dependent routine gov. spending (% of GDP)	X	0.45
γ_{gr}	Sensitivity of green investment to MOIS	X	2	υ_{mois}	Dependent government MOIS spending (% of GDP)	X	0.00

γ_{tech}	Sensitivity of other innovative investment to MOIS	X	2	ϕ	Sensitivity of investment share to utilis. rate gap	X	0.001
δ_c	Conventional capital depreciation rate	X	0.04	χ	New shares to real investment ratio	X	0.20
δ_{gr}	Green capital depreciation rate	X	0.00	ψ	Adaptation coefficient in price expectations	X	0.00
ε_c	Energy intensity coefficient, conventional prod.	X	0.219	ω	Narrowly-defined wage share to GDP ratio	X	0.60
ζ_0	Autonomous depletion rate of natural reserves (NR)	X	0.05				

Note: X = parameter or exogenous variable; EN = endogenous variable. Remaining coefficients and starting values of endogenous variables are all set to zero.

Table 4. Coefficients of portfolio equations of capitalists (or rentiers)

Asset type	Shares		Bonds		Cash		Deposits	
Coeff. type	Symbol	Value	Symbol	Value	Symbol	Value	Symbol	Value
Intercept	λ_{10}	0.20	λ_{20}	0.20	λ_{30}	0.20	λ_{40}	0.40
Corporate shares	λ_{11}	0.20	λ_{21}	-0.20	λ_{31}	-0.20	λ_{41}	0.20
Transaction motive	λ_{12}	-0.20	λ_{22}	-0.20	λ_{32}	0.20	λ_{42}	0.20
Government bonds	λ_{13}	-0.20	λ_{23}	0.20	λ_{33}	-0.20	λ_{43}	0.20
Bank deposits	λ_{14}	0	λ_{24}	0	λ_{34}	0.40	λ_{44}	-0.40

Note: shaded areas highlight values defined by adding-up constraints.[35]

[35] Following the Tobinesque principles, vertical constraints of portfolio equations are: $1-(\lambda_{10}+\lambda_{20}+\lambda_{40})$, $\lambda_{31}=-(\lambda_{11}+\lambda_{21}+\lambda_{41})$, $\lambda_{32}=-(\lambda_{12}+\lambda_{22}+\lambda_{42})$, $\lambda_{33}=-(\lambda_{13}+\lambda_{23}+\lambda_{43})$, $\lambda_{34}=-(\lambda_{14}+\lambda_{24}+\lambda_{44})$; horizontal constraints are: $\lambda_{14}=-(\lambda_{11}+\lambda_{13})$, $\lambda_{24}=-(\lambda_{21}+\lambda_{23})$, $\lambda_{44}=-(\lambda_{41}+\lambda_{43})$. Chosen values are purely theoretical. In addition, since expected values of wealth, income and return rates are considered, instead of their actual values, the amount of bank deposits is determined residually. In other words, λ_{4j} values (with $j=1,2,3,4$) can be slightly different from those displayed by the last column of Table 4, due to errors in capitalists' expectations (which are assumed to be fully adaptive).

Figure 1. Main interactions between financial sector (purple shade), productive sector (blue shade), government sector (yellow shade), households (orange shade), foreign sector (grey shade) and the ecosystem (green shade).

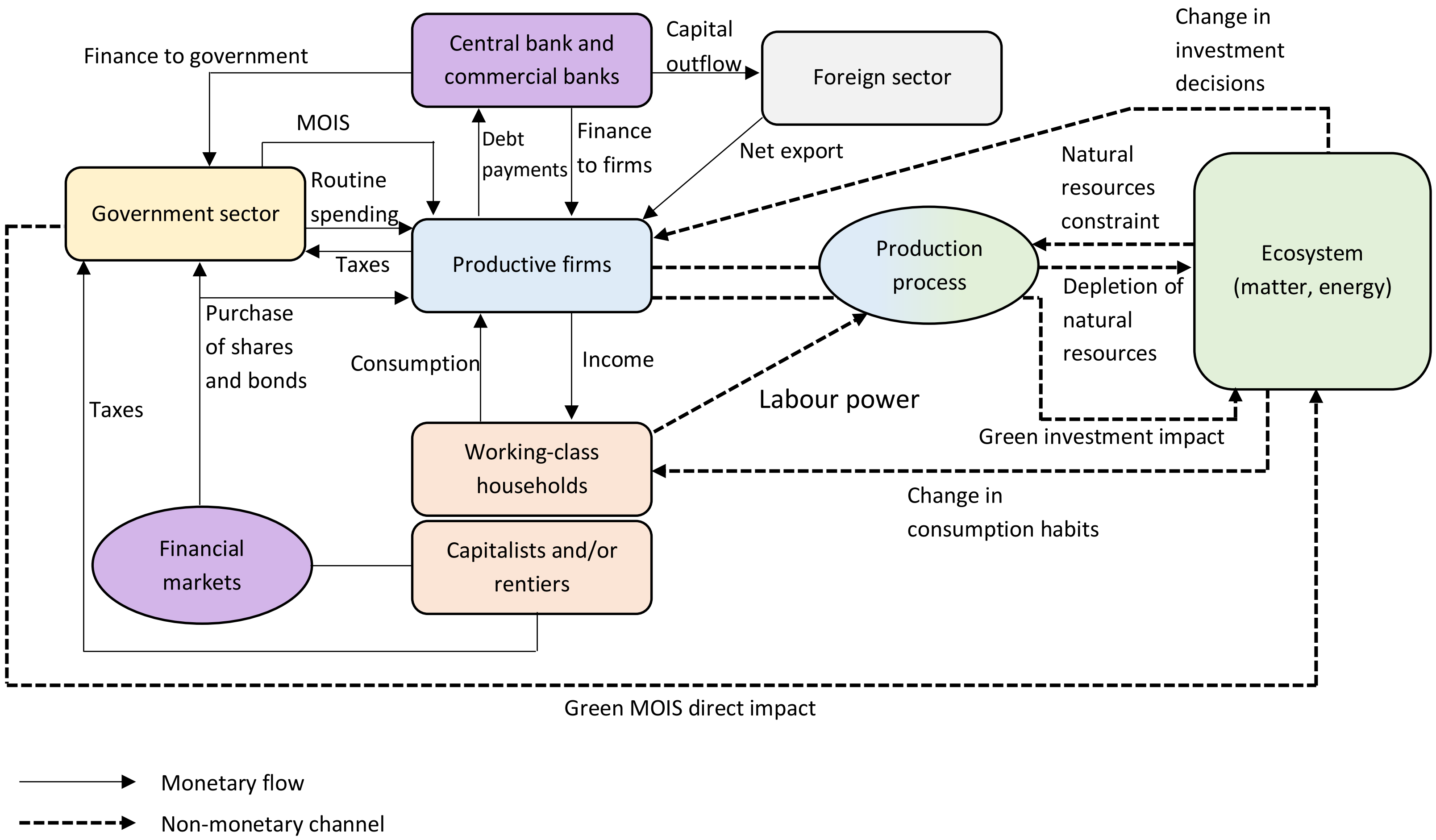


Figure 2. Reaction of output (GDP), total consumption and investment following a positive shock to innovative (a) and routine (b) government spending, respectively.

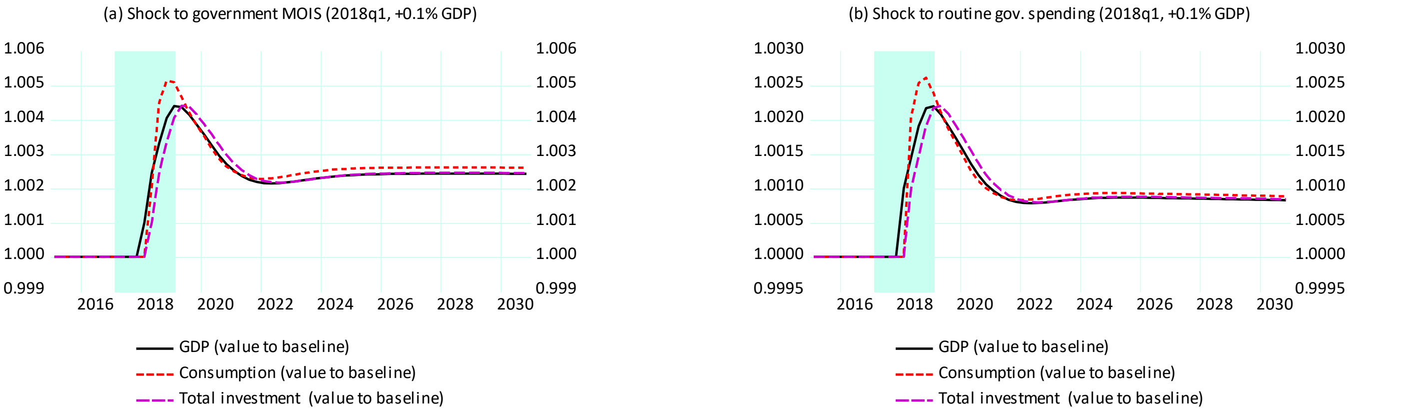


Figure 3. Reaction of output (GDP), total consumption and investment following a negative shock to taxes paid by workers (a) and capitalists (b), respectively.

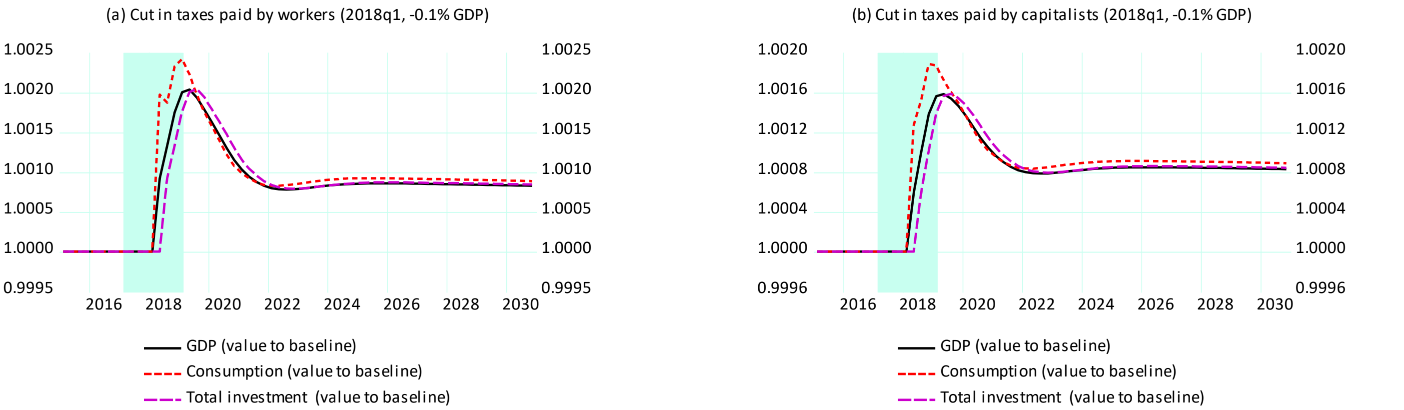


Figure 4. Reaction of output (a) and capacity utilisation (b) following different fiscal shocks.

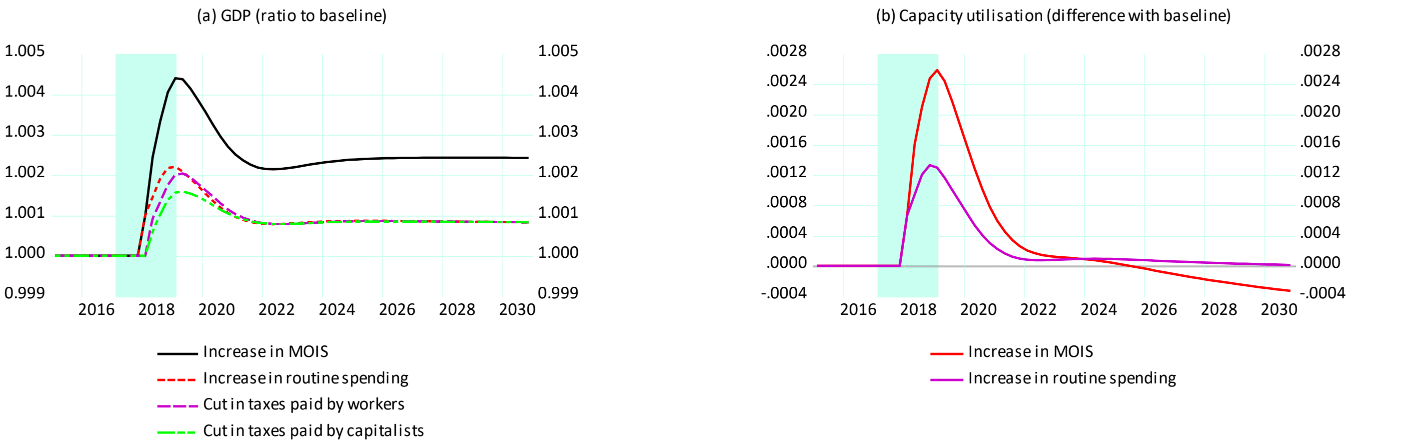


Figure 5. Reaction of government debt to GDP ratio following different fiscal shocks (a) and using different initial value of debt (b).

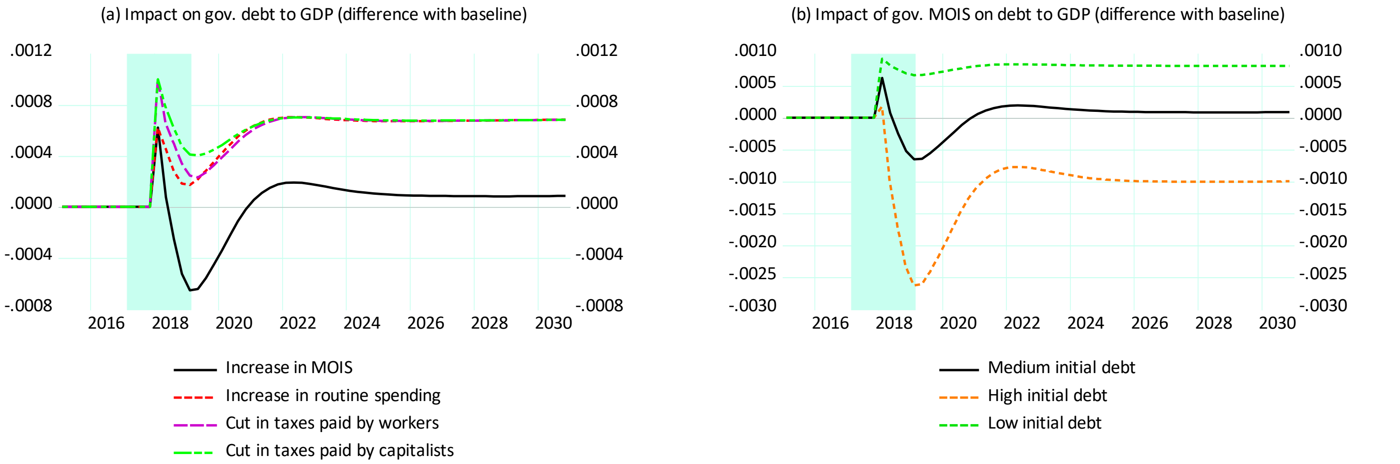


Figure 6. Reaction of output growth rate following different shocks (a) and reaction of aggregate demand components following a positive shock to government MOIS (b).

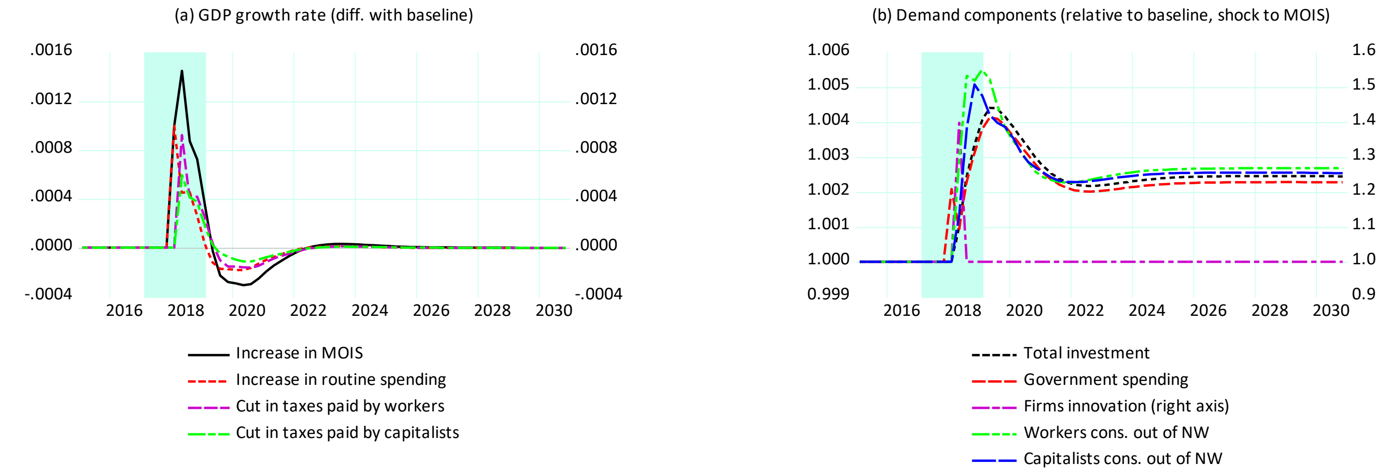


Figure 7. Impact of the increase in MOIS on natural reserves' depletion ratios.

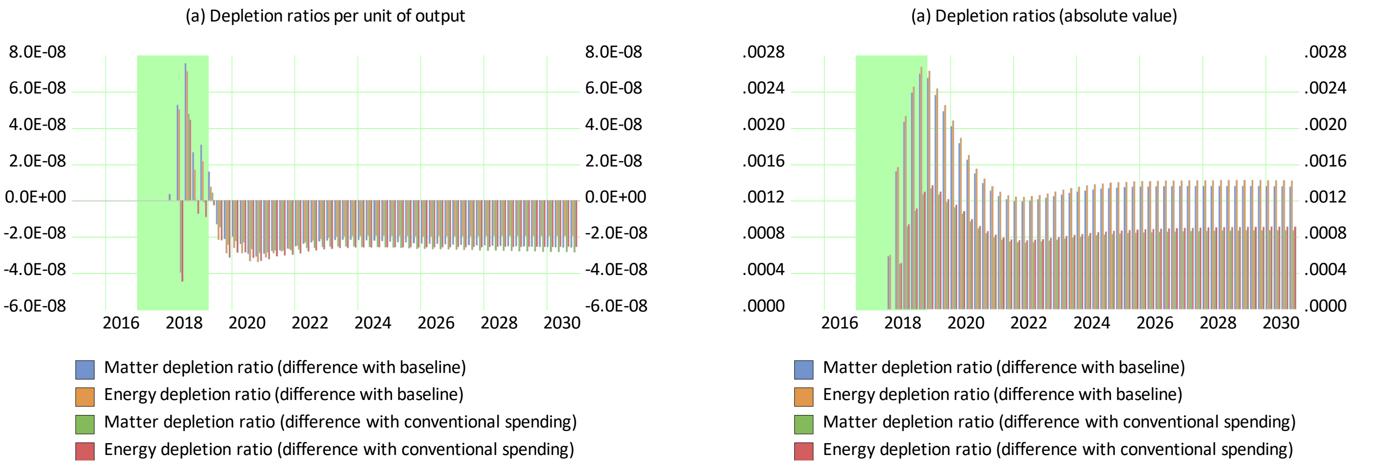


Figure 8. Ecological feedbacks: impact on GDP components.

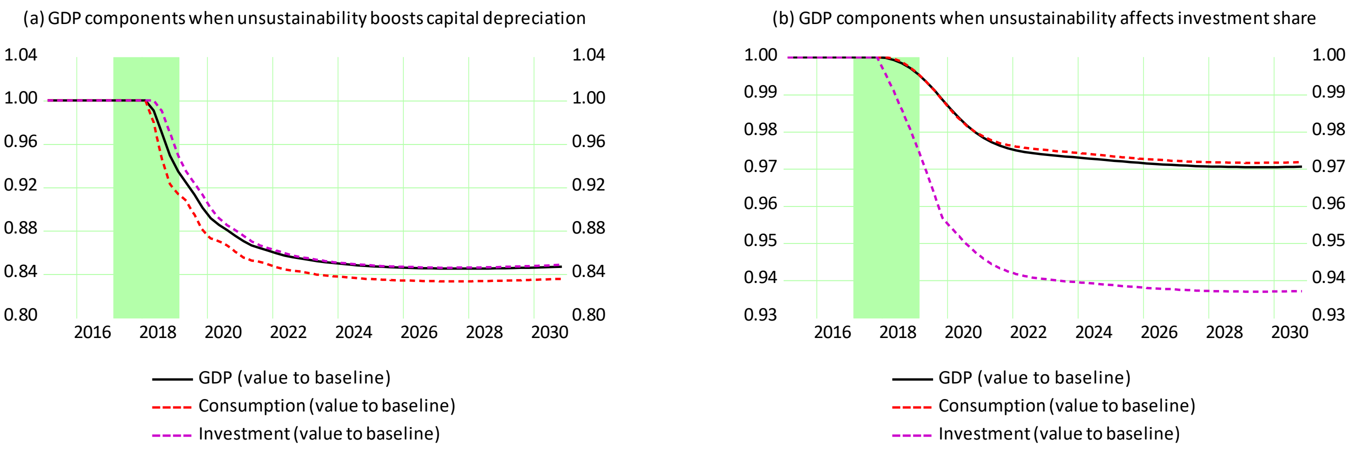


Figure 9. Ecological feedbacks: impact on GDP components (cont'd).

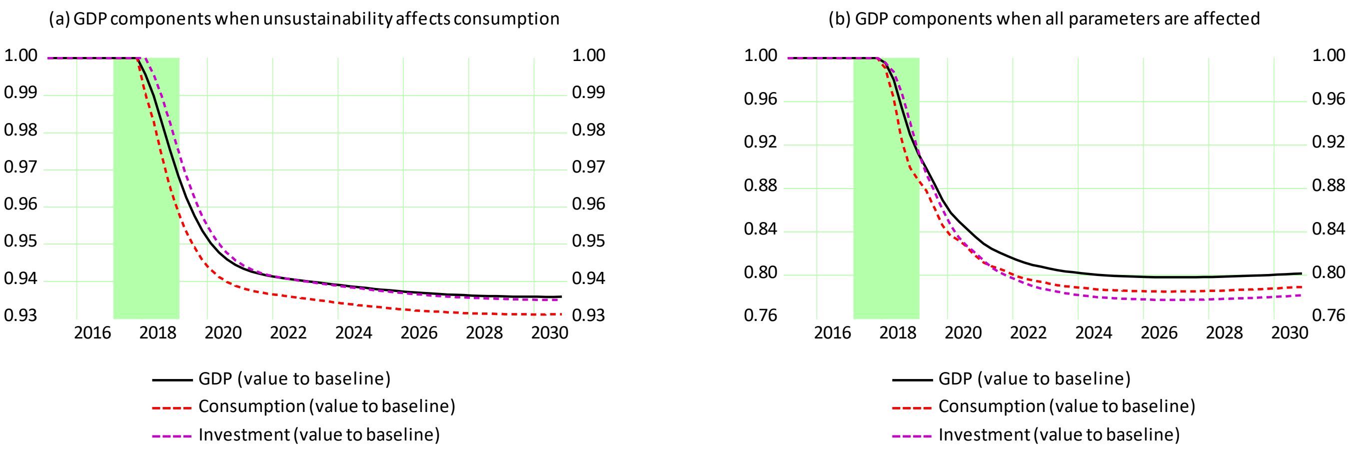


Figure 10. Ecological feedbacks: impact of MOIS on GDP and depletion rate of material and energy reserves.

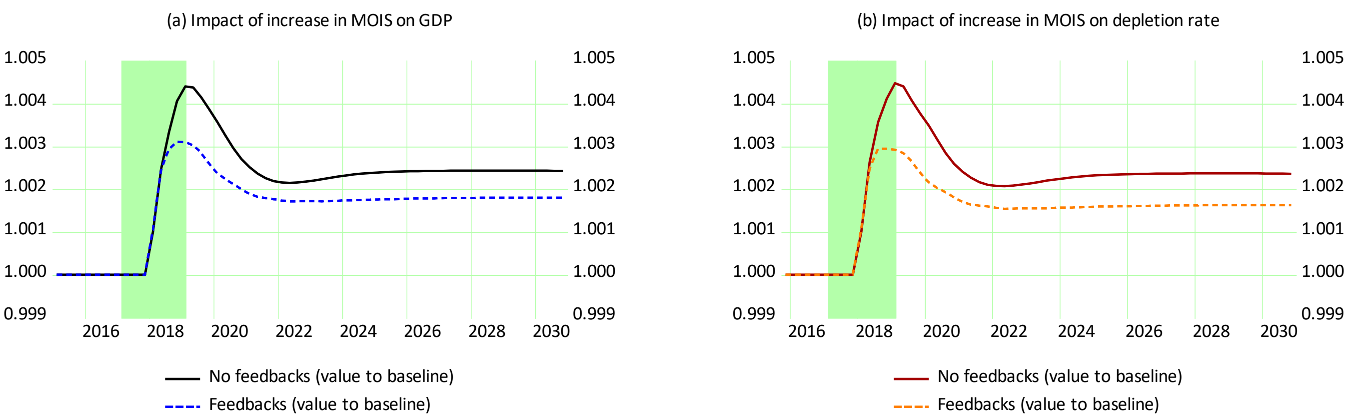


Figure 11. Ecological feedbacks: depletion of material and energy reserves and financial markets.

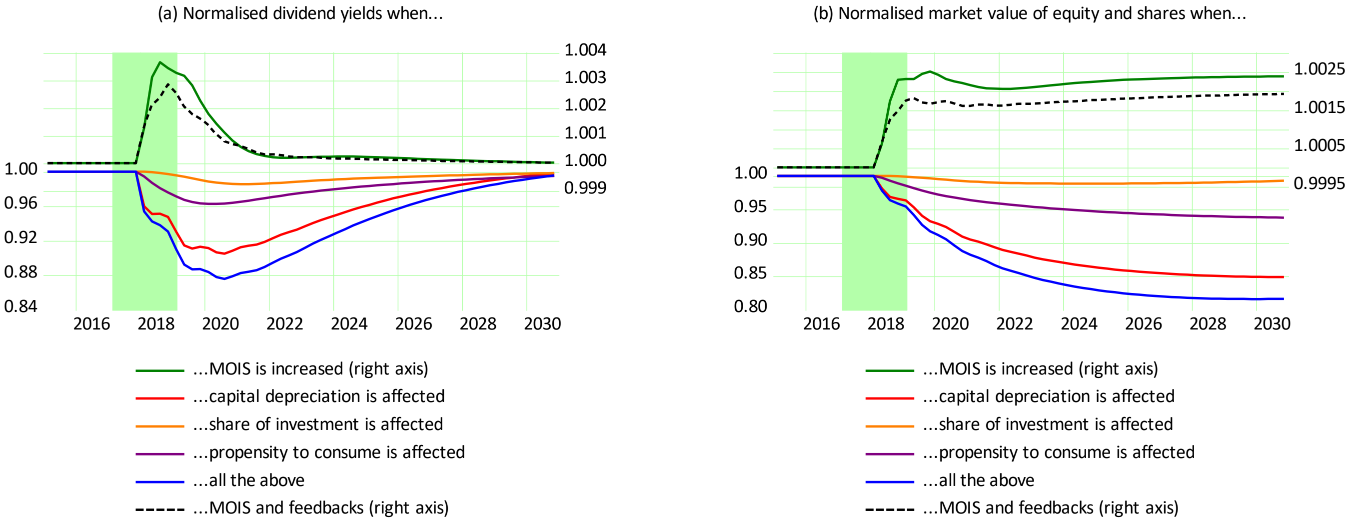


Figure 12. Ecological feedbacks: depletion of material and energy reserves and financial markets (cont'd).

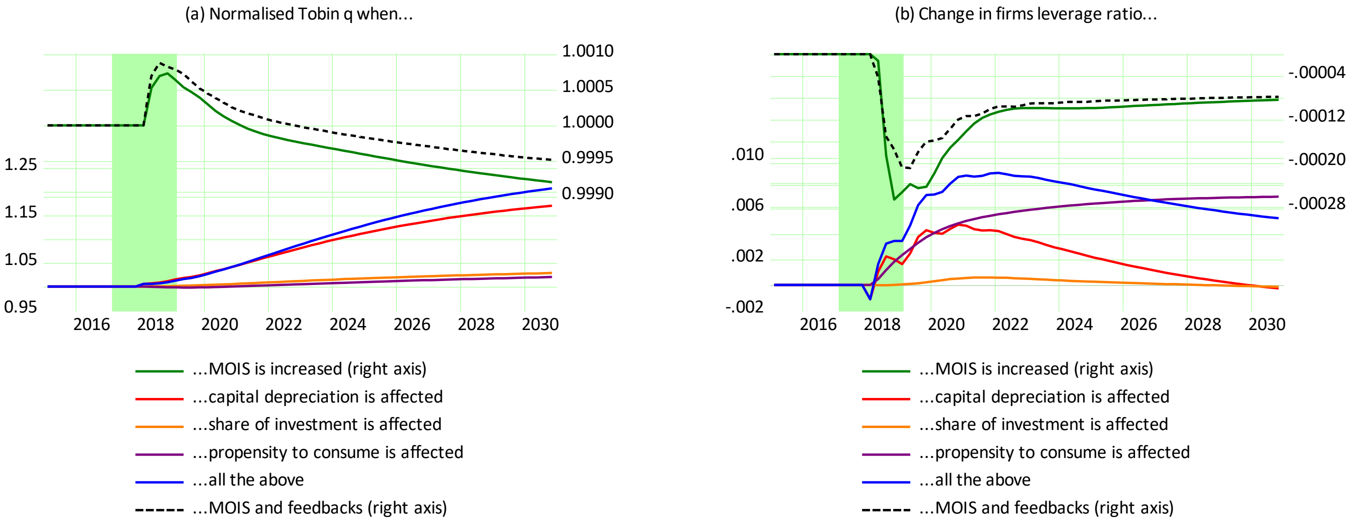
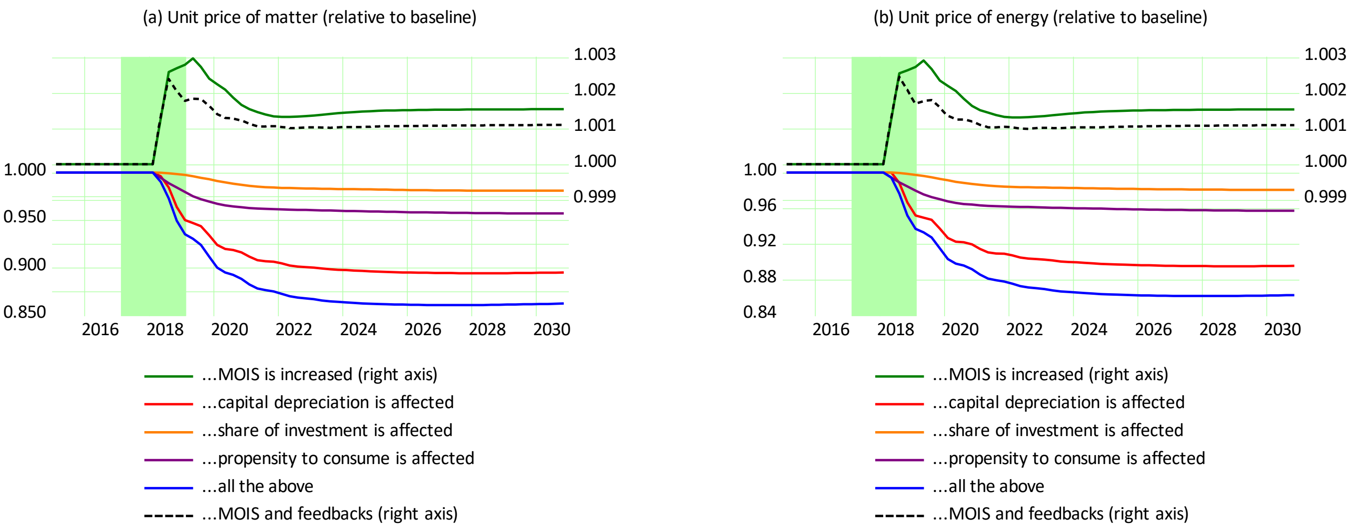


Figure 13. Ecological feedbacks: matter and energy prices.



Appendix A. The complete model (endogenous variables: 115; exogenous variables and parameters: 73)

Firms Transactions

$Y_d = C + BE + I_c + G + NX$	Aggregate demand (nominal output)
$y_s = \frac{Y_d}{p}$	Real output
$WB = \omega \cdot Y$	Wage bill
$AF = DA_f$	Amortisation funds or retained profit
$L_f = L_{f,-1} + I_c + BE - d(e_s) \cdot p_e - AF$	Change in loans to firms
$F_f = Y_d - WB - AF - r_{l,-1} \cdot L_{f,-1}$	Firms' profit

Firms Investment Decisions

$K_c = K_{c,-1} + I_c - DA_c$	Total conventional capital (in nominal terms)
$I_f = h \cdot E(Y)$	Total private investment
$h = h_{-1} + h \cdot \phi \cdot (u_{-1} - u_n) + h_0$	Total investment share to output
$I_c = I_f - I_{gr}$	Conventional investment undertaken by firms
$u = u_{-1} + u_{-1} \cdot (g_y - g_k)$	Actual utilisation rate of plants (note: $0 < u \leq 1$)
$DA_c = \delta_c \cdot K_{c,-1}$	Depreciation allowances on conventional capital
$I_{gr} = \gamma_{gr} \cdot G_{gr,-1} + DA_{gr}$	Green private investment
$K_{gr} = K_{gr,-1} + I_{gr} - DA_{gr}$	Nominal stock of green capital
$K_f = K_c + K_{gr}$	Total stock of capital in nominal terms
$k_f = \frac{K_f}{p}$	Total stock of capital in real terms
$DA_{gr} = \delta_{gr} \cdot K_{gr,-1}$	Depreciation allowances on green capital
$DA_f = DA_c + DA_{gr}$	Total depreciation allowances
$BE_{tech} = BE_{tech,a} + \gamma_{tech} \cdot G_{tech,-1}$	Private non-green innovative spending
$BE = BE_{tech} + I_{gr}$	Total private innovation expenditure

$e_s = e_{s,-1} + \chi \cdot \frac{I_{f,-1}}{p_{e,-1}}$	Quantity of new shares issued by firms as a percentage of planned investment
$g_y = \frac{\Delta Y}{Y_{-1}}$	Output growth rate
$g_k = \frac{\Delta K_f}{K_{f,-1}}$	Rate of accumulation of total capital

Households Income and Wealth

$YD_w = WB + r_{d,-1} \cdot D_{w,-1} - T_w$	Workers disposable income: labour income plus interests on deposits minus taxes
$YD_\mu = F_f + F_b + r_{d,-1} \cdot D_\Pi + r_{b,-1} \cdot B_{d,-1} - T_\Pi$	Capitalists' disposable income: entrepreneurial and financial incomes net of taxes
$YD_\mu^{hs} = YD_\mu + CG$	Capitalists' Haig-Simons disposable income
$YD = YD_w + YD_\mu$	Total disposable income
$NW_w = NW_{w,-1} + YD_w - C_w$	Net wealth of workers
$NW_\pi = NW_{\pi,-1} + YD_\pi^{hs} - C_\pi$	Net wealth of capitalists
$NW = NW_w + NW_\pi$	Total net wealth of households

Households Consumption Decisions

$C_w = c_w \cdot E(YD_w) \cdot \frac{p}{E(p)} + c_{aw} \cdot NW_{w,-1} \cdot \frac{p}{p_{-1}}$	Consumption of workers
$C_\pi = c_\pi \cdot E(YD_\pi^{hs}) \cdot \frac{p}{E(p)} + c_{a\pi} \cdot NW_{\pi,-1} \cdot \frac{p}{p_{-1}}$	Consumption of capitalists
$C = C_w + C_\pi$	Total consumption

Households Portfolio Decisions

$p_e = E(NW_\pi) \cdot \left[\lambda_{10} + \lambda_{11} \cdot E(r_e) + \lambda_{12} \cdot \frac{E(YD_\pi)}{E(NW_\pi)} + \lambda_{13} \cdot E(r_b) + \lambda_{14} \cdot E(r_d)\right] \cdot \frac{1}{e_d}$	Unit price of shares
$e_d = e_s$	Equilibrium condition for the stock market
$E_d = e_d \cdot p_e$	Nominal shares held by capitalist households
$B_d = E(NW_\pi) \cdot \left[\lambda_{20} \cdot + \lambda_{21} \cdot E(r_e) + \lambda_{22} \cdot \frac{E(YD_\pi)}{E(NW_\pi)} + \lambda_{23} \cdot E(r_b) + \lambda_{24} \cdot E(r_d)\right]$	Nominal government bonds held by capitalist households
$H_\pi = E(NW_\pi) \cdot \left[\lambda_{30} + \lambda_{31} \cdot E(r_e) + \lambda_{32} \cdot \frac{E(YD_\pi)}{E(NW_\pi)} + \lambda_{33} \cdot E(r_b) + \lambda_{34} \cdot E(r_d)\right]$	Cash held by capitalist households
$D_\pi = NW_\pi - E_d - B_d - H_\pi$	Deposits held by capitalist households

$H_w = NW_w - D_w$ Cash held by workers

$D_w = D_s - D_\pi$ Deposits held by workers[36]

$D_d = D_w + D_\pi$ Total demand for bank deposits

$H_d = H_w + H_\pi$ Total demand for cash

Commercial Banks and Central Bank

$D_s = D_{s,-1} + d(L_s)$ Supply of bank deposits

$L_s = L_{s,-1} + d(L_d)$ Supply of loans (endogenous)

$L_d = L_f + L_{row}$ Total demand for loans (including loans granted to foreign sector)

$F_b = L_{s,-1} \cdot r_{l,-1} - D_{s,-1} \cdot r_{d,-1}$ Bank profit

$B_{cb} = B_s - B_d$ T-bonds purchased by CB (residual amount)

$H_s = H_{s,-1} + d(B_{cb})$ Money created by CB 'on demand'

$r_b = r_{cb} + \mu_1$ Return rate on government bonds

$r_l = r_{cb} + \mu_2$ Interest rate on bank loans

$r_d = r_{cb}$ Return rate on bank deposits

Other Financial Variables and Indices

$CG = e_{s,-1} \cdot d(p_e)$ Capital gains/losses on shares

$r_e = \frac{F_f}{e_{s,-1} \cdot p_{e,-1}}$ Dividend yields

$q = \frac{e_s \cdot p_e + L_f}{K_f}$ Tobin's q

$\ell = \frac{L_f}{e_s \cdot p_e + L_f}$ Firms' leverage ratio

Government Spending and Taxation

$T = T_w + T_\pi$ Total tax revenue

$T_w = \tau_w \cdot \left(WB + r_{d,-1} \cdot D_{w,-1}\right) + \epsilon_4$ Taxes on workers' income

[36] For the sake of simplicity and accounting consistency, it is assumed that workers hold as many interest-bearing deposits as they can. They hold the remaining wealth in terms of cash.

$T_\pi = \tau_\pi \cdot (F_f + F_b + r_{d,-1} \cdot D_{\pi,-1} + r_{b,-1} \cdot B_{d,-1}) + \epsilon_3$	Taxes on capitalists' income (excluding capital gains)
$G = G_{rout} + G_{mois}$	Total government spending (net of interest payments)
$G_{rout} = \upsilon_{rout} \cdot Y_{-1} + \epsilon_1$	Routine government spending
$G_{mois} = \upsilon_{mois} \cdot Y_{-1} + \epsilon_2$	Mission-oriented innovation spending by government (MOIS)[37]
$G_{gr} = \alpha \cdot G_{mois}$	Government MOIS devoted to green conversion
$G_{tech} = (1 - \alpha) \cdot G_{mois}$	Other government MOIS (e.g. new technologies)

Government Budget

$B_s = B_{s,-1} + GDEF$	Nominal supply of government bonds
$GDEF = G + r_{b,-1} \cdot (B_{s,-1} - B_{cb,-1}) - T$	Government deficit (note: no interest payments on government bonds held by CB)
$GDEB = GDEB_{-1} + GDEF$	Stock of government debt

Foreign Sector

$NX = \nu_0 + \nu_1 \cdot e^{(\nu_2 \cdot t)} - \eta \cdot Y_{-1}$	Net export or trade balance surplus
$ROWDEF = NX + r_{l,-1} \cdot L_{row,-1}$	Deficit of foreign sector (surplus of domestic sector)
$ROWDEB = L_{row} = L_{row,-1} + ROWDEF$	New loans (debt) of foreign sector (or loans granted by foreign to domestic banks if $L_{row} < 0$)

Innovation and Green Investment

$Z_{gr} = I_{gr} + G_{gr}$	Total green innovation expenditure
$g_{gr} = \frac{\Delta Z_{gr}}{Z_{gr,-1}}$	Growth rate of total green innovation expenditure
$Z_{tech} = BE_{tech} + G_{tech}$	Total non-green innovation expenditure (e.g. education)
$g_{tech} = \frac{\Delta Z_{tech}}{Z_{tech,-1}}$	Growth rate of total non-green innovation expenditure

[37] Coefficients ϵ_j (with: $j = 1,2,3,4$) are autonomous components of taxes and government spending. We have assumed a balanced budget in the baseline scenario. Taxes equal spending: $T = G + r_{b,-1} \cdot B_{d,-1} - \sum \epsilon_j$. Alternatively, one can re-define total government spending as: $G = T - r_{b,-1} \cdot B_{d,-1} + \sum \epsilon_j$. When the second option is chosen, T_w and T_Π are amended proportionally, so they sum up to T.

The Ecosystem: Material Resources and Reserves

$y_{mat} = \mu \cdot y_s$	Production of material goods
$mat = y_{mat} - rec$	Extracted matter
$rec = \rho_{rec} \cdot des$	Recycled socio-economic stock
$des = \mu \cdot \frac{DA_f}{p}$	Destruction of socio-economic stock
$k_{se} = k_{se,-1} + y_{mat} - des$	Socio-economic stock
$wa = mat - \Delta k_{se}$	Waste generated by production process
$k_m = k_{m,-1} + conv_m - mat$	Stock of material reserves
$conv_m = \max(\sigma_{m,-1} \cdot res_{m,-1}, mat_{-1})$	Material resources converted to reserves
$res_m = res_{m,-1} - conv_m$	Stock of material resources
$p_m = p_m^0 + p_m^1 \cdot \left(mat_{-1} - \sigma_{m,-1} \cdot res_{m,-1}\right)$	Unit price of extracted matter
$\sigma_m = \sigma_m^0 + \sigma_m^1 \cdot E(p_m)$	Actual conversion rate of matter resources

The Ecosystem: Energy Resources and Reserves

$en = \varepsilon \cdot y_s$	Energy required for production
$ed = en$	Dissipated energy at the end of the period
$k_{en} = k_{en,-1} + conv_{en} - en$	Stock of energy reserves
$conv_{en} = \max(\sigma_{en,-1} \cdot res_{en,-1}, en_{-1})$	Energy resources converted to reserves
$res_{en} = res_{en,-1} - conv_{en}$	Stock of energy resources
$p_{en} = p_{en}^0 + p_{en}^1 \cdot \left(en_{-1} - \sigma_{en,-1} \cdot res_{en,-1}\right)$	Unit price of energy
$\sigma_{en} = \sigma_{en}^0 + \sigma_{en}^1 \cdot E(p_{en})$	Actual conversion rate of energy resources

Ecological Feedbacks

$\rho_m = \frac{mat}{k_{m,-1}}$	Matter depletion ratio (net of recycling)
$\rho_{en} = \frac{en}{k_{en,-1}}$	Energy depletion ratio
$g_m = \frac{conv_m}{k_{m,-1}}$	Growth rate of material reserves

$g_{en} = \frac{conv_{en}}{k_{en,-1}}$ Growth rate of energy reserves

$g_{ac} = \max(\rho_m, \rho_{en})$ Actual depletion rate of natural reserves

$g_{su} = \min(g_m, g_{en})$ Sustainable depletion rate of natural reserves

$\delta_c = \delta_0 + \delta_1 \cdot (g_{ac,-1} - g_{su,-1})$ Impact of excess growth on conventional capital stock depreciation

$h_0 = h_{00} + h_{01} \cdot (g_{ac,-1} - g_{su,-1})$ Impact of excess growth on investment share

$c_w = c_{w0} + c_{w1} \cdot (g_{ac,-1} - g_{su,-1})$ Impact of excess growth on propensity to consume

Production Function and Price Level

$y_f^* = a_f \cdot k_{f,-1}$ Capital-determined real potential output

$y_m^* = \frac{k_{m,-1}+rec}{\mu}$ Matter-determined real potential output

$y_{en}^* = \frac{k_{en,-1}}{\varepsilon}$ Energy-determined real potential output

$y^* = \min\left(y_f^*, y_m^*, y_{en}^*\right)$ Real potential output (Leontief function)

$\mu = \mu_{gr} \cdot \frac{K_{gr}}{K_f} + \mu_c \cdot \frac{K_c}{K_f}$ Matter intensity coefficient

$\varepsilon = \varepsilon_{gr} \cdot \frac{K_{gr}}{K_f} + \varepsilon_c \cdot \frac{K_c}{K_f}$ Energy intensity coefficient

$p = p_0 + p_1 \cdot \left[\left(\frac{Y_{-1}}{p_{-1}}\right) - y_{-1}^*\right]$ Price level of homogenous output

Employment and Wages

$l_d = \frac{Y}{p \cdot a_l}$ Firms' demand for labour inputs

$l_s = l_d$ Supply of labour inputs

$w = p \cdot \frac{a_l}{1+\mu_p} = p \cdot a_l \cdot \omega$ Nominal wage rate

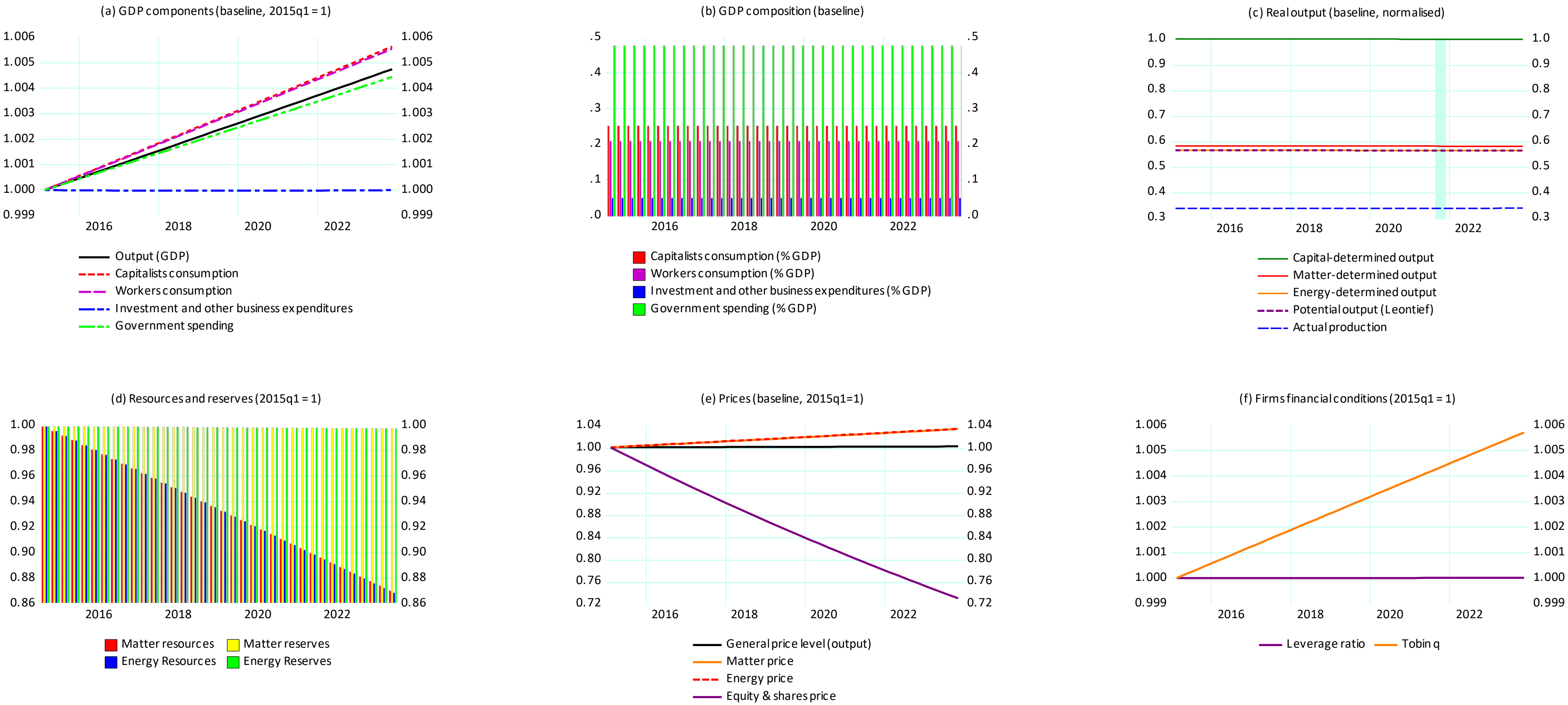
Expectations

$E(x) = x_{-1} + \psi \cdot [E(x_{-1}) - x_{-1}]$ Expected value of x

Redundant Equation

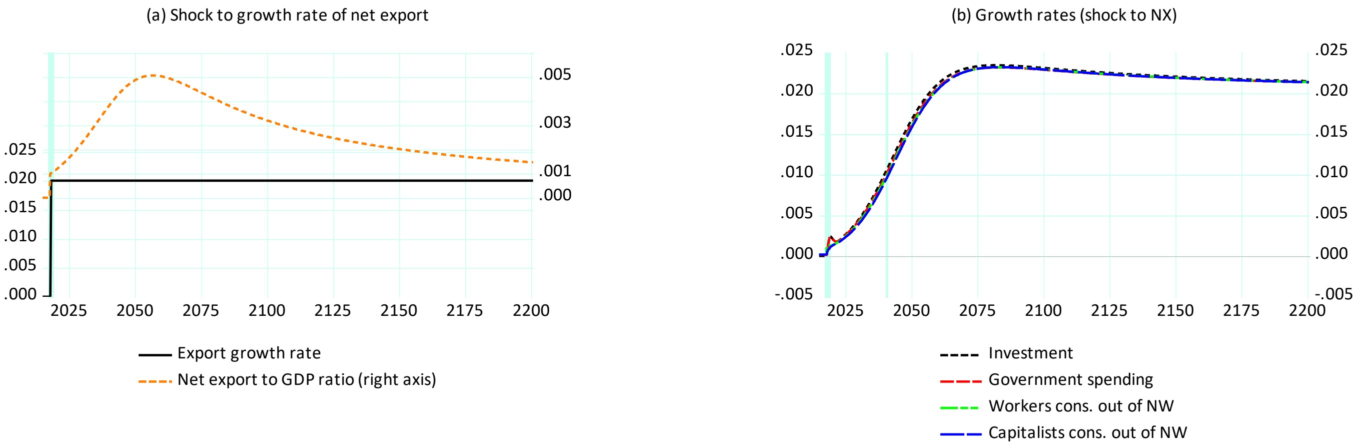
$H_s = H_d$ Cash money equilibrium condition

Figure A1. Baseline scenario: selected variables.



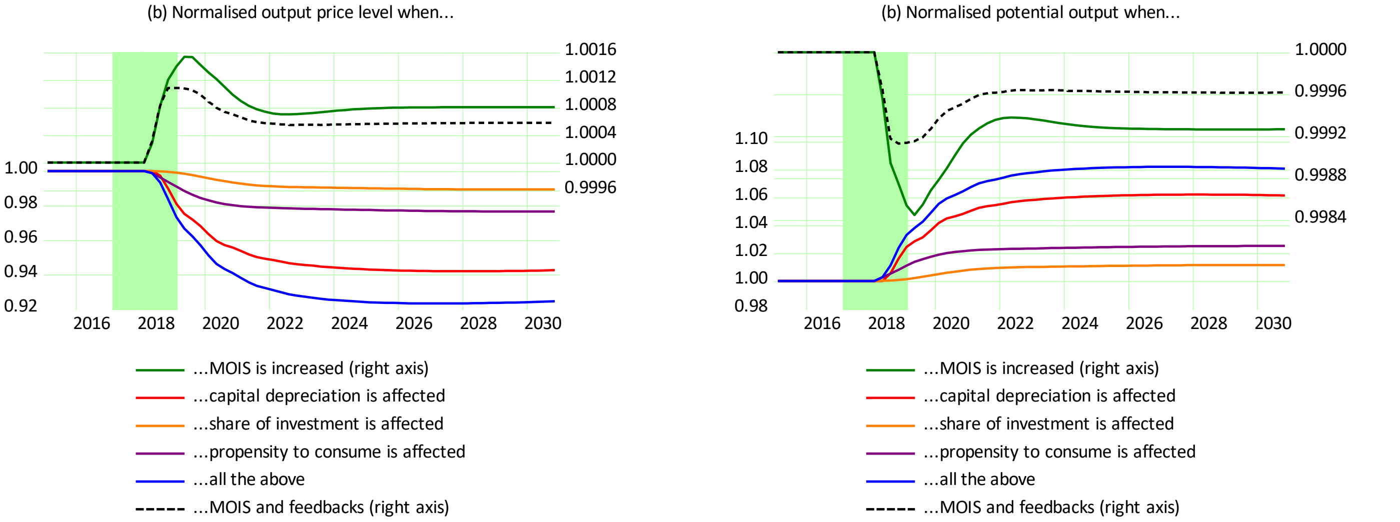
Appendix B. Shock to export level and growth rate

Figure B1. Shock to export level (from 0 to 0.1% GDP in 2018) and growth rate (from 0 to 2%, starting from 2018)



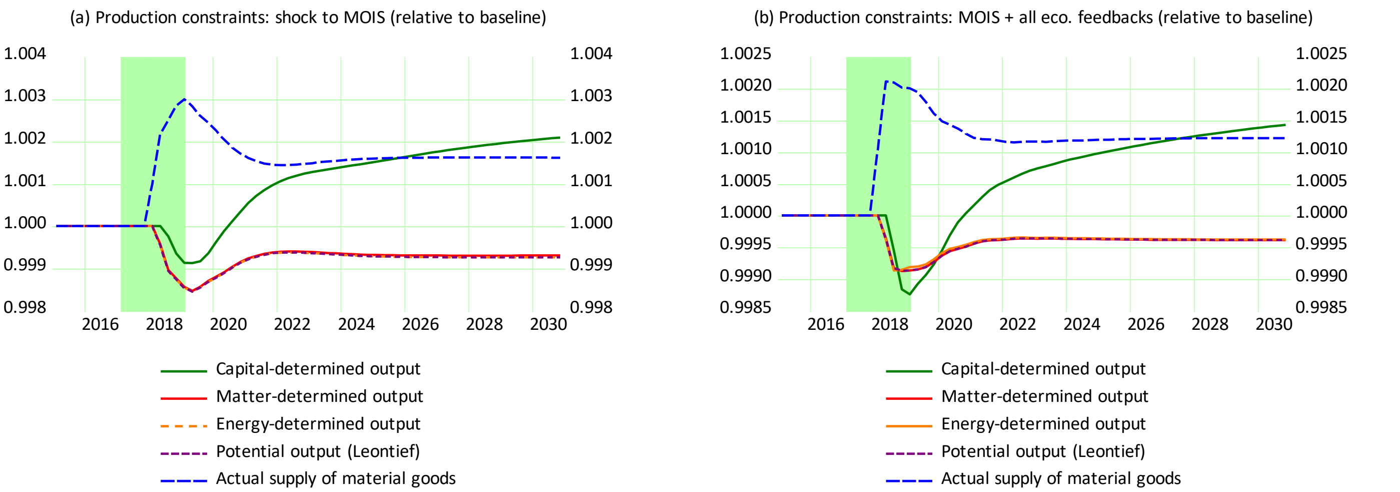
Appendix C. Potential output and price level

Figure C1. Ecological feedbacks: potential output and price level.



Note: Output price declines (compared with its baseline value) when ecological feedbacks are considered. The reason is that the lower growth rate (due to ecological feedbacks) entails a lower depletion rate of natural resources, thereby loosening ecological constraints on potential output.

Figure C2. Ecological feedbacks: potential output and price level.



Note: MOIS policies increase both capital-determined output and real supply of goods in the economy. However, they can affect resources-determined output levels and thus potential output.