

Supermultiplier, Innovation and the Ecosystem: A Stock-Flow Dynamic Model

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Abstract. This work builds upon four different theoretical approaches: i. the Sraffian supermultiplier model; ii. the Schumpeterian framework of evolutionary economics that emphasises the entrepreneurial role of the State; iii. the ‘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: *a*) the impact of government spending on private innovation; *b*) the impact of innovation on economic growth and the ecosystem; and *c*) the impact of ecological feedbacks on economic growth and government spending effectiveness. We find that, in principle, government can be successful in supporting innovation and growth while slowing down matter & energy reserves’ depletion rates and tackling climate change. However, the latter may well affect government policy effectiveness.

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

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1. Introduction

This work builds upon four different theoretical approaches: i. the Sraffian supermultiplier model (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 ‘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 so-called ‘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, climate change and the depletion rate of material and (non-renewable) energy reserves? What is the impact of climate change and natural capital depletion on fiscal policy effectiveness? Finally, what is the indirect impact of innovation and ecological feedbacks 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 combined effect arising from the interaction between fiscal (and industrial) policies, private innovation and the ecosystem. Section 3 is methodological and theoretical. We highlight assumptions, key features 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, climate change and their impact on narrowly-defined macroeconomic variables are considered. In section 5 we sum up our main results and we discuss 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) among others, 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 Harroddian 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 on the supermultiplier. 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 its main implications, in particular the role of autonomous demand as the driver of economic growth, have 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 provides 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). We focus, in particular, on mission-oriented innovation policies (MOIPs), which create new landscapes (rather than simply fixing market failures) 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): *a*) flow consistency, meaning that every flow comes from somewhere and goes somewhere; *b*) stock consistency, meaning that financial liabilities of an economic unit must be held as financial assets by other economic units; *c*) stock-flow consistency, meaning that flows affect stocks and this impact must be accurately registered (including capital gains and losses); *d*) 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. Their approach is based on three principles: *a*) the main force driving economic growth is effective demand; *b*) 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; *c*) there is a strong interconnection between the narrowly-defined economic system, the social environment and the ecosystem. As a result, feedback and/or spillover 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,

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.

2016; Dafermos et al., 2018). Central 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 bond market. Feedback mechanisms between government policies, private innovation, climate change, material & energy reserves' availability, and the stock market, are usually not (utterly) investigated. Our paper can be regarded as an attempt at bridging this gap.

In this regard, notice that our work can help assess pros and cons of ecological policies and plans, such as the already-mentioned *Energiewende Programme* (EWP). EWP can be regarded as an example of green MOIP. In short, it is quite a 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. The goal of EWP is to transform the Germany economy by enhancing energy efficiency and reducing greenhouse gas emissions (EC, 2018c). This is expected to allow Germany to stop the energy production derived by nuclear plants by 2022 and 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. 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, its empirical applications are expected to help detect the general impact of MOIPs on main macroeconomic variables and the 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 climate change and matter & energy reserves' depletion on the stock market? To address the questions above we follow a four-step process. First, we extend the supermultiplier approach to account for mission-oriented innovation policies. Second, we 'implant' our extended supermultiplier mechanism into a complete stock-flow consistent model (including 122 endogenous variables along with 82 exogenous variables and parameters overall). Third, we add green spending to the original model and we account for climate change and material & 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

$$Y = C + BE + I_f + G + NX \quad (1)$$

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:

$$C_w = C_{aw}(r_l, NW_w) + c_w \cdot YD_w \quad (2)$$

$$C_\pi = C_{a\pi}(r_l, NW_\pi) + c_\pi \cdot YD_\pi \quad (3)$$

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 houses⁵ and consumption goods (e.g. Garegnani, 2015; Deleidi, 2018).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 aggregate demand. 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 . 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 routine 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.

Notice that G_{mois} stands for mission-oriented innovation spending (MOIS), which can lead to major technological advances.⁹ 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:

$$BE = BE_a + \gamma \cdot G_{mois} \quad (10)$$

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:

$$X = E(Y_{row}) \quad (11)$$

$$M = m \cdot Y \quad (12)$$

$$NX = X - M \quad (13)$$

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.¹⁰

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

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

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

⁹ 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.

¹⁰ 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, we neglect this complication hereafter.

supermultiplier, call it $1/\eta$. 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:

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

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

$$Y = Z \cdot \frac{1}{s-h} \quad (14B)$$

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:

$$g_y = g_z + \frac{\Delta h}{s-h} \quad (16)$$

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:

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

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

$$g_y = g_k = g_z \quad (18)$$

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.¹¹ 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:

¹¹ 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.¹² 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:

- a) working-class households (i.e. the recipients of labour incomes and a share of interest payments on bank deposits);
- b) capitalist households or rentiers (i.e. the recipients of the remaining interest payments on bank deposits, entrepreneurial profits and other financial incomes);
- c) production firms (or non-financial corporations) producing a homogenous good that can be used for both consumption and investment purposes;
- d) the financial sector (including commercial banks, financial intermediaries and the central bank);
- e) the government sector (including both local and central government);
- f) 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:

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

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

¹² See Brochier and Macedo e Silva (2018). To our knowledge, this is the first attempt at analysing the properties of the supermultiplier model within a complete SFC framework.

impact of borrowing costs on household consumption plans. Consumption is also affected by the social class 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 import has been defined 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 concerning 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:

$$K_c = K_{c,-1} + I_c - DA_c \quad (22)$$

$$I_f = h \cdot E(Y) \quad (23)$$

$$h = h_{-1} + h \cdot \phi \cdot (u_{-1} - u_n) + h_0 \quad (24)$$

$$I_c = I_f - I_{gr} \quad (25)$$

$$u = u_{-1} + u_{-1} \cdot (g_y - g_k) \quad (26)$$

$$DA_c = \delta_c \cdot K_{c,-1} \quad (27)$$

$$K_f = K_c + K_{gr} \quad (28)$$

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 share of the latter the lower the share of the former, as firms first define total investment (as a share

¹³ We refer again to Godley and Lavoie (2007). 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, but it is entirely held by the central bank, which purchased it by issuing cash. Consequently, no *additional* government bonds are issued (and hence no *additional* reserves are created) *before* the shocks.

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. For the sake of simplicity, we assume that $\psi = 0$ in the simulations presented in section 4, so that: $E(x) = x_{-1}$.

of output) and then choose its composition. Green and ecological variables are presented in the next section.

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 two additional types of constraints: the progressive depletion of material and energy reserves or 'natural capital', and the increase in the atmospheric temperature (climate change) due to production activities. On the supply side, a Leontief production function is used to determine potential output. In other words, in line with the Keynes-Sraffa tradition, 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 countering material and energy reserves' depletion through an increase in their unit market prices. Socially and ecologically suboptimal results are possible and persistent in our model. The role of the State and the innovation cascade triggered by government MOIS are also considered.

More precisely, the link between government spending, innovation and 'green investment' undertaken by private firms (meaning, the type of investment that enables reducing matter and energy intensity coefficients) is embedded in the following subset of equations:

$$G_{gr} = \alpha \cdot G_{mois} \quad (29)$$

$$I_{gr} = \gamma_{gr} \cdot G_{gr,-1} + DA_{gr} \quad (30)$$

$$K_{gr} = K_{gr,-1} + I_{gr} - DA_{gr} \quad (31)$$

$$DA_{gr} = \delta_{gr} \cdot K_{gr,-1} \quad (32)$$

$$Z_{gr} = I_{gr} + G_{gr} \quad (33)$$

Equation (29) defines government green innovation-oriented spending as a percentage, α , of total MOIS. This type of expenditure generates spin-offs through which green technologies are developed and diffused to the private sector. Its effect is captured by equation (30), where γ_{gr} is a positive parameter.¹⁷ As a result, green MOIS contribute to the reduction of the impact of production activities on the ecosystem. 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 green capital stock, as shown by equation (32). Finally, equation (33)

¹⁷ Private green investment at time t_n is likely to depend on the cumulative (not current) value of green MOIS. In formal terms, one could assume that: $I_{gr} = \gamma_{gr} \cdot G_{gr,-1}^{\Sigma} + DA_{gr}$, with $G_{gr}^{\Sigma} = \sum_{t=0}^{t_n} G_{gr,t}$. However, we neglect this complication hereafter. Notice also that the equation (30) implicitly entails that green innovation is not convenient for private firms, unless it is supported by the State. This assumption is the reason why private green investment is assumed not to depend *directly* on matter and energy prices.

defines total green expenditure as the summation of private green investment and government green spending.¹⁸

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, matter & energy reserves and the socio-economic stock in our model.¹⁹ The latter allows accounting for the First and the Second Law of Thermodynamics. Taken together, these two matrices provide the accounting structure the ecosystem is built upon.²⁰ More precisely, three subsets of equations for the ecosystem can be identified. The first subsystem is related to material resources and reserves:

$$y_{mat} = \mu \cdot y_s \quad (34)$$

$$mat = y_{mat} - rec \quad (35)$$

$$rec = \rho_{rec} \cdot des \quad (36)$$

$$des = \mu \cdot (DA_f + C_{-1}) \cdot \frac{1}{p_{-1}} \quad (37)$$

$$k_{se} = k_{se,-1} + y_{mat} - des \quad (38)$$

$$wa = mat + cen + o2 - emis - \Delta k_{se} = mat - \Delta k_{se} \quad (39)$$

$$cen = \frac{emis}{car} \quad (40)$$

$$o2 = emis - cen \quad (41)$$

$$k_m = k_{m,-1} + conv_m - mat \quad (42)$$

$$conv_m = \max(\sigma_m \cdot res_{m,-1}, mat_{-1}) \quad (43)$$

$$res_m = res_{m,-1} - conv_m \quad (44)$$

$$p_m = p_m^0 + p_m^1 \cdot \frac{mat_{-1}}{\sigma_{m,-1} \cdot res_{m,-1}} \quad (45)$$

$$\sigma_m = \sigma_m^0 + \sigma_m^1 \cdot E(p_m) \quad (46)$$

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 the 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, matter is discarded because of both capital depreciation and the consumption of (non-durable) goods. The discard pace depends on the material intensity coefficient. Equation (38) defines the change in socio-economic stock as matter embodied in newly-produced goods *minus* discarded goods. Equation (39) determines waste as a residual, that is, extracted matter net of the change in socio-economic stock (see Table 5-b). Equations (40) and (41) define the carbon mass of non-renewable energy estimated from industrial

¹⁸ See Appendix A for non-green innovative spending entries, marked by subscript ‘tech’.

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 similar to 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, $y_s = Y_d/p$.

emissions (where car is the coefficient converting Gt of carbon into Gt of CO₂) and the mass of oxygen emitted, respectively. Equation (42) 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 (43). 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 (44) shows that material resources stock reduces as conversion into reserves proceeds. Equation (45) defines the unit price of extracted matter as a function of both an autonomous component (e.g. accounting for costs of production, setting the price floor) and the ratio between current demand (as determined by production needs) and normal supply (as determined by the normal rate of conversion, σ_m). Finally, equation (46) shows that the pace of conversion depends on the market price of matter: the higher the latter the higher the normal rate of conversion. So, the overall (cumulative) causation chain or sequence is: higher (lower) matter extraction to conversion ratio in $t \rightarrow$ higher (lower) unit price of matter in $t + 1 \rightarrow$ higher (lower) conversion rate in $t + 1$ (due to adaptive expectations) \rightarrow higher (lower) reserves, but lower (higher) resources in $t + 1$.

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

$$en = \varepsilon \cdot y_s \quad (47)$$

$$ed = en \quad (48)$$

$$k_{en} = k_{en,-1} + conv_{en} - en \quad (49)$$

$$conv_{en} = \max(\sigma_{en,-1} \cdot res_{en,-1}, en_{-1}) \quad (50)$$

$$res_{en} = res_{en,-1} - conv_{en} \quad (51)$$

$$p_{en} = p_{en}^0 + p_{en}^1 \cdot \frac{en_{-1}}{\sigma_{en,-1} \cdot res_{en,-1}} \quad (52)$$

$$\sigma_{en} = \sigma_{en}^0 + \sigma_{en}^1 \cdot E(p_{en}) \quad (53)$$

Equation (47) defines the amount of energy required for production purposes. For the sake of simplicity, we do not distinguish renewable from non-renewable energy: energy sources are all regarded as non-renewable. Equation (48) shows that dissipated energy equals the energy used in the production process. Equation (49) shows that the stock of energy reserves increases as conversion proceeds and decreases as energy reserves are used. Equation (50) defines newly-created energy reserves from energy resources. Equation (51) shows that the stock of energy resources declines as conversion proceeds. Finally, equations (52) and (53) determine the unit price of energy and the endogenous conversion rate, respectively.

The third subsystem deals with industrial emissions and climate change:

$$emis = \beta \cdot en \quad (54)$$

$$co2 = \psi_1 \cdot co2_{-1} + emis \quad (55)$$

$$temp = temp_{-1} + \psi_2 \cdot co2 \quad (56)$$

Equation (54) defines new industrial emissions of CO₂ as a linear function of energy used in the production process, where β is the CO₂ intensity coefficient. Total atmospheric concentration of CO₂ is calculated by equation (55) as a positive function of past level plus current emissions.²² Finally, equation (56) defines the change in the atmospheric temperature based on CO₂ emissions.

3.4 Step four: modelling feedback mechanisms and production

The last step is to add the impact of climate change and the depletion of natural capital on narrowly-defined economic variables, i.e. to define green arrows in Figure 1. Focusing on natural reserves, this would require identifying a ‘sustainable’ rate of depletion to be compared with the actual one. The latter depends on the pace of extraction/use of matter and energy, which is expressed by the two rates below:

$$\rho_m = \frac{mat}{k_{m,-1}} \quad (57)$$

$$\rho_{en} = \frac{en}{k_{en,-1}} \quad (58)$$

Since energy and matter are treated as complementary inputs, not substitutes, the actual speed of depletion of matter & energy reserves is defined by the *maximum* depletion rate:

$$g_{ac} = \max(\rho_m, \rho_{en}) \quad (61)$$

As mentioned, the rate above must be compared to the sustainable rate of depletion of natural reserves. In this regard, it can be noticed that the availability of natural reserves for production purposes depends on the speed of conversion of resources into reserves. The related growth rates are, respectively:

$$g_m = \frac{conv_m}{k_{m,-1}} \quad (59)$$

$$g_{en} = \frac{conv_{en}}{k_{en,-1}} \quad (60)$$

Consequently, we can identify the sustainable depletion rate with the *minimum* rate of growth of newly-created reserves, even though other definitions are certainly possible.²³ In formal terms:

²² In principle, CO₂ concentration depends also on the exchange of carbon between the atmosphere and the upper ocean/biosphere, and between the upper ocean/biosphere and the lower ocean. For the sake of simplicity, we simply assume that the impact of the carbon cycle on the atmospheric CO₂ concentration is implicitly captured by the term ψ_1 , so that it amounts to: $(1 - \psi_1) \cdot co2_{-1}$.

²³ In principle, the sustainable rate can be also inferred from available data, perhaps using equations (63)-(64)-(65) below. However, our aim is not to provide a brand-new definition of sustainability. Rather, our model can be used to assess and compare different theoretical implications arising from different definitions.

$$g_{su} = \min(g_m, g_{en}) \quad (62)$$

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

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

- i. both climate change and the depletion of matter & energy reserves can undermine existing capital (e.g. by accelerating capital depreciation) 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;
- iii. both climate change and the depletion of matter & energy reserves can also impact on the propensity to consume of households by:
 - rising ecological awareness, thus changing population's habits in an 'anti-consumerist' way;
 - increasing uncertainty, thus triggering hoarding behaviours.

In our model, these channels are embedded in the equations below:

$$\delta_c = \delta_0 + \delta_1 \cdot (g_{ac,-1} - g_{su,-1}) + \delta_2 \cdot \Delta temp \quad (63)$$

$$h_0 = h_{00} + h_{01} \cdot (g_{ac,-1} - g_{su,-1}) + h_{02} \cdot \Delta temp \quad (64)$$

$$c_w = c_{w0} + c_{w1} \cdot (g_{ac,-1} - g_{su,-1}) + c_{w2} \cdot \Delta temp \quad (65)$$

where $\delta_0, \delta_1, \delta_2, h_{00}, c_{w0} > 0$, while $h_{01}, h_{02}, c_{w1}, c_{w2} < 0$.

Equations (63), (64) and (65) hold that the higher the change in atmospheric temperature and the higher the actual depletion rate of natural reserves (compared to the sustainable one), the higher capital depreciation and the lower private sector spending for both consumption and investment. Notice that c_{wj} parameters (with $j = 0,1,2$) refer to workers' propensity of consumption out of their disposable income. For the sake of simplicity, we assume away the impact of climate change and reserves' depletion on workers' propensity to consume out of net wealth. The effect on capitalists' consumption plans is neglected as well. Similarly, ecological feedbacks are assumed to affect the depreciation rate of conventional capital only. Furthermore, while investment (and other private sector's spending decisions) are not directly linked with matter & energy prices, there is an indirect effect. For changes in prices impact on extraction/use rates of reserves, which, in turn, affect $(g_{ac} - g_{su})$ and thus δ_c, h_0 and c_w .

As mentioned, potential output is determined by a Leontief function, whose inputs are matter & 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, $k_f = K_f/p = K_c/p + K_{gr}/p$. 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:

$$y_f^* = a_f \cdot k_{f,-1} \quad (66)$$

$$y_m^* = \frac{k_{m,-1} + rec}{\mu} \quad (67)$$

$$y_{en}^* = \frac{k_{en,-1}}{\varepsilon} \quad (68)$$

$$y^* = \min(y_f^*, y_m^*, y_{en}^*) \quad (69)$$

Equation (66) defines the capital-determined potential output as a function of the real product per unit of (both conventional and green) capital, a_f .²⁴ Equation (67) defines matter-determined potential output as a function of the material intensity coefficient, μ , and recycling. Equation (68) 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 (69).

Although conventional capital and green capital are substitutes, material, energy and also CO2 intensity coefficients depend on the specific techniques of production chosen by the firms.²⁵ More precisely, we assume that the higher the amount of green capital relative to traditional capital, the lower the intensity coefficients:

$$\mu = \mu_{gr} \cdot \frac{K_{gr}}{K_f} + \mu_c \cdot \frac{K_c}{K_f} \quad (70)$$

$$\varepsilon = \varepsilon_{gr} \cdot \frac{K_{gr}}{K_f} + \varepsilon_c \cdot \frac{K_c}{K_f} \quad (71)$$

$$\beta = \beta_{gr} \cdot \frac{K_{gr}}{K_f} + \beta_c \cdot \frac{K_c}{K_f} \quad (72)$$

where $\mu_{gr} < \mu_c$, $\varepsilon_{gr} < \varepsilon_c$ and $\beta_{gr} < \beta_c$ are the material, energy and CO2 intensity coefficients implied by purely green and purely traditional capital inputs, respectively. As a result, the higher the green-capital intensity of the techniques of production, the lower the impact of production processes on natural reserves and the lower the level of CO2 emissions.

²⁴ The ‘productivity’ of capital, in turn, can be assumed to depend on firms’ innovation. The higher the latter, the higher the former. A simple formulation is therefore: $a_f = a_f^0 + a_f^1 \cdot BE_{-1}$, where BE is private innovative spending, including both green and non-green innovation, while $a_f^0 > 0$ and $a_f^1 \geq 0$. Unlike conventional investment, innovative spending not only affects the demand side, but also the supply side of the economy. For it makes existing capital stock more ‘productive’. However, we turn off this effect when simulating the model, as we do not want to tarnish our qualitative findings on green spending and ecological spillovers.

²⁵ Output composition also matters, but we keep assuming that a homogenous good is produced for consumption purposes.

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

$$p = p_0 + p_1 \cdot (y_{-1} - y_{-1}^*) \quad (73)$$

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

$$l_d = \frac{Y}{p \cdot a_l} \quad (74)$$

$$l_s = l_d \quad (75)$$

This does not entail full employment.²⁶ 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:

$$w = p \cdot \frac{a_l}{1 + \mu_p} \quad (76)$$

where $\mu_p = 1/\omega - 1$ is the costing margin applied to unit labour costs. Equations (74)-(75)-(76) 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. We focus on ecological feedback mechanisms instead.²⁷

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

²⁶ 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.

²⁷ The interaction between class struggle and ecological feedbacks is an interesting topic to be developed. In principle, our model allows accounting for it. However, we chose not to deal with this subject.

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 employed to identify the long-run stochastic trend of variables. Alternatively, SFC models can 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 displays the coefficients used for portfolio equations. The model is run for a very long period: from the first quarter of the twentieth century to the fourth quarter of 2040.²⁸ 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, CO2 emissions and atmospheric temperature, 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 natural reserves can be binding constraints 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. CO2 emissions grow year by year, thereby pushing up the atmospheric temperature – quadrants (e) and (f), respectively. Because of point (d), matter and energy prices tend to increase over time, while the general price level is stagnating and the price of equity and shares faces a decline – quadrant (g). Firms are marked by a stable leverage ratio and their market value (expressed by the Tobin'q) is slightly increasing – see quadrant (h). We believe that this is a realistic scenario (for an early-industrialised country) to be used as a baseline for our experiments.²⁹ 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 to narrowly-defined economic shocks to government spending and taxation.

²⁸ All the simulations have been performed using *EViews*. Both model's program file and sensitivity tests and can be provided upon request.

²⁹ We also assume that the government is balancing its budget and is characterised by a stock of debt $\cong 38\%$.

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 the ecosystem by turning on feedback effects linked with both climate change and the progressive exhaustion of matter & 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 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 and last for one period only. The size of each shock is 0.1% of current output. The policy scenarios we have considered are:

- a) an increase in the absolute level of MOIS undertaken by the government;
- b) an increase in the absolute level of routine government spending;
- c) a cut in the absolute level of taxes on workers' income;
- d) 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 of 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 coefficient are high enough. Figure 5-b compares a medium-low debt situation ($\approx 38\%$ of GDP in 2018) with a medium-high debt ($\approx 83\%$) and a very low debt ($\approx 8\%$) 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 positive impacts on output, but their sizes are 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 is long-lasting.

4.2 Green expenditures, ecological sustainability and feedback effects

While several studies have been published about the impact of economic policies on ecological sustainability, they typically deal with monetary policies. By contrast, fiscal and industrial policy effects are usually neglected. This is the reason we focus on the role of government.³⁰ For the sake of simplicity, we assume that green investments undertaken by private firms entail fixed capital accumulation, while non-green innovative spending (e.g. new technology programmes) does not.

The increase in MOIS leads to both a direct and an indirect effect on green expenditure: on 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 both atmospheric temperature (climate change) and the actual depletion rates of matter & energy reserves. The increase in green expenditures allows reducing the depletion rate of matter & energy reserves *per unit of output* relative to both the baseline and a conventional spending scenario – Figure 7-a. However, this may not suffice to offset the higher depletion of natural reserves due to output growth – Figure 7-b. Similarly, MOIS policies can be associated with higher CO₂ emissions (and so a higher atmospheric temperature, in our simple model), especially when they are not specifically focused on green innovation – Figure 8-a and Figure 8-b. Notice that ecological feedbacks smooth the impact of MOIS policies on both the economy and the ecosystem. As a result, a conundrum shows up for the policy-makers: green investment is associated with lower matter-, energy- and CO₂-intensity coefficients, but also with higher growth rates and hence higher utilisation rates of natural reserves and higher emissions, which can possibly offset the ecological efficiency gains. So, only those innovations which enable for remarkable efficiency gains should be targeted by the government.

Turning to ecological feedback effects, in section 3.4 we identified three main channels through which climate change and the depletion of matter & energy reserves can affect both level and composition of output: i. by accelerating capital depreciation; ii. by reducing the

³⁰ Actually, 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).

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 9 and 10. For the sake of simplicity, only the effect generated by climate change is considered. However, the same qualitative findings are found when the impact of matter & energy resources' depletion (exceeding the sustainable rate) is considered. The effects triggered by channels (i), (ii) and (iii) are shown separately by Figure 9-a, 9-b and 10-a, respectively. Their combined impact is shown by figure 10-b. Overall, the impact on output is negative, even though consumption and investment can react differently to different shocks. Figure 11-a shows that an increase in government MOIS still entails a positive impact on output. As mentioned, ecological feedbacks can reduce innovation policies effectiveness, while at the same time smoothing their impact on matter & energy reserves – Figure 11b.

Turning to the supply side of the model, simulations for the output price level and potential output are shown by Figure 12. The former declines (relative to its baseline value) when ecological feedbacks are considered. The reason is that a lower growth rate (due to ecological feedbacks) entails a lower depletion rate of natural resources, thereby temporarily loosening ecological constraints on potential output. However, non-linear effects may well show up in the medium- to long-run. The blue faded areas in figures 12-a and 12-b highlight that possibility. Starting from 2023, the capital-determined potential output falls below both matter- and energy-determined output levels, due to ecological feedbacks. Potential output falls sharply, thereby pushing upwards the output price level. The change in production constraints following a positive shock to MOIS is stressed further by Figure 13. When ecological feedbacks are turned on, the maximum or potential output is no longer determined by the availability of natural reserves, but by the availability of productive capital – see purple dotted line in Figure 13-a relative to the same line in Figure 13-b. This paradoxical effect is due to climate change (or other adverse ecological conditions) slowing down accumulation through a reduction in consumption, a fall in investment and an increase in fixed capital depreciation. Potential production increases, but this can go along with a stable (or even lower) actual supply of goods in the economy (see blue dashed lines).

Financial variables are also affected. Figure 14 and 15 show that ecological feedbacks affect dividend yields, the market value of shares, firms Tobin's q and their (sectoral) leverage ratio, respectively. Dividend yields always fall relative to their baseline values – Figure 14-a. An identical dynamics is recorded for the market value of equity & shares – Figure 14-b. In addition, the positive impact of MOIS policies is (partially) affected by ecological feedbacks. By contrast, both the Tobin's q and firms' leverage ratio – figures 15a and 15-b, respectively – increase relative to their baseline values when ecological effects are considered. The reason is that capital accumulation slows down relative to 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 private sector overall.³¹ Finally, both matter and energy prices reduce relative to their baseline values when economic growth is affected, due to the reduction in demand for production inputs – see Figure 16. 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 reserves and higher CO₂ emissions, 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, the government can be successful in supporting innovation and growth while slowing down material and energy reserves' depletion and tackling climate change. However, this requires targeting green innovations characterised by the highest ecological efficiency gains. In addition, the over-consumption of material and energy reserves, as well as the increase in atmospheric temperature, should be expected to 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 tuning coefficient values of behavioural equations. In addition, the way we modelled central bank's behaviour does not suit every country, while financial institutions are just sketched. Conflicting claims and class struggle between workers and firms, and between firms and financial institutions, are also ruled out. Furthermore, the ecosystem is still quite stylised.

Despite these limitations, the model has three main strengths. First, it allows shedding light on the role of the State in actively promoting green innovation, thus driving a change in the overall economic structure. Second, it shows that the policy-makers are likely to face a conundrum: green innovation allows for lower matter-, energy- and CO₂-intensity coefficients, but the higher production (due to the higher private investment) may well frustrate these efficiency gains. Third, the model provides a (relatively) simple mechanism to account for the tendency of growth rates of early-industrialised countries to slow down, while being incapable to address the progressive erosion of natural capital and global warming.³²

³¹ It could be observed that it is the leverage ratios of households (and non-bank financial intermediaries), not production firms, which have recorded a remarkable increase in the last two decades. Since consumer credit and mortgages are not explicitly modelled, loans can be only granted to firms in our model. As a result, firms' owners (i.e. capitalists) are affected by rising leverage ratios, but workers' are not. While this assumption can be relaxed, we ignore this complication hereafter.

³² The exact quantification of these phenomena at the national level (and hence the solution of the conundrum above) would require adjusting the model to match country-specific institutional features as well as estimating model coefficients from available data. In fact, this is expected to be one of the most promising developments or applications of our model.

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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)					(b)	
	Material reserves	Energy reserves	Atmospheric CO2 concentrat.	Socio-economic stock	Material balance	Energy balance
Initial stock	$k_{m,-1}$	$k_{en,-1}$	$CO2_{-1}$	$k_{se,-1}$		
Resources converted into reserves	$+conv_m$	$+conv_{en}$			Extracted matter	$+mat$
Emissions			$+emis$		Non-renewable energy	$+cen$
Production of material goods				$+y_{mat}$	Oxygen	$+O2$
Extraction/use of matter/energy	$-mat$	$-en$			Outputs	

Net transfer to oceans/biosph.			$-(1 - \psi_1) \cdot CO2_{-1}$		Industrial emissions	$-emis$	
Destruction of s.e.s.				$-des$	Waste and emissions	$-wa$	
Final stock	k_m	k_e	$CO2$	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
<i>Memo: capital gains</i>		$-\Delta p_e \cdot e_{s,-1}$						

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_0	Autonomous depletion rate of natural reserves	X	0.05
car	Conversion rate of Gt of carbon into Gt of CO2	X	3.67	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 K	X	0.219
p_0	Autonomous component of output price level	X	1.00	μ_{gr}	Matter intensity coefficient, green K	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	0.025
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	v_{rout}	Dependent routine gov. spending (% of GDP)	X	0.45
β_c	CO2 intensity coefficient, conventional K	X	0.08	v_{mois}	Dependent government MOIS spending (% of GDP)	X	0.00
β_{gr}	CO2 intensity coefficient, green K	X	0.05	ϕ	Sensitivity of investment share to utilis. rate gap	X	0.001
γ_{gr}	Sensitivity of green investment to MOIS	X	2	χ	New shares to real investment ratio	X	0.20
γ_{tech}	Sensitivity of other innovative investment to MOIS	X	2	ψ	Adaptation coefficient in price expectations	X	0.00
δ_c	Conventional capital depreciation rate	X	0.04	ψ_1	Autoregressive component of total emissions	X	0.80
δ_{gr}	Green capital depreciation rate	X	0.00	ψ_2	Sensitivity of temperature to total emissions	X	0.000015
ε_c	Energy intensity coefficient, conventional K	X	0.219	ω	Narrowly-defined wage share to GDP ratio	X	0.60

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}	0.10	λ_{20}	0.10	λ_{30}	0.10	λ_{40}	0.70
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.³⁶

³⁶ Following the Tobinesque principles, the so-called vertical constraints of portfolio equations are: $\lambda_{40} = 1 - (\lambda_{10} + \lambda_{20} + \lambda_{30})$, $\lambda_{41} = -(\lambda_{11} + \lambda_{21} + \lambda_{31})$, $\lambda_{42} = -(\lambda_{12} + \lambda_{22} + \lambda_{32})$, $\lambda_{43} = -(\lambda_{13} + \lambda_{23} + \lambda_{33})$, $\lambda_{44} = -(\lambda_{14} + \lambda_{24} + \lambda_{34})$; horizontal constraints (for coefficients associated with interest-bearing assets) are: $\lambda_{14} = -(\lambda_{11} + \lambda_{13})$, $\lambda_{24} = -(\lambda_{21} + \lambda_{23})$, $\lambda_{34} = -(\lambda_{31} + \lambda_{33})$. Notice that we swapped columns for rows in Table 4. As a result, vertical constraints define row totals, while horizontal constraints define column totals. Chosen values are purely theoretical. They have been tuned in such a way to obtain economically significant values for household holdings of financial assets. They imply no demand for cash in the baseline scenario. 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' (adaptive) expectations.

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).

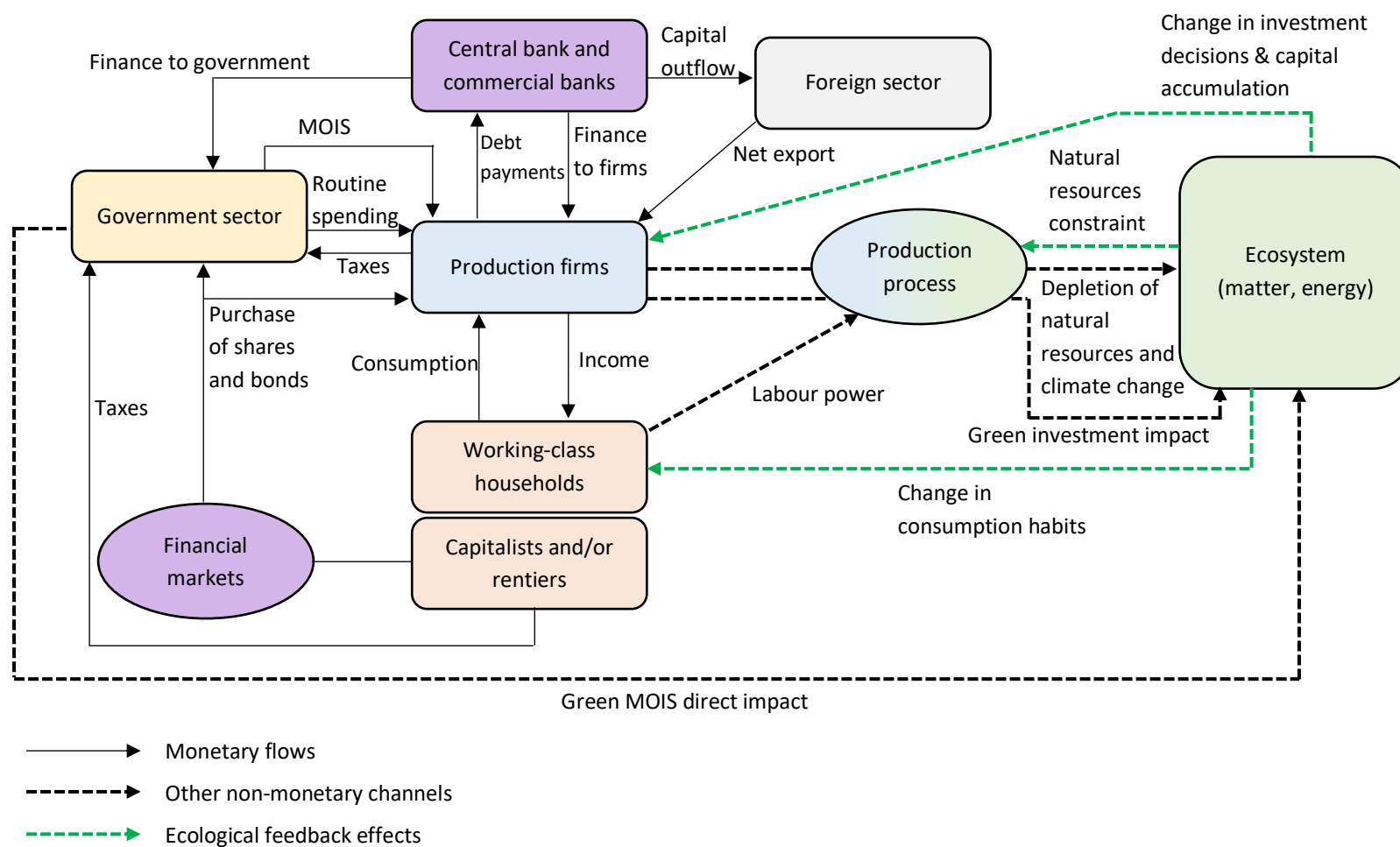


Figure 2. Reaction of output (GDP), total consumption and investment following a positive shock to innovative (a) and routine (b) government spending, respectively.

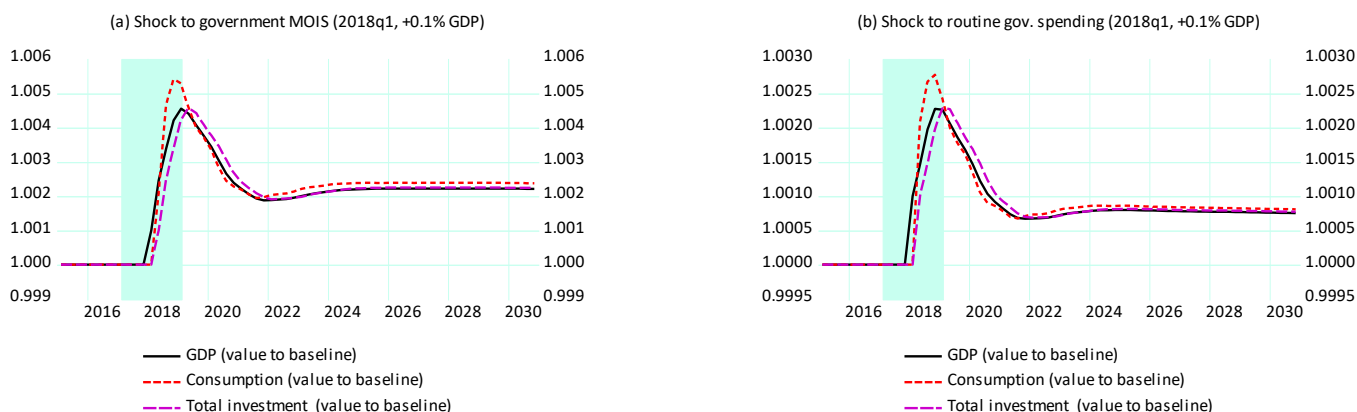


Figure 3. Reaction of output (GDP), total consumption and investment following a negative shock to taxes paid by workers (a) and capitalists (b), respectively.

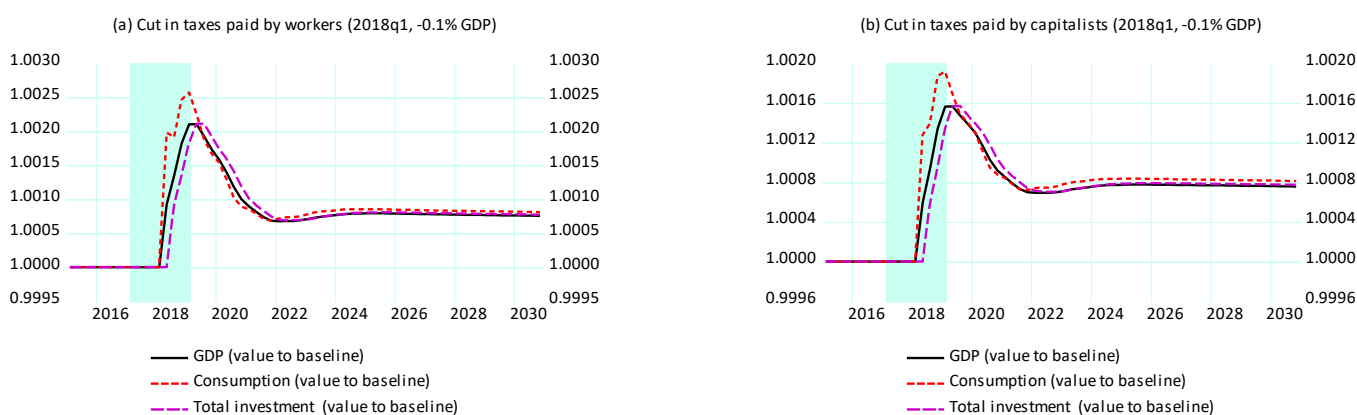


Figure 4. Reaction of output (a) and capacity utilisation (b) following different fiscal shocks.

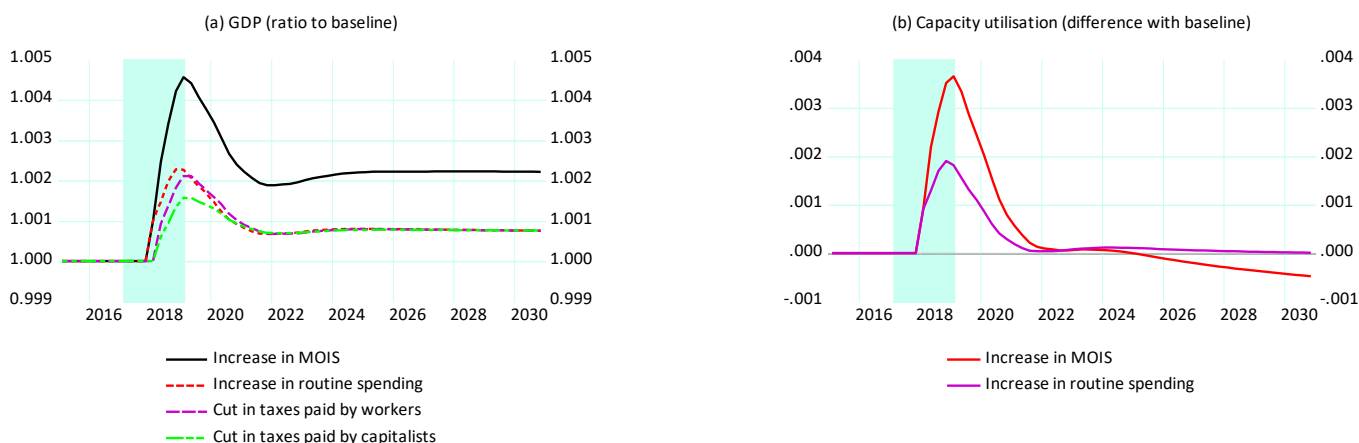


Figure 5. Reaction of government debt to GDP ratio following different fiscal shocks (a) and using different initial value of debt (b).

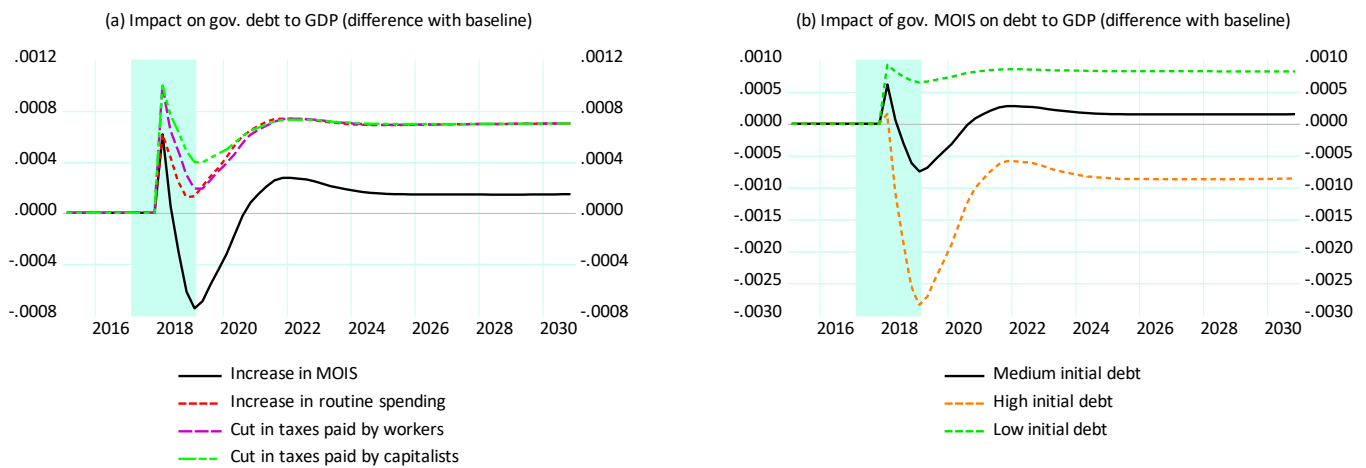


Figure 6. Reaction of output growth rate following different shocks (a) and reaction of aggregate demand components following a positive shock to government MOIS (b).

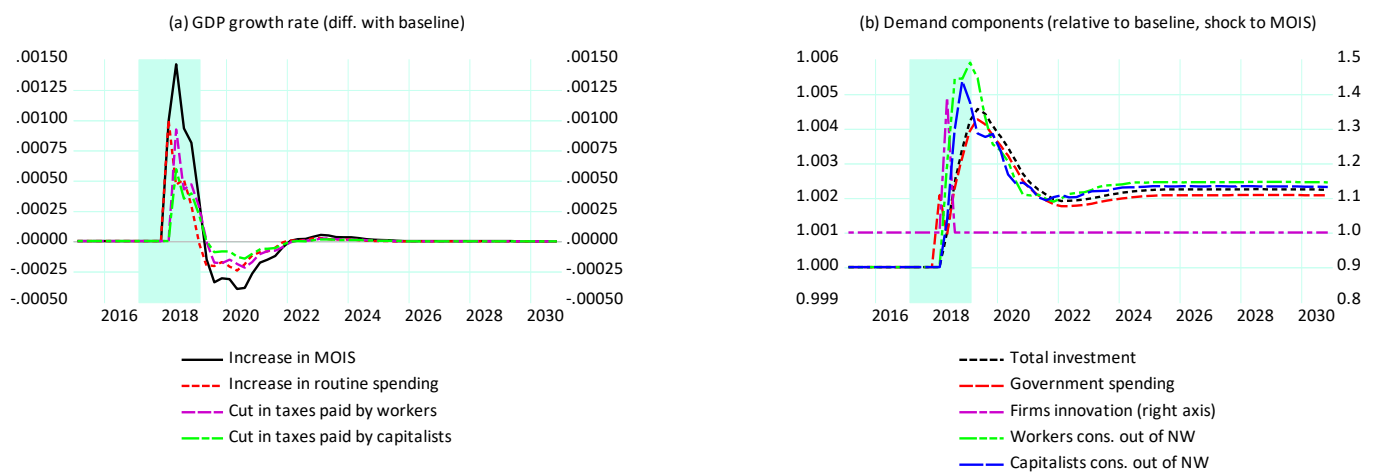


Figure 7. Impact of the increase in MOIS on natural reserves' depletion ratios.

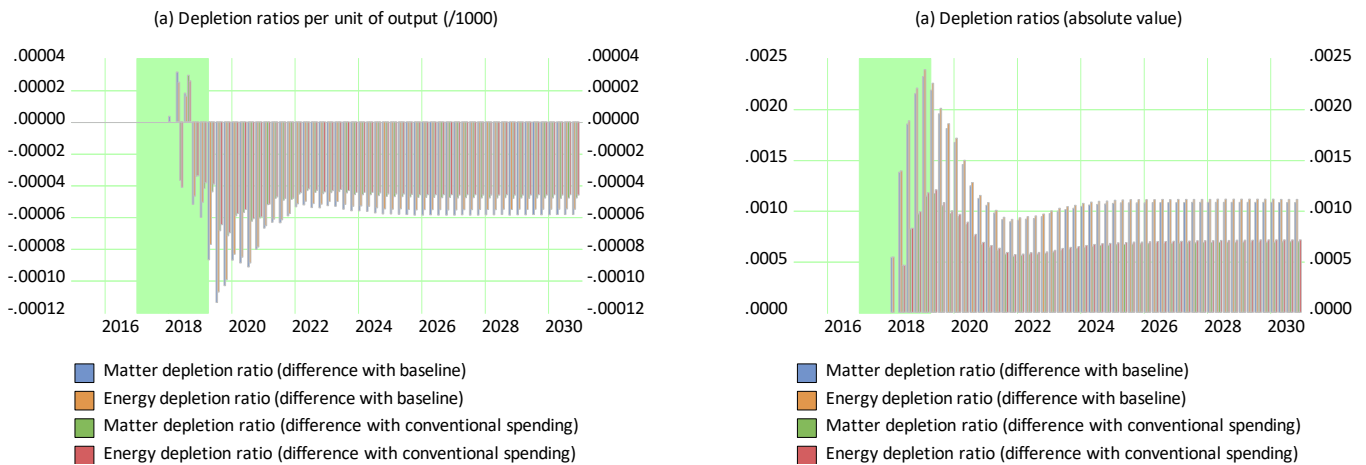


Figure 8. Impact of the increase in MOIS on CO2 emissions and temperature.

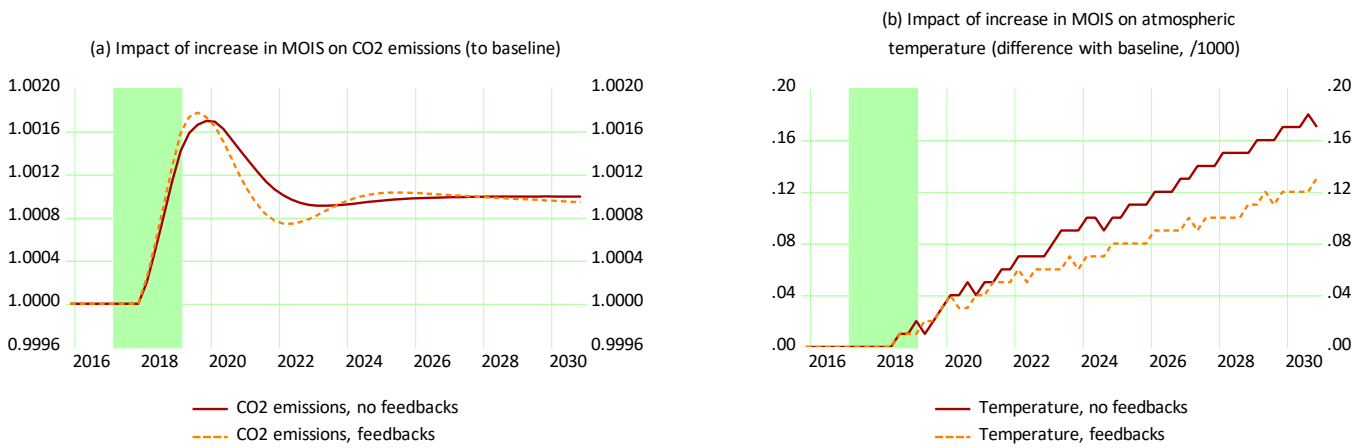


Figure 9. Ecological feedbacks: impact on GDP components.

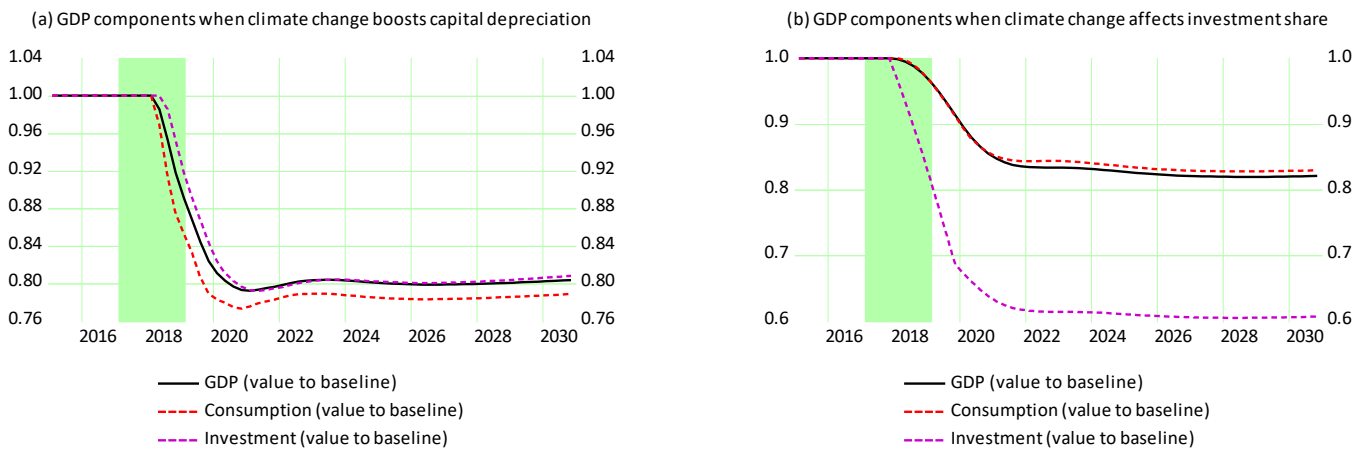


Figure 10. Ecological feedbacks: impact on GDP components (cont'd).

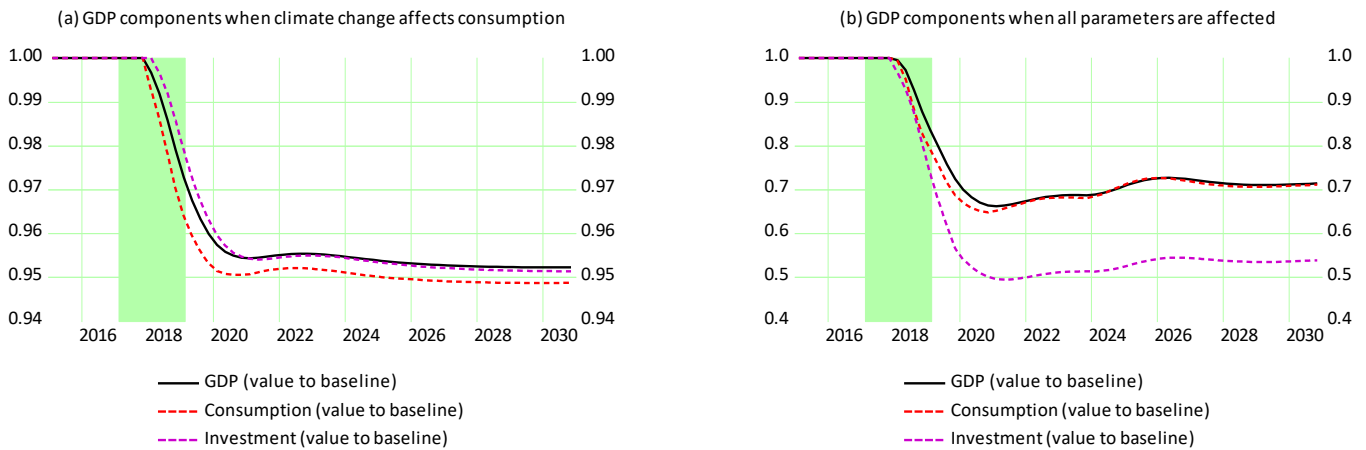


Figure 11. Ecological feedbacks: impact of MOIS on GDP and depletion rate of material and energy reserves.

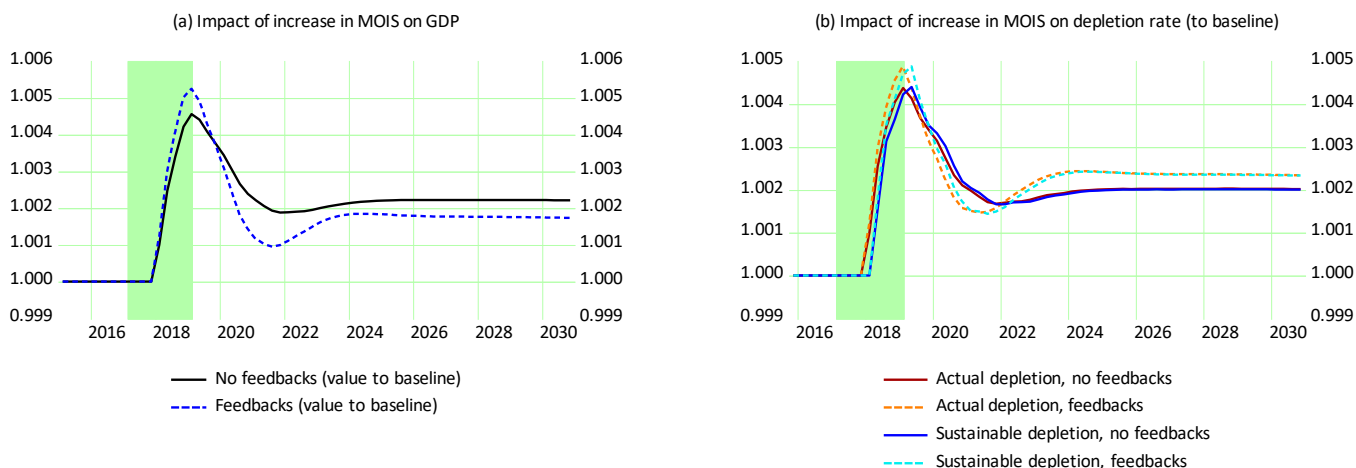


Figure 12. Ecological feedbacks: potential output and price level.

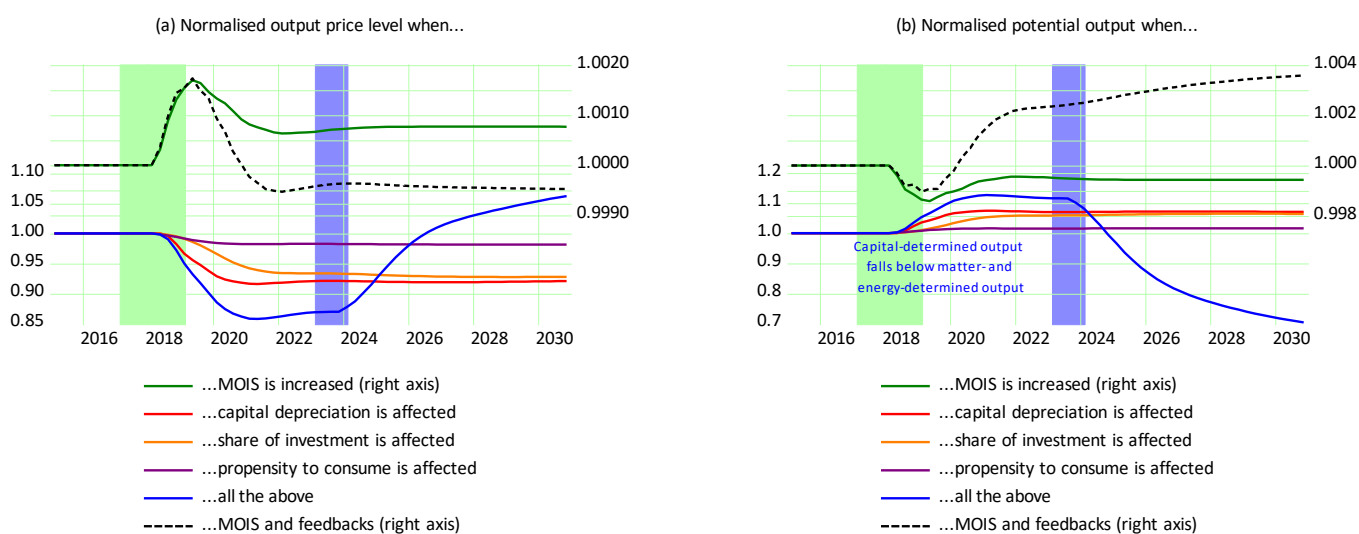


Figure 13. Ecological feedbacks: production constraints.

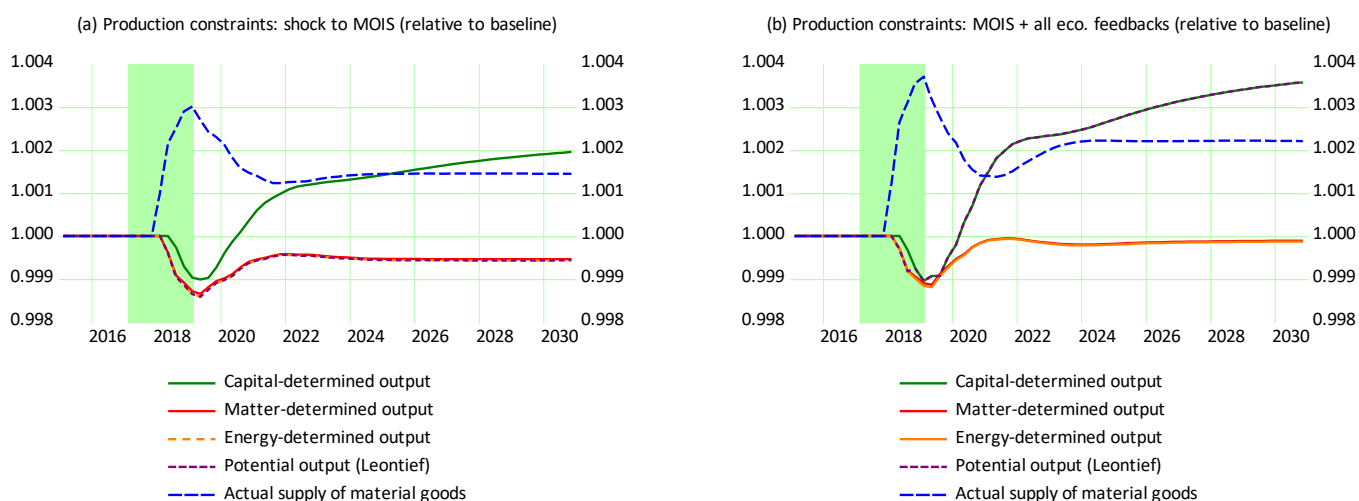


Figure 14. Ecological feedbacks: depletion of material and energy reserves and financial markets.

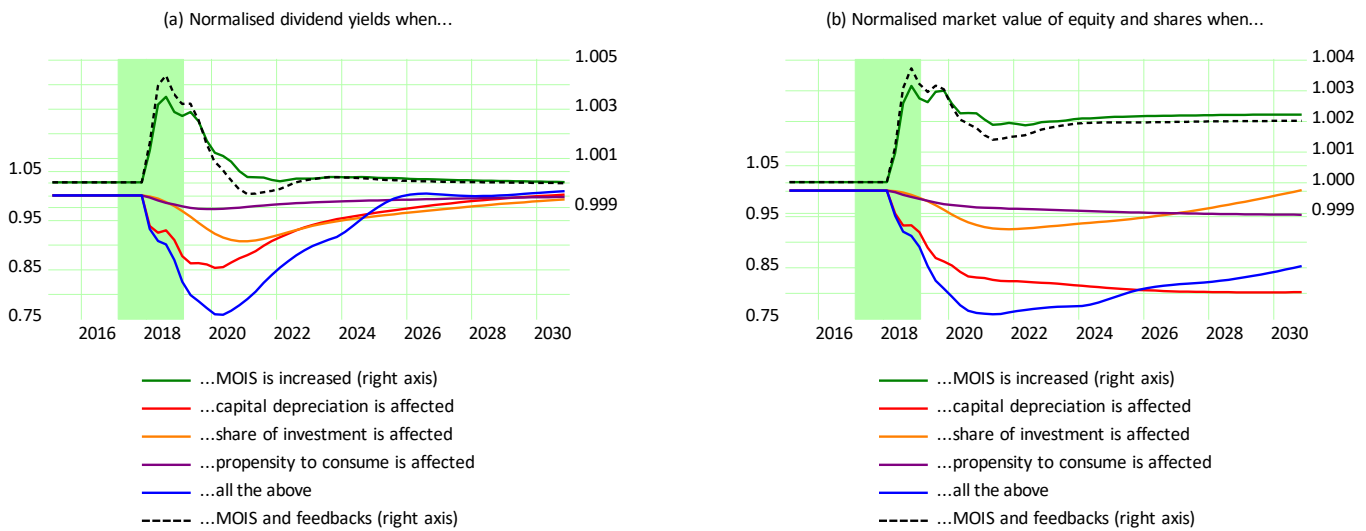


Figure 15. Ecological feedbacks: depletion of material and energy reserves and financial markets (cont'd).

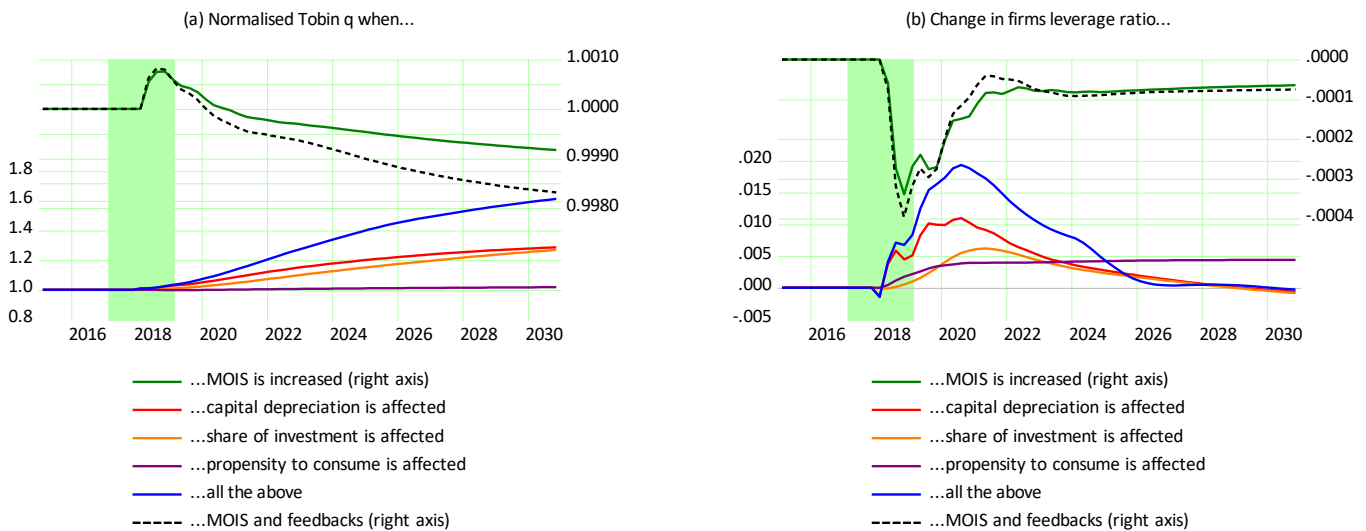
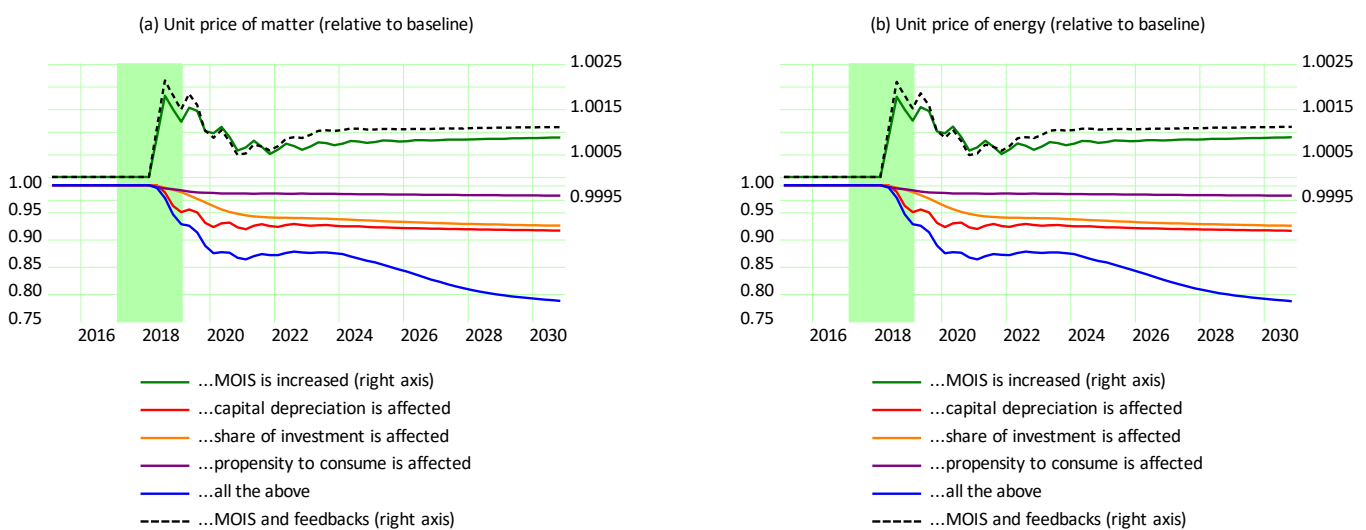


Figure 16. Ecological feedbacks: matter and energy prices.



Appendix A. The complete model (endogenous variables: 122; exogenous variables and parameters: 82)

Firms Transactions

$$Y_d = C + BE + I_c + G + NX$$

$$y_s = \frac{Y_d}{p}$$

$$WB = \omega \cdot Y$$

$$AF = DA_f$$

$$L_f = L_{f,-1} + I_c + BE - d(e_s) \cdot p_e - AF$$

$$F_f = Y_d - WB - AF - r_{l,-1} \cdot L_{f,-1}$$

Aggregate demand (nominal output)

Real output

Wage bill

Amortisation funds or retained profit

Change in loans to firms

Firms' profit

Firms Investment Decisions

$$K_c = K_{c,-1} + I_c - DA_c$$

$$I_f = h \cdot E(Y)$$

$$h = h_{-1} + h \cdot \phi \cdot (u_{-1} - u_n) + h_0$$

$$I_c = I_f - I_{gr}$$

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

$$DA_c = \delta_c \cdot K_{c,-1}$$

$$I_{gr} = \gamma_{gr} \cdot G_{gr,-1} + DA_{gr}$$

$$K_{gr} = K_{gr,-1} + I_{gr} - DA_{gr}$$

$$K_f = K_c + K_{gr}$$

$$k_f = \frac{K_f}{p}$$

$$DA_{gr} = \delta_{gr} \cdot K_{gr,-1}$$

$$DA_f = DA_c + DA_{gr}$$

$$BE_{tech} = BE_{tech,a} + \gamma_{tech} \cdot G_{tech,-1}$$

$$BE = BE_{tech} + I_{gr}$$

Total conventional capital (in nominal terms)

Total private investment

Total investment share to output

Conventional investment undertaken by firms

Actual utilisation rate of plants (note: $0 < u \leq 1$)

Depreciation allowances on conventional capital

Green private investment

Nominal stock of green capital

Total stock of capital in nominal terms

Total stock of capital in real terms

Depreciation allowances on green capital

Total depreciation allowances

Private non-green innovative spending

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

$$H_w = NW_w - D_w$$

$$D_w = D_s - D_\pi$$

$$D_d = D_w + D_\pi$$

$$H_d = H_w + H_\pi$$

Cash held by workers

Deposits held by workers³⁷

Total demand for bank deposits

Total demand for cash

Commercial Banks and Central Bank

$$D_s = D_{s,-1} + d(L_s)$$

$$L_s = L_{s,-1} + d(L_d)$$

$$L_d = L_f + L_{row}$$

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

$$B_{cb} = B_s - B_d$$

$$H_s = H_{s,-1} + d(B_{cb})$$

$$r_b = r_{cb} + \mu_1$$

$$r_l = r_{cb} + \mu_2$$

$$r_d = r_{cb}$$

Supply of bank deposits

Supply of loans (endogenous)

Total demand for loans (including loans granted to foreign sector)

Bank profit

T-bonds purchased by CB (residual amount)

Money created by CB 'on demand'

Return rate on government bonds

Interest rate on bank loans

Return rate on bank deposits

Other Financial Variables and Indices

$$CG = e_{s,-1} \cdot d(p_e)$$

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

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

$$\ell = \frac{L_f}{e_s \cdot p_e + L_f}$$

Capital gains/losses on shares

Dividend yields

Tobin's q

Firms' leverage ratio

Government Spending and Taxation

$$T = T_w + T_\pi$$

$$T_w = \tau_w \cdot (WB + r_{d,-1} \cdot D_{w,-1}) + \epsilon_4$$

Total tax revenue

Taxes on workers' income

³⁷ 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.

$$T_{\pi} = \tau_{\pi} \cdot (F_f + F_b + r_{d,-1} \cdot D_{\pi,-1} + r_{b,-1} \cdot B_{d,-1}) + \epsilon_3$$

$$G = G_{rout} + G_{mois}$$

$$G_{rout} = v_{rout} \cdot Y_{-1} + \epsilon_1$$

$$G_{mois} = v_{mois} \cdot Y_{-1} + \epsilon_2$$

$$G_{gr} = \alpha \cdot G_{mois}$$

$$G_{tech} = (1 - \alpha) \cdot G_{mois}$$

Government Budget

$$B_s = B_{s,-1} + GDEF$$

$$GDEF = G + r_{b,-1} \cdot (B_{s,-1} - B_{cb,-1}) - T$$

$$GDEB = GDEB_{-1} + GDEF$$

Foreign Sector

$$NX = v_0 + v_1 \cdot e^{(v_2 \cdot t)} - \eta \cdot Y_{-1}$$

$$ROWDEF = NX + r_{l,-1} \cdot L_{row,-1}$$

$$ROWDEB = L_{row} = L_{row,-1} + ROWDEF$$

Innovation and Green Investment

$$Z_{gr} = I_{gr} + G_{gr}$$

$$g_{gr} = \frac{\Delta Z_{gr}}{Z_{gr,-1}}$$

$$Z_{tech} = BE_{tech} + G_{tech}$$

$$g_{tech} = \frac{\Delta Z_{tech}}{Z_{tech,-1}}$$

Taxes on capitalists' income (excluding capital gains)

Total government spending (net of interest payments)

Routine government spending

Mission-oriented innovation spending by government (MOIS)³⁸

Government MOIS devoted to green conversion

Other government MOIS (e.g. new technologies)

Nominal supply of government bonds

Government deficit (note: no interest payments on government bonds held by CB)

Stock of government debt

Net export or trade balance surplus

Deficit of foreign sector (surplus of domestic sector)

New loans (debt) of foreign sector (or loans granted by foreign to domestic banks if $L_{row} < 0$)

Total green innovation expenditure

Growth rate of total green innovation expenditure

Total non-green innovation expenditure (e.g. education)

Growth rate of total non-green innovation expenditure

³⁸ 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

$$y_{mat} = \mu \cdot y_s$$

$$mat = y_{mat} - rec$$

$$rec = \rho_{rec} \cdot des$$

$$des = \mu \cdot (DA_f + C_{-1}) \cdot \frac{1}{p_{-1}}$$

$$k_{se} = k_{se,-1} + y_{mat} - des$$

$$wa = mat + cen + o2 - emis - \Delta k_{se} = mat - \Delta k_{se}$$

$$cen = \frac{emis}{car}$$

$$o2 = emis - cen$$

$$k_m = k_{m,-1} + conv_m - mat$$

$$conv_m = \max(\sigma_{m,-1} \cdot res_{m,-1}, mat_{-1})$$

$$res_m = res_{m,-1} - conv_m$$

$$p_m = p_m^0 + p_m^1 \cdot \frac{mat_{-1}}{\sigma_{m,-1} \cdot res_{m,-1}}$$

$$\sigma_m = \sigma_m^0 + \sigma_m^1 \cdot E(p_m)$$

Production of material goods

Extracted matter

Recycled socio-economic stock

Destruction of socio-economic stock

Socio-economic stock

Waste generated by production process

Carbon mass of (non-renewable) energy

Mass of oxygen (O2)

Stock of material reserves

Material resources converted to reserves

Stock of material resources

Unit price of extracted matter

Actual conversion rate of matter resources

The Ecosystem: Energy Resources and Reserves

$$en = \varepsilon \cdot y_s$$

$$ed = en$$

$$k_{en} = k_{en,-1} + conv_{en} - en$$

$$conv_{en} = \max(\sigma_{en,-1} \cdot res_{en,-1}, en_{-1})$$

$$res_{en} = res_{en,-1} - conv_{en}$$

$$p_{en} = p_{en}^0 + p_{en}^1 \cdot \frac{en_{-1}}{\sigma_{en,-1} \cdot res_{en,-1}}$$

$$\sigma_{en} = \sigma_{en}^0 + \sigma_{en}^1 \cdot E(p_{en})$$

Energy required for production

Dissipated energy at the end of the period

Stock of energy reserves

Energy resources converted to reserves

Stock of energy resources

Unit price of energy

Actual conversion rate of energy resources

Emissions and climate change

$$emis = \beta \cdot en$$

$$co2 = \psi_1 \cdot co2_{-1} + emis$$

Industrial emissions of CO2

Total emissions of CO2 (where ψ_1 accounts for carbon cycle)

$$temp = temp_{-1} + \psi_2 \cdot co2$$

Atmospheric temperature

Ecological Efficiency

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

Matter intensity coefficient

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

Energy intensity coefficient

$$\beta = \beta_{gr} \cdot \frac{K_{gr}}{K_f} + \beta_c \cdot \frac{K_c}{K_f}$$

CO2 intensity coefficient

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

$$\delta_c = \delta_0 + \delta_1 \cdot (g_{ac,-1} - g_{su,-1}) + \delta_2 \cdot \Delta temp$$

Impact of excess growth and climate change on conventional capital stock depreciation

$$h_0 = h_{00} + h_{01} \cdot (g_{ac,-1} - g_{su,-1}) + h_{02} \cdot \Delta temp$$

Impact of excess growth and climate change on investment share

$$c_w = c_{w0} + c_{w1} \cdot (g_{ac,-1} - g_{su,-1}) + c_{w2} \cdot \Delta temp$$

Impact of excess growth and climate change on propensity to consume

Production Function and Price Level

$$a_f = a_f^0 + a_f^1 \cdot BE_{-1}$$

Endogenous real product per unit of capital

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

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

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

Real potential output (Leontief function)

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

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.

